Nitrogen Status Estimation of Winter Wheat by Using an IKONOS Satellite Image in the North China Plain

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Abstract. The objective of this study was to determine relationship between high resolution satellite image and wheat N status, and develop a methodology to predict wheat N status in the farmers' fields. Field experiment with 5 different N rates was conducted in Huimin County in the North China Plain, and farmers' fields in 3 separated sites were selected as validation plots. The IKONOS image covering all research sites was obtained at shooting stage in 2006. The results showed that single band reflectance of NIR, Red and Green and vegetation indices of NDVI, GNDVI, RVI and OSAVI all well correlated with wheat N status parameters. Field validation results indicated that the prediction models using OSAVI performed well in predicting N uptake in the farmers' fields (R^2 = 0.735). We conclude that high resolution satellite images like IKONOS are useful tools in N fertilization management in the North China Plain.

Keywords: IKONOS image, vegetation indices, nitrogen status, winter wheat

1 Introduction

The North China Plain is one of the most important grain yield production areas in China. Excessive N fertilizer application is considered as a common problem for wheat production in this area and results in low nutrient use efficiency and potentially exerts more pressure on the environment such as nitrate leaching to the ground water[1-4]. In recent years, scientists have developed several in-field soil-plant analysis methods to monitor the N status of various crops to optimize the timing and rate of N application, including the plant total N content and SPAD readings[5], the testing of sap nitrate in the basal stem of wheat at specific growth stage[6-7] and soil Nmin test[8-9]. All these approaches, however, need destructive sampling and laboratory analysis, which limited their applications for wheat N management for large areas in the North China Plain.

Considering these problems, some researches now focus on remote sensing methods especially using canopy multispectral reflectance or aerial photography to monitor wheat growth conditions. Aerial photography, which uses color or infrared film, has been used in detection N deficiency, evaluation of plant growth status and prediction of N fertilizer requirements of wheat[10-11] and maize[12-14]. In these contributions, aerial photography provided high spatial resolution images of crop canopy and showed the potential of quantifying crop N status variation within and between fields. However, aerial photography is always restricted by the weather conditions and flying control on the ground. Another shortcoming is that aerial photography can only cover small areas with plane[12] or hellium balloon[11,15]. When it comes to regional scale, such as a county level or provincial level, the acquisition of crop canopy images will be too time-consuming and expensive.

With the development of remote sensing technology, satellites now can provide commercial, public accessible and high spatial resolution image data. For example, IKONOS or Quickbird can provide multi-spectral data of 2-4 meter resolution covering the blue to near infrared spectrum, which may be used for crop N management[16]. Wright et al.[17] found significant correlations between NDVI, extracted from IKONOS image, with N content of wheat flag leaves and pre-season N input. Zhang et al.[18]indicated the IKONOS image successifully estimate the rice leaves N content. Shou et al.[19]found significant correlations between vegetation indices (NDVI, RVI, GNDVI and DVI) and digital values of NIR, Red, Green and Blue bands extracted from a Quickbird image with N status indicators (chlorophyll meter readings, stem sap nitrate concentration, aboveground biomass and shoot N concentration at shooting stage). However, all these researches were conducted in small and controlled experiments. Studies conducted in real farmers' fields, especially in overfertilized fields in the North China Plain, and which transfer the small experimental based studies results to farmers fields N recommendation, are very limited. Therefore, the objective of this research was to use high spatial resolution, multispectral satellite image to predict winter wheat N status in farmers' fields at the shooting stage, which was the critical N sensitive stage to wheat, and evaluate this approach against conventional soil and plant sampling methods.

