Estimating the Nitrogen Nutrition Index of Winter Wheat Using an Active Canopy Sensor in the North China Plain

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Abstract*—Precision nitrogen (N) management requires real-time diagnosis of crop N status, and recommends N application rates accordingly. Nitrogen nutrition index (NNI) has been proposed as a better indicator of crop N status, but it is not suitable for practical applications, because it requires destructive plant sampling and time-consuming analysis of plant N concentration. There has been increasing interest in using remote sensing technology to non-destructively estimate NNI. The objective of this study was to determine how well an active canopy sensor could be used to estimate NNI of winter wheat (*Triticumaestivum* L.) in North China Plain, and develop prediction models of NNI using its spectral vegetation indices. A N rate experiment was conducted in Quzhou Experimental Station of China Agricultural University in Hebei Province in 2009/2010. GreenSeeker canopy sensor was used to collect canopy reflectance at different growth stages, and aboveground biomass of the scanned plants were collected and N concentration was determined. The results indicated that vegetation indices (normalized difference vegetation index, NDVI, and red vegetation index, RVI) were significantly related to NNI at different stages, with R^2 being 0.63-0.91, and 0.62-0.87, respectively, except the early stage of Feekes 4. Response index (RI) calculated with NDVI (RI_{NDVI}) or RVI (RI_{RVI}) were significantly related to NNI across growth stages, with R^2 being 0.73 and 0.70, respectively. This result implies that the NNI can be estimated in a rapid, cost-effective way using active canopy sensor. The RI is also a good indicator of winter wheat N status. The GreenSeeker active canopy sensor has a good potential for precision N management in North China Plains.

Keywords: Precision nitrogen management; nitrogen status diagnosis; active canopy sensor; nitrogen nutrition index; nitrogen response index

I. INTRODUCTION

Over-application of nitrogen (N) fertilizers has been a common problem in China, resulting in low nitrogen use efficiencies and pollution of the environment [1-5]. Precision N management is a promising strategy to solve this problem, considering both spatial and temporal variability of crop N demand and supply. This precision management requires real-time diagnosis of crop N status, and recommends N application rates accordingly. Nitrogen nutrition index (NNI) has been proposed as a better indicator of crop N status. For winter wheat, much work has already been done to understand the relationship between N concentration and biomass, with several studies having examined the minimum or critical N concentration required for maximum biomass production [6]-[8]. According to the dilution law, the critical N concentration is related to above ground biomass (DM, Mg ha^{-1}) as follows: $N_c(\%) = a \times DM^{-b}$. For winter wheat in NCP, the values of a and b parameters are 4.15 and 0.38, respectively [9]. This curve was lower than that of Justes et al. in France, possibly due to differences in climatic conditions and wheat varieties. Then, maximal and minimal plant N concentration limits may be determined. NNI is calculated by dividing actual N concentration by N_c. A value of NNI of 1 indicating optimal N status, while a value of NNI<1 or NNI>1 generally indicated N deficiency or excessive fertilization, respectively. However, it is not suitable for practical applications, because it requires destructive plant sampling and time-consuming analysis of plant nitrogen concentration.

There has been increasing interest in using remote sensing technology to non-destructively estimate NNI. Several studies, for example, have shown that NNI could be replaced by SPAD measurements. Vouillot et al. have studied the relationship between SPAD and NNI of winter wheat, but at early stem elongation [10]. Debaeke et al. have proposed that the normalized SPAD index and NNI were closely related irrespective of year, cultivar, and growth stage, but only for durum wheat [11]. Prost et al. have showed that the SPAD index can substitute NNI measurements to assess N deficiencies [12]. Although there was a year effect on the relationship between the SPAD index and NNI, the general model gave a prediction accurate enough to detect N deficiencies correctly. However, this conclusion should be further evaluated at other locations. Ziadi et al. have studied the relationship between SPAD and NNI of corn and found that the SPAD and SPAD index were significantly related to NNI, but affected by site-year interactions [13].

Although several studies have proved that relationship between SPAD/SPAD index and NNI were closely related, these measurements are equally time consuming with values being accurate only for the measured spot [14]. N concentration is neither homogeneous within the flag leaf nor within the canopy [15-16]. Spectral measurements appear to offer several advantages over more traditional methods to determine the N status. However, specific knowledge about the relationship between NNI and spectral canopy reflectance is limited. Mistele and Schmidhalter used field spectrometer similar to the Yara sensor to get spectral information of the crop canopy reflectance and founded that the NNI can indeed be determined in a rapid, cost-effective fashion using spectra-based measurements. The relationship between the NNI and the canopy reflectance intensity was validated in a three year field experiment for winter wheat with an overall average R^2 of 0.95 [17].

Review of the literature indicated that there are little studies that have focused on using active canopy sensor to estimate NNI under field conditions in NCP. The objective of this study was to determine how well an active canopy sensor could be used to estimate NNI of winter wheat in North China Plain, and develop prediction models of NNI using spectral vegetation indices.

II. MATERIAL AND METHODS

A. Field experiment

Field experiment was conducted in Quzhou county (36.9°N, 115.0°E) in Hebei province. Five N treatments, including no N as a control (CK); optimal N rate based on in-season root-zoon N management (Opt.); farmer's N practice (FNP); and 50% and 150% of Opt., were applied in 2010. The Opt. was determined according to an in-season root-zoon N-management strategy [1-4]. In this strategy, the wheat-growing season is divided into two periods: from planting to stage Feekes 6, and from Feekes 6 to the mature stage. The amount of N fertilizer applied at the beginning of each growing period was determined by deducting the amount of soil Nmin (NH_4^+-N+NO_3^--N) in the root zoon from the target N value, which was estimated based on the yield target and crop N uptake. The target N values for the above two periods were150 and 200, respectively. The FNP was set at 300 kg N ha^{-1} (150 kg N ha^{-1} applied before planting and 200 kg N ha^{-1} applied at stage Feekes 6), which is typical for Hebei province. Based on soil P and K test results, all treatments received appropriate amounts of triple superphosphate (150 kg P_2O_5 ha^{-1}) and potassium chloride (120 kg K_2O ha^{-1}) before planting. The N source for all treatments was urea. A widely used winter wheat variety in this region, Liangxing 99, was used in the experiment.

B. Active canopy sensor data collection

The GreenSeeker Hand Held optical reflectance sensor uses active radiation from red (650±10nm) and near infrared (770±15nm) band independent of solar radiations. The device uses built-in software to calculate NDVI and ratio vegetation index (RVI, NIR/Red) directly and generates sensor readings at a rate of 10 readings per second. Sensors readings (NDVI and RVI) were collected approximately 0.6 to 1.0 m above winter wheat canopy and walking the same speed in each plot, and the average values were used to represent each plot. Sensor readings were collected at five different stages (Feekes Growth Stage 4, 5, 6, 9, 10.5) in all plots and the sensor path was parallel to the seed rows or the beam of light was perpendicular to the seed row.

To compensate for factors other than N status that affect sensor readings, the sensor readings taken from plants in a fully fertilized reference plot in the same field could eliminate or reduce the effect of growth stage and hybrid. The normalized NDVI and RVI were calculated as the ratio of the NDVI and RVI of the plot which receiving the highest N rate to that of one treatment in the same experiment.

C. Plant sampling and measurement

Aboveground biomass was collected by randomly clipping 100 by 30 cm vegetation from scanned plants following sensing in each plot. All plant samples were oven dried at 75℃ to constant weight then weighed, ground, and Kjeldahl-N was determined. Plant samples were taken at Feekes Growth Stages 4, 5, 6, 9 and 10.5. The plant N uptake was determined by multiplying plant N concentration by dry biomass.

D. Determination of the nitrogen nutrition index

The critical N dilution curve for winter wheat was described by the following equation, based on several N fertilization experiments conducted in NCP on winter wheat crops [9]:

$$Nc = 4.15 * W^{-0.38}$$

where N_c is the critical N concentration as a percentage of above ground dry matter, expressed in %DM and W is the above ground biomass, expressed in Mg dry matter (DM) ha^{-1}. This critical N dilution curves can be applied most robustly when above ground biomass was between 1 and 10 Mg DM ha^{-1}. When above ground biomass was <1 Mg DM ha^{-1}, a constant critical value N_c = 4.15%DM was used, which was independent of above ground biomass. To indicate the N status for each plot, independent of the growth stage and differing biomasses, the NNI was calculated as follows:

$$NNI = \frac{Nact}{Nc}$$

where N_{act} is the actual measured N concentration as a percent of the dry matter of the canopy biomass and N_c is the critical N content for the crops of each plot given their amount of dry weight [16].

E. Statistical analysis

Correlation, regression, and analysis of variance (ANOVA) were conducted using STATISTICA 6.0 (StatSoft, Inc., Tulsa, Oklahoma, USA) and MicroSoft Excel (MicroSoft Cooperation, Redmond, Washington, USA).

III. RESULTS AND DISCUSSION

A. Destructive anylysis of the biomass samples

The results of the destructive analysis of the biomass samples are indicated in Fig. 1. The N status during crop growth differs between the different growth stages. At Feekes growth stage 4, all plots displayed N efficiency. 45%, 65%, 25% and 20% of the plots possessed adequate N statuses at the Feekes growth stage 5, 6, 9 and 10.5, respectively. With increasing biomass the slopes of the curves tended to decrease and the values decrease. Yue et al. found that for the experiments used to validate critical N dilution curve, the NNI values at different sampling stages of N deficiency treatment were generally <1, while generally >1 for N excessive treatments [9]. However, in our results, the NNI values at different sampling stages of N excess treatment were not always >1, especially at the late growth stages, e.g. Feekes 9 and 10.5.

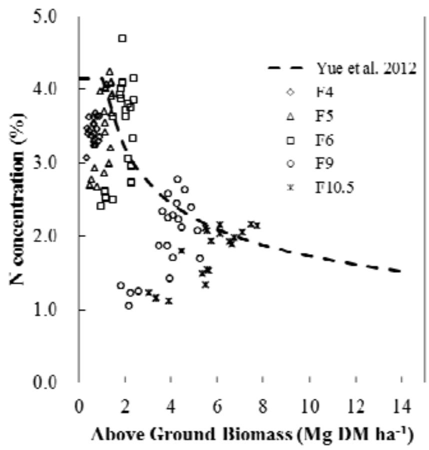

Figure 1. Relationships between biomass dry weight and N concentration with critical N curves.

B. Relationship between VIs (NDVI and RVI) and NNI

At the early growth stage of Feekes 4, the relationship between vegetation indices (NDVI and RVI) and NNI were not significant. Because it might be difficult to differentiate crop canopies at earlier growth stages due to less structural tissue is found and the same relationship between structural tissue and metabolic tissue applies [17]. From Feekes 5 to Feekes 10.5, the relationship between NDVI and NNI was strong, with R^2 being 0.63, 0.67, 0.77 and 0.91, respectively. RVI showed similar relationship as NDVI, with R^2 being 0.69, 0.62, 0.71 and 0.87, respectively.

Combining all growth stages, however, the relationship between NDVI or RVI and NNI were weaker than at different growth stage except Feekes 4, with R^2 being less than 0.25 (Table 1).

C. Relationship between N response index and NNI

The relationships between response index calculated with GreenSeeker values (RI_{NDVI} or RI_{RVI}) and NNI were exponential across different growth stages except for Feekes 4, with R^2 being 0.73 and 0.70, respectively. It's stronger as compared with the relationship between NDVI or RVI and NNI. We found no references to compare this relationship with other research results. Debaeke et al. identified an exponential relationship between the SPAD index and the NNI during stem elongation and a linear SPAD/NNI relationship at flowering [11]. However, Prost and Jeuffroy found a positive exponential relationship between the NNI and the SPAD index with a R^2 of 0.87. The RI_{NDVI} and RI_{RVI} seemed to be able to replace NNI measurements to assess N status of winter wheat but the experiments which allowed us to build the relationship between RI_{NDVI} or RI_{RVI} and NNI were done at only one location and only one year, and thus need to be tested in various other locations and years. This result about the N status of winter wheat by using active canopy sensor is useful to support variable rate N application, especially because the active canopy sensor allowed N status to be estimated quickly and non-destructively.

TABLE I. RELATIONSHIPS BETWEEN GREENSEEKER VALUES (NDVI & RVI) AND NNI AT DIFFERENT GROWTH STAGES IN 2010

Stage	Index	linear Equation	R^2	Nonlinear Equation	R^2
Feekes4	NDVI	NS	NS	NS	NS
Feekes4	RVI	NS	NS	NS	NS
Feekes5	NDVI	Y=2.16X+0.25	0.57	$Y=2.09X^{0.70}$	0.63
Feekes5	RVI	Y=0.62X-0.32	0.66	$Y=0.34X^{1.40}$	0.69
Feekes6	NDVI	Y=1.65X+0.21	0.54	$Y=-7.98X^2+9.15X-1.44$	0.67
Feekes6	RVI	Y=0.29X+0.22	0.40	$Y=-0.35X^2+2.29X-2.53$	0.62
Feekes9	NDVI	Y=1.42X+0.02	0.67	$Y=1.45X^{1.01}$	0.77
Feekes9	RVI	Y=0.15X+0.27	0.46	$Y=-0.10X^2+0.86-0.825$	0.71
Feekes10.5	NDVI	Y=1.40X-0.01	0.87	$Y=0.24e^{2.0068X}$	0.91
Feekes10.5	RVI	Y=0.18X+0.14	0.85	$Y=0.27X^{0.82}$	0.87
All	NDVI	Y=0.54X+0.65	0.20	$Y=0.46X^2+0.95X+0.57$	0.20
All	RVI	Y=0.07X+0.68	0.14	$Y=0.05X^2+0.43X+0.18$	0.22

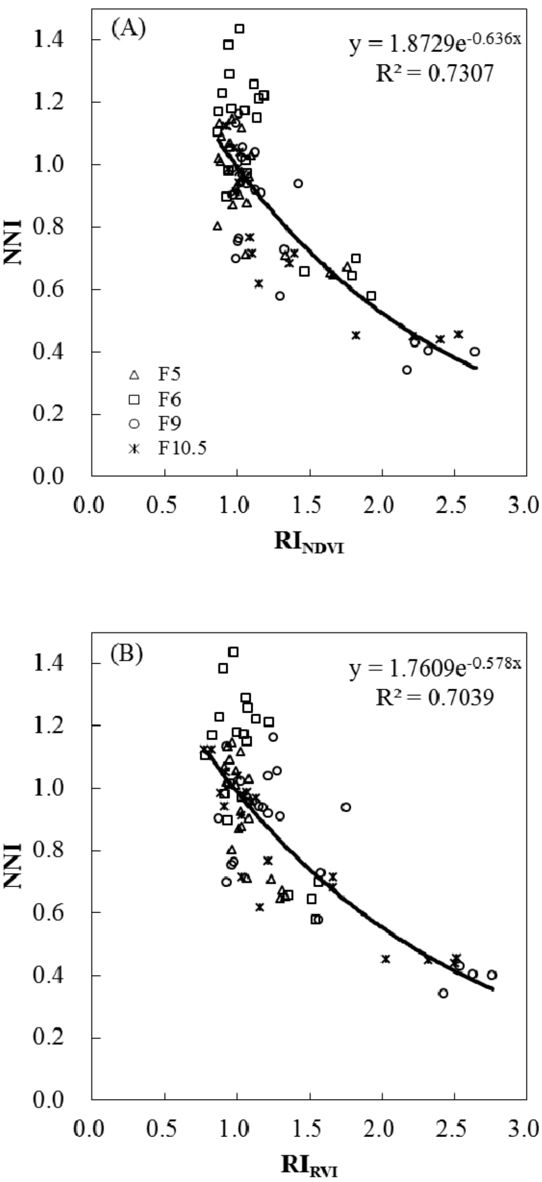

Figure 2. (A) Relationship between RINDVI and Nitrogen Nutrition Index (NNI). (B) Relationship between RIRVI and NNI.

IV. CONCLUSION

The results of this study indicated that vegetation indices (normalized difference vegetation index, NDVI, and red vegetation index, RVI) were significantly related to NNI at different stages, with R^2 being 0.63-0.91, and 0.62-0.87, respectively, except the early stage of Feekes 4. Response index (RI) calculated with NDVI (RI_{NDVI}) or RVI (RI_{RVI}) were significantly related to NNI across growth stages except Feekes 4, with R^2 being 0.73 and 0.70, respectively. This conclusion should be evaluated at other locations and years. This result implies that the NNI can be estimated in a rapid, cost-effective way using active canopy sensor. The response index is also a good indicator of winter wheat N status. The GreenSeeker active canopy sensor has a good potential for precision nitrogen management in North China Plains.

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REFERENCE

[1] Z. Cui, X. Chen, Y. Miao, F. Zhang, J. Schrode, H. Zhang, “On-farm Evaluation of the Improved Soil Nmin-based Nitrogen Management for Summer Maize in North China Plain,” Agron. J., vol. 100, pp. 517-525, 2008.

[2] Z. Cui, F. Zhang, X. Chen, Y. Miao, J. Li, J. Xu, et al., “On-farm evaluation of an in-season nitrogen management strategy based on soil Nmin test,” Field Crops Research, vol. 105, pp. 48-55, 2008.

[3] X. T. Ju, C. L. Kou, F. S. Zhang, P. Christie, “Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain,” Environmental Pollution, vol. 143, pp. 117-125, 2006.

[4] X. T. Ju, G. X. Xing, X. P. Chen, S. L. Zhang, L. J. Zhang, X. J. Liu et al., “Reducing environmental risk by improving N management in intensive Chinese agricultural systems,” Proceedings of National Academy of Sciences USA (PNAS), vol. 106, pp. 3041–3046, 2009.

[5] Y. Miao, B. A. Stewart, F. Zhang, “Long-term experiments for sustainable nutrient management in China,” Agronomy for Sustainable Development, vol. 31, pp. 397–414, 2011.

[6] Lemaire, M. Khaity, B. Onillon, J. M. Allirand, M. Chartier, G. Gosse, “Dynamics of Accumulation and Partitioning of N Leaves, Stems and Roots of Lucerne in a Dense Canopy,” Annals of Botany, vol. 70, pp. 429-435, 1992.

[7] Lemaire, J. C. Avice, T. H. Ourry, “Developmental Changes in Shoot N Dynamics of Lucerne (Medicago satival L.) in Relation to Leaf Growth Dynamics as a Function of Plant Density and Hierarchical Position within the Canopy,” J. Exp. Bot., vol. 56, pp. 935-943, 2005

[8] J. Greenwood, F. Gastal, G. Lemaire, A. Draycott, P. Millard, J. J. Jeeteson, “Growth Rate and %N of Field Grown Crops: Theory and Experiments,” Annals of Botany, vol. 67, pp. 181-190, 1991.

[9] S. Yue, Q. Meng, R. Zhao, F. Li, X. Chen, and F. Zhang, et al., “Critical Nitrogen Dilution Curve for Optimizing Nitrogen Management of Winter Wheat Production in the North China Plain,” Agron. J., vol. 104, pp. 523-529, 2012.

[10] M. O. Vouillot, P. Huet, P. Boissard, “Early Detection of N Deficiency in a Wheat Crop Using Physiological and Radiometric Methods,” Agronomie, vol. 18, pp. 117-130, 1998.

[11] P. Debaeke, P. Rouet, and E. Justes, “Relationship Between the Normalized SPAD Index and the Nitrogen Nutrition Index: Application to Durum Wheat,” J. Plant Nutr., vol. 29, pp. 75-92, 2006.

[12] L. Prost and M. H. Jeuffroy, “Replacing the Nitrogen Nutrition Index by the Chlorophyll Meter to Assess Wheat N Status,” Agron. Sustain. Dev., vol. 27, pp. 321-330, 2007.

[13] N. Ziadi, M. Brassard, G.Bélanger, A. Claessens, N. Tremblay, and A. N. Cambouris, et al., “Chlorophyll Measurements and Nitrogen Nutrition Index for the Evaluation of Corn Nitrogen Status,” Agron. J., vol.100, pp. 1264-1273, 2008.

[14] T. M. Blackmer, J. S. Schepers, G. E. Varvel, “Light Reflectance Compared with Other Nitrogen Stress Measurements in Corn Leaves,” Agronomy J., vol. 86, pp. 934-938, 1994.

[15] A. Cartelat, Z. G. Cerovic, Y. Goulas, S, Meyer, C. Lelarge, J. L. Prioul et al., “Optically Assessed Contents of Leaf Polyphenolics and Chlorophyll as Indicators of Nitrogen Deficiency in Wheat,” Field Crops Research, vol. 91, pp. 35-49, 2005.

[16] Lemaire, F. Gastal, “N Uptake and Distribution in Plant Canopies,” in G. Lemaire, (Ed.), Diagnosis of the Nitrogen Status in Crops, pp. 3-41, 1997.

[17] B. Mistele and U. Schmidhalter, “Estimating the Nitrogen Nutrition Index Using Spectral Canopy Reflectance Measurements,” Europ. J. Agronomy, vol. 29, pp. 184-190, 2008.