Recommendations for Nitrogen Fertilizer in Winter wheat Based on Nitrogen Nutrition Index

Yu Zhao
Beijing Research Center for Information Technology in Agriculture, Beijing Academy of Agriculture and Forestry Sciences
Beijing, China
zy928286257@163.com

Zhenhai Li*
Beijing Research Center for Information Technology in Agriculture, Beijing Academy of Agriculture and Forestry Sciences
Beijing, China
lizh323@126.com

Jianwen Wang
Beijing Research Center for Information Technology in Agriculture, Beijing Academy of Agriculture and Forestry Sciences
Beijing, China
15313918695@163.com

Wude Yang
Institute of Dry Farming Engineering, Shanxi Agricultural University
Shanxi, China
sxauywd@126.com

Dandan Duan
Beijing Research Center for Information Technology in Agriculture, Beijing Academy of Agriculture and Forestry Sciences
Beijing, China
duandd@nercita.org.cn

Xiaobin Xu
Beijing Research Center for Information Technology in Agriculture, Beijing Academy of Agriculture and Forestry Sciences
Beijing,China
64358748@qq.com

***Abstract*—A critical nitrogen (N_c) concentration, defined as the minimum nitrogen (N) concentration required for maximum plant growth, could be used as an intermediate variable between remote sensing data and recommendation for N fertilizer. In this study, the critical N concentration dilution curve was established based on aboveground biomass (AGB) from data at jointing, booting, anthesis and filling stages. The quantitative correlations between normalized difference vegetation (NDVI) and nitrogen nutrition index (NNI) were established. Finally, an N recommendation model combined with the N fertilizer effect function and NDVI was established and verified by field test data. Results showed that the N concentration of winter wheat decreased gradually during the reproductive growth period, and The plant N concentration could be described by $N_c = 6.27 * AGB^{-0.54}$,with the R^2 value of 0.80. Moreover, the thresholds of NDVI were 0.87, 0.91, 0.91 and 0.81 at jointing, booting, anthesis and filling stages, respectively, and the amounts of recommending nitrogen fertilizer were 2.63, 10.00, 11.11 and 10.00 kg N/hm^2 when NNI value lowed 1% of corresponding period's thresholds. Field experiments illustrated that jointing and booting stage could be used as the N fertilizer periods to guarantee winter wheat yield, and integrating N_c curve and hyperspectral data had advantages in N fertilizer recommendations.**

Keywords—Nitrogen Nutrition Index; NDVI; Nitrogen recommendations; Winter wheat

Introduction

Nitrogen is an important element to limit the production of winter wheat. The researches demonstrated that the fundamental basis for applying remote sensing methods to fertilizer recommendations is an accurate diagnosis of plant nutrition [1]. The canopy spectral characteristics at visible, near-infrared and middle-infrared wavelengths have been correlated to chlorophyll concentration, which in return are related to N concentration in crop [2-3]. Compared with traditional methods, the approaches for determining N rates based on remote sensing, e.g., N application model, N fertilizer optimization algorithm (NFOA) [4], leaf area index (LAI) [5] and nitrogen nutrition index (NNI) [6], could decrease the environmental and increase the N use efficiency. Above all, N recommendations are generally calculated by using characteristic canopy wavelengths or the vegetation indices derived from them.

The N_c dilution concentration was expressed by a power function, which was defined as the minimum N concentration required for maximum crop growth [7-9]. NNI is sensitive to nitrogen nutrition level of crops and superior to other nutrition diagnostic indexes (plant N concentration, biomass and chlorophyll concentration), which can accurately distinguish the concentration of crop N and satisfy the demand of crop growth [10,11]. The method could be used for predicting site-specific fertilizer rates and implementation of site-specific N management schemes that account for real-time variations in crop N demand at major crop growth stages.

In China, farmers often apply large amounts of chemical fertilizer to increase yields to feed increasing populations at a limited amount of arable land [12]. Therefore, research for field-specific N management that are based on in-season assessment of the N requirements is both necessary and challenging. The specific objectives of the current study were to construct and validate an N_c dilution curve based on AGB, to establish the NNI model based on N_c dilution and NDVI, and to confirm the N topdressing model at jointing, booting, anthesis and filling stages of winter wheat.Estimating and dynamic monitoring of nitrogen (N) in winter wheat is critical for optimizing the management strategies and evaluating winter wheat quality[13].

MATERIALS AND METHODS

A. Experimental design

Experiments were carried out during the 2012/2013, 2013/2014 and 2014/2015 growing seasons at Xiaotangshan experimental site (40°10′30″-40°11′18″N, 116°26′10″-117°27′05″E) of Beijing, China). The soil type in test plot was fine-loamy soil (Alfisols in U.S. taxonomy) developed

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from loess parent material with 3.16-14.82 mg kg^{-1} nitrate N (NO_3-N), 10.20-12.32 mg kg^{-1} ammonium N (NH_3-N), 86.83-120.62 g kg^{-1} organic matter, 15.84-20.24 mg kg^{-1} available potassium, and 18.43 mg kg^{-1} available phosphorus. Tested fertilizers include Urea with 46% of N, and superphosphate with 12% of P_2O_5.

Experiment 1: The experiment was a randomized block with two replications. The nitrogen treatments in 2012-2013 growing season were 0 kg N hm^{-2}, 104 kg N hm^{-2}, 208 kg N hm^{-2}, and 416 kg N hm^{-2}. Nongda 211, Zhongmai 175，Zhongyou 206 and Jing 9843 were chosen as test cultivar. The plot area was 90 m^2 (10 m × 9 m). Other field management was the same as the local standard practices. The data obtained from this experimental were used for modeling.

Experiment 2: The experiment was orthogonal experimental design, L_{16} (3^4), with three factors including N rates, varieties and irrigation volume onver 2013-2014. The winter wheat varieties were Jing 9843 and Zhongmai 175. Four nitrogen levels (0, 90, 180, 360 kg N hm^{-2}) were designed. The irrigation volume levels were 25 mm, 171 mm, and 317 mm. The plot area was 150 m^2 (10 m×15 m) with three replications at each plot. Other field management was the same as the local standard practices. The data obtained from this experimental were used for modeling.

Experiment 3: Orthogonal experimental design, L_{16}(3^4), with three factors including N rates, varieties and irrigation volume over 2014-2015 was designed. Wheat cultivars were Jing 9843 and Zhongmai 175. Four nitrogen levels (0, 90, 180, 360 kg N hm^{-2}) were designed. The irrigation volume levels were 25 mm, 217 mm, and 409 mm. The plot are was 48 m^2 (6 m×8 m) with 3 replications. Other field management was the same as the local standard practices. These data were used as verification.Field experiments were implemented at National Experiment Station for Precision Agriculture, Changping District, Beijing, China (40.17°N, 116.43°E). The experiment was designed as an orthogonal experiment design with two wheat cultivars, four application rates of N fertilizer, and three irrigation regimes (Fig. 1). Three replications of each plot were considered during data collecting.

B. Data collection

The canopy reflectance of winter wheat was collected by an ASD FieldSpec Handheld spectrometer (Analytical Spectral Devices Inc., USA)field actinography with the wavelength range of 350 ~ 2500 nm, with the sampling intervals of 1.4 nm (350 ~ 1000 nm) and 2 nm (1000 ~ 2500 nm). The viewing angle was set to 25°. The test was conducted at 10:00 ~ 14:00 under the weather with clear, breezeless, and low wind speed. The sensor probe located about 1.0 m perpendicular to the top of the canopy. The standard white board was used to calibrate spectral reflectance before the measurement. The average of 10 spectra was used as the final spectrum at each measurement point.

At the corresponding position of the acquired canopy spectral reflectance, the winter wheat samples of 20 wheat tillers per plot were sealed bag and taken to the laboratory for N concentration and AGB measurements. All samples were wrapped 30 minutes in the oven at 105 °C and baked at 80 °C until the weight is constant. Weighed the samples once every two hours, the difference between two measurements was <5‰. The plant N concentration (PNC) was measured via Kjedahl method [13].

Table 1 List of dta acquisition in 2012-2013, 2013-2014, 2014-2015 wheat experiments.

Phenology	No.	Canopy spectral	AGB	PNC
2012/2013				
Jointing	32	-	√	√
Booting	32	√	√	√
Anthesis	32	√	√	√
Filling	32	√	√	√
2013/2014				
Jointing	48	√	√	√
Booting	48	√	√	√
Anthesis	48	√	√	√
Filling	48	√	√	√
2014/2015				
Jointing	48	√	√	√
Booting	48	√	√	√
Anthesis	48	√	√	√
Filling	48	√	√	√

Note: No., AGB, and PNC represent the number of samples, aboveground biomass and plant nitrogen concentration, respectively. √ and - represent the data of measured and not measured, respectively.

C. Nitrogen topdressing recommendation approach based on NNI

With this approach, it is essential to find out the plant N_c point which neither limits crop growth nor excessively absorbs N fertilizer. The computational procedures of plant N_c points, following Justes et al. [7], were as follows:

1) AGB and PNC were used to analyze whether plant growth was limited by N management;

2) the simple linear regression was used to fit data from N limitation;

3) the maximum AGB was calculated with data from the non-N-limiting treatments as the average of the observed data and vertical line perpendicular to horizontal axis was fitted;

4) the N_c points were the intersection of above two curves;

5) these N_c points of different periods were fitted by power function curve to construction the plant N_c curve. The plant N_c curve is calculated as:

$$N_c=\lambda_1*AGB^{\lambda_2} \quad (1)$$

Where λ_1 and λ_2 were parameters obtained by calibrating the N_c points with AGB value.

Traditional NNI value was a function of the ration between PNC and N_c. Thus:

$$NNI=PNC/N_c$$
$$=PNC/\lambda_1*AGB^{\lambda_2} \quad (2)$$

In this study, determine the NNI of current crop by NDVI calculated by canopy reflectance at 800 nm (NIR) and 670 nm (Red), according to Tucker (1979) et al.:

$$NDVI=(R_{800}-R_{670})/ (R_{800}+R_{670}) \quad (3)$$
$$NNI=\lambda_3*\exp(\lambda_4*NDVI) \quad (4)$$

Where λ_3 and λ_4 were parameters obtained by calibrating NNI value with NDVI value.

According to the linear relationship between the NNI value of different periods and N rates in winter wheat, an N recommendation model based on NNI value could be established. The linear regression relationship between NNI value and N rates was as follows:

$$NNI=a+b*N_{con} \quad (5)$$
$$Ntopdressing=N_{opt}-N_{con}$$
$$=N_{opt}+a/b-NNI/b \quad (6)$$

Where a and b represented the intercept and the regression coefficient of linear equation. N_{opt} was the optimal N topdressing rates. N_{con} represented the actual N rates.

D Model evaluation

Determination coefficient (R^2), root mean squared error (RMSE) [13], and residual prediction deviation (RPD) were used to judge model performance synthetically. R^2 represents the fitting of the model between the predicted and measured value, and RPD reflects the accuracy and robustness of the model. It is generally believed that the prediction ability of the model is better with (RPD > 2), poor (1.4 < RPD < 2) or difficult to be applied to practice (RPD < 1.4) [14].

$$R^2 = 1\frac{\sum_{i=1}^{n}(Y_i - Y_i')\Big/(n-p-1)}{\sum_{i=1}^{n}(Y_i - Y_i')^2\Big/(n-1)} \tag{7}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Y_i - Y_i')^2} \tag{8}$$

$$RPD = \frac{SD}{RMSE} \tag{9}$$

Where n and p indicate the number of samples and independent variable, respectively; Y_i' and Y_i express the predicted value and measured value, respectively; and SD is the standard deviation of measured value.

II. RESULTS AND DISCUSSION

A. Plant N concentration and aboveground biomass under varied N treatments

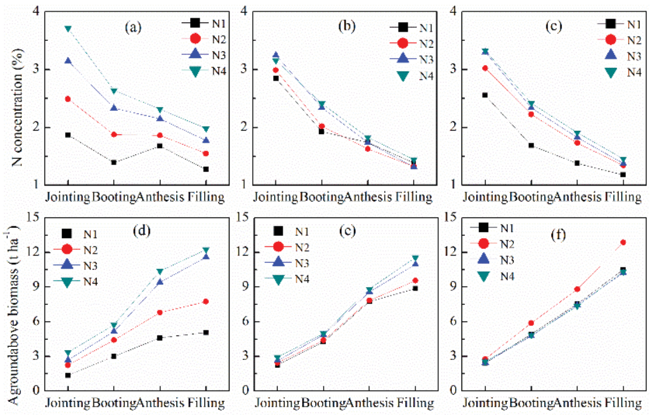

Fig.1 Changes in winter wheat N concentration (PNC) and aboveground biomass (AGB) at various growth stages for different nitrogen treatments in 2012-2013 (a, PNC; d, AGB), 2013-2014 (b, PNC; e, AGB) and 2014-2015 (c, PNC; f, AGB).

The N application rate had a significant effect on PNC and AGB during the growth stages. The change in winter wheat from 2012-2013, 2013-2014 and 2014-2015 showed that the PNC decreased gradually during the reproductive growth period, ranged from 4% to 1%. At the same stage, the order of PNU value from high to low generally was N4, N3, N2, and N1.

AGB increased gradually with the increasing rate of N rates, ranged from 1 to 13 t hm^{-2}. In 2012-2013 and 2013-2014, AGB increased significantly from N1 to N2 treatments, but there were no significant differences among N3 and N4 treatments. In 2014-2015, AGB increased linearly with the growth period. In 2012-2013, 2013-2014 and 2014-2015, the maximum AGB of NNI method was obtained at the N3, N3, and N4, respectively.

B. Determining the critical dilution curve for winter wheat

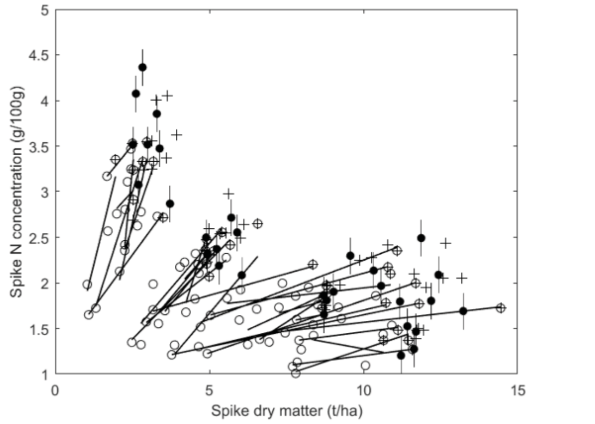

Fig.2 Critical N data points used to develop plant N_c curves. The symbols (○) and (+)represent the data points of N-limiting treatments and non-N-limiting treatments obtained from the for 2012-2013, 2013-2014 and 2014-2015 seasons. The symbols (●) represents the calculated N_c points for each sampling date.

The plant N_c points were found based on AGB and PNC from the experiments conducted in 2012-2013 and 2013-2014. The results showed that PNC in winter wheat decreased with the growing AGB. According to the N_c points, the plant N_c could be described by $N_c = 6.27*AGB^{-0.54}$, with R^2 value of 0.80 (Fig.3). According to N_c curve, the average threshold value of AGB for two years was 3.01 t hm^{-2} (jointing stage), 5.37 t hm^{-2} (botting stage), 9.70 t hm^{-2} (anthesis stage) and 11.88 t hm^{-2} (filling stage), respectively. The average threshold value of PNC for two years was 3.59% (jointing stage), 2.38% (botting stage), 2.02% (anthesis stage) and 1.61% (filling stage), respectively. The N_c curve divides the samples into 3 cases: N limited status below the curve, N-excess status above the curve and N balance closed this curve

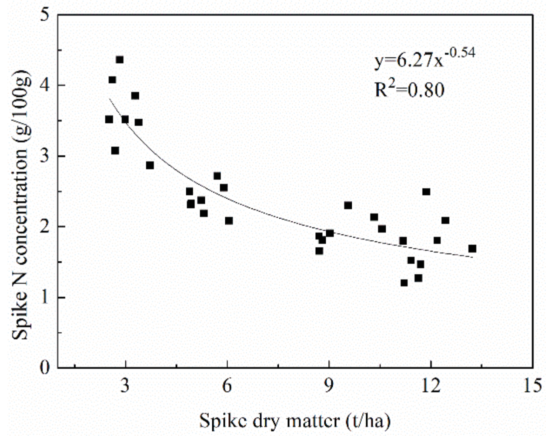

Fig.3 Nitrogen concentration dilution curve for winter wheat

C. The relationship between NNI and NDVI

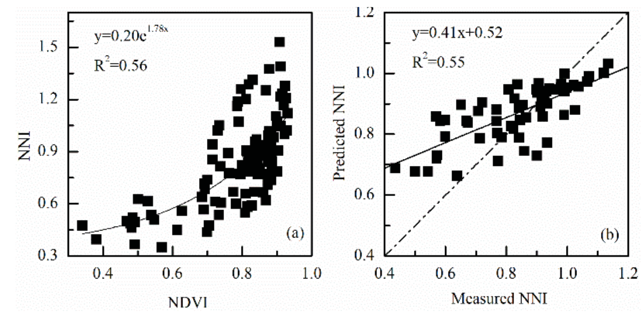

Fig.4 Relationship between NDVI and NNI at jointing, booting, anthesis and filling stages. The solid line is used to fit the predicted and measured value. The dotted line is indicating that the predicted values are equal to measured values.

The NDVI and NNI value from 2012-2013 and 2013-2014 seasons were used to establish an exponential model (Fig.4). Results showed that NNI values increased with growing NDVI values and trended to saturation. The NNI value could now be reliably predicted over stage of growth with an exponential equation, and the calculated values of λ_3 and λ_4 were 0.20 and 1.78, respectively (R^2=0.56**, n=112). Moreover, the validated model which derived from 2014-2015 season also achieved a better accuracy and robustness with a determination coefficient of 0.55.

D. Recommended N application model

Table 2 Recommended nitrogen application model at various growth stages of winter wheat

	Jointing	Booting	Anthesis	Filling
a	0.59	0.71	0.70	0.50
b (%)	0.38	0.10	0.09	0.10
R^2	0.77**	0.56**	0.53**	0.55**
RMSE	0.11	0.12	0.12	0.18
RPD	1.81	3.17	3.08	1.91
N_{opt}	90	180	—	—
N_r (kg hm^{-2})	2.63	10.00	11.11	10.00

Note: N_{opt} and N_c represented the optimal N topdressing rates and the N requirements when NNI value lowed 1%, respectively. The probability levels were indicated by * and ** for 0.05 and 0.01, respectively.

In the recommended N application model based on NNI from remote sensing data, the determination of crop N requirement per unit NNI was crucial. In this study, NNI was used as an estimator of N rates. The results showed a better relationship between NNI and actual N rates. At jointing stage, the calculated a and b were 0.59 and 0.38%, respectively (n=16, R^2=0.77**, RMSE=0.11 kg hm^{-2} and RPD=1.81). At booting stage, the calculated a and b were 0.71 and 0.10%, respectively (n=32, R^2=0.77**, RMSE=0.12 kg hm^{-2} and RPD=3.17). At anthesis stage, the calculated a and b were 0.70 and 0.09%, respectively (n=32, R^2=0.53, RMSE=0.12 kg hm^{-2} and RPD=3.08). At filling stage, the calculated a and b were 0.50 and 0.10%, respectively (n=32, R^2=0.55**, RMSE=0.18 kg hm^{-2} and RPD=1.19). The amounts of recommended nitrogen fertilizer were 2.63, 10.00, 11.11 and 10.00 kg N hm^{-2} when NNI value lowed 1% at jointing, booting, anthesis and filling stages, respectively.

III. Conclusion

The present study confirmed the recommended N topdressing model using NNI of winter wheat was a practical method for making in-season fertilizer N recommendations. The field test data treated with different fertilizer levels in 2012-2013, 2013-2014 and 2014-2015 were obtained, N concentration decreased with increasing AGB. Based on the theory of N_c dilution, the N_c curve was described by the power equation N_c=6.24*AGB$^{-0.54}$, with the R^2 value of 0.80. The NNI model with the power function based on NDVI, which yielded the determination coefficient of 0.56. Moreover, the validated model also achieved a better accuracy and robustness with a determination coefficient of 0.55. The amounts of recommended nitrogen fertilizer were 2.63, 10.00, 11.11 and 10.00 kg N hm^{-2} when NNI value lowed 1% at jointing, booting, anthesis and filling stages, respectively. We conclude that NNI offers an effective method to determine the N topdressing rate at critical growth stages.

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