2 Material and Methods

2.1 The Experiments

2.1.1 Experiment 1: Nitrogen fertilization rate experiment

A winter wheat field experiment was conducted in 2005/2006 in Zijiao town, Huimin County in Shandong province in the North China Plain. This area was representative for soil and crop management in North China Plain. The soil of the experimental field was fine-loam with total nitrogen of 0.79 g/kg, Olsen P of 14.2 mg/kg, exchangeable K of 201.5 mg/kg and organic matter content of 13.8 g/kg in the 0-30 cm layer. The experiment included 5 pre-plant N levels of 0, 25, 50, 75 and 100 kg/ha with 4 replications. The pre-plant N levels covered the basal fertilization rate on the North China Plain. At shooting stage, each plot was divided into two parts, one received no N topdressing while for the other part N topdressing was applied. The fertilization rate was determined based on an improved Nmin method[8]. The detailed N fertilization management practices in this research are described in Table 1. The area of each plot was 150 m^2 (10 m×15 m). All plots received 120 kg/ha P_2O_5 as triple super-phosphate and 90 kg/ha K_2O as potassium sulfate before wheat sowing in order to avoid soil P and K deficiency. The wheat variety Lumai 23 was sown on 14 October, 2005, and harvested on 10 June, 2006.

Table 1. N fertilizer management of the winter wheat experiment

N fertilizer management	1	2	3	4	5
Nmin before sowing (0-60 cm, kg/ha)	49	59	81	98	95
Basal N fertilizer (kg/ha)	0	25	50	75	100
N topdressing rate (kg/ha)	113	107	94	55	54
Total N input (kg/ha)	49	84	131	173	195

2.1.2 Experiment 2: Farmers' fields

Besides the field experiment, three separate sites of Xujia, Xili and Shizhang were selected as the sub-study areas (Figure 1), which included 10, 12 and 16 farmers' fields, respectively. The sites were selected due to similar wheat varieties were planted in each sites. All the farmers' fields were managed by the farmers themselves, and the basal and topdressing nitrogen fertilization rates for the selected fields were summarized in Table 2.

Table 2. The average basal N fertilization rate for the selected farmers' fields in 2005/2006 wheat season

Sites	Total area (ha)	Number of Fields	Varieties	Planting date	Averaged basal N rate (kg/ha)
Xujia	3.81	12	JM21	14, Oct. 2005	117 (58-180)
Xili	4.00	16	JM23	15, Oct, 2005	149 (49-316)
Shizhang	3.75	10	JM22 and LM23	18, Oct, 2005	78 (34-120)

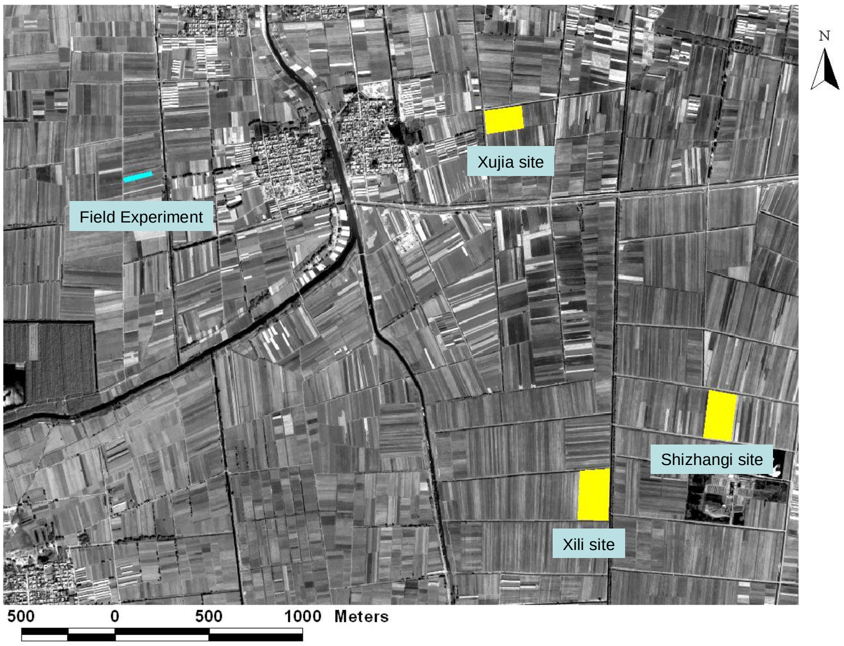

Figure 1. The distribution of experiment and research sites at 2005/2006 wheat season in Huimin County, Shandong Province

2.2 Field survey and agronomic measurements

Wheat N status indicators were measured at the shooting stage in Apr. 10, 2006. The nitrate concentration of the plant stem sap was determined with a Reflect Meter (Merck Co., Darmstadt, Germany), and SPAD readings were taken on the uppermost fully expanded leaves from 30 randomly selected plants in per plot and the average value was used for further analysis. Five soil cores were collected from each plot and pooled at 0 to 30 cm, 30 to 60 cm, and 60 to 90 cm depth intervals. To analyze the soil Nmin, all samples were sieved, extracted with 0.01 M CaCl2 and analyzed for NH4+-N and NO3--N by continues flow analyzer TRAACS 2000[20]. The soil Nmin was used to determine the optimum N topdressing rate at shooting stage as described by Chen et al.[8]. Aboveground wheat biomass were harvested (1 m^2 per plot) for the experiment, and dried at 60 ℃ to constant weight for biomass dry weight, and then analyzed for total N concentration using Kjeldahl digestion method.

For the selected farmers' fields in Xili, Xujia and Shizhang sites, only the aboveground plant biomass and total shoot N concentration were determined at shooting stage.

A “Trimble-AgGPS® 132” GPS receiver was used to georeference the sampling points in the experiment and farmers’ fields, and the boundaries of the experiment plots.

2.3 IKONOS Image processing

The IKONOS images, which included 4-m resolution multispectral bands (Blue band: 0.45-0.53 µm; Green band: 0.52-0.61 µm; Red: band 0.64-0.72 µm; and NIR band: 0.77-0.88 µm) and 1 m resolution panchromatic band (0.45-0.90 µm), were acquired on Apr. 20th, 2006, at the shooting stage of winter wheat. Since no temporal comparison or with other imagery was planned, the atmospheric corrections in this research was not performed [21]. The collected DGPS points at the transaction points around the study sites were converted to shapefiles using ArcGIS 8.1 and were imported into ENVI 4.2 as a vector layer. This layer was used to georectify the IKONOS image and to extract the plotted pixels’ raw digital spectral reflectance values of NIR, Red, Green and Blue bands. At least 3 pixels in each experiment plots were used to get averaged raw digital spectral reflectance values.

2.4 Data analysis

The vegetation indices (VIs) of NDVI (normalized vegetation index[22]), RVI (ratio vegetation index[23]), GNDVI (green vegetation index[24]) and OSAVI (optimized soil-adjusted vegetation index[25]) were calculated for the obtained IKONOS satellite image. The detailed expressions of the vegetation indices were listed in Table 3.

Table 3. Broadband vegetation indices used for image analysis

Abbreviation	Name	Vegetation Index	Reference
NDVI	Normalized Difference Vegetation Index	NDVI=（NIR-Red）/（NIR+Red）	Rouse et al., 1973
RVI	Ratio Vegetation Index	RVI=NIR/Red	Jordan, 1969
GNDVI	Green Normalized Difference Vegetation Index	GNDVI=(NIR-Green)/(NIR+Green)	Gitelson and Merzlyak, 1998
OSAVI	Optimized soil-adjusted vegetation index	OSAVI =(NIR–Red)/(NIR+Red+0.16)	Rondeaux et al., 1996

Nitrogen effects were analyzed quantitatively by comparing the means of agronomic parameters of each treatment through LSD test at a probability of 0.05. The single band reflectance of R, G, B and NIR bands and the vegetation indices of NDVI, GNDVI, RVI and OSAVI were regressed with the chlorophyll meter readings (SPAD), soil N input before sowing (including initial Nmin and basal N), stem sap nitrate concentration, shoot N concentration, aboveground biomass and nitrogen uptake. The regressions of single bands reflectance and VIs with plant N status indicators were made using Statistical Analysis System version 8.1 [26]. Linear or nonlinear models were fitted based on the plot patterns and best-fit R^2 values for the relationship. When linear relationships were not significant, exponential or logarithm models were attempted. Then the best-fit models were used to predict, nitrogen uptake in the farmers' fields. The root mean square error (RMSE) and relative error was calculated to compare the precision of estimation between the measured values (X) and the estimated values (X').

3 Results:

3.1 Nitrogen status of wheat at shooting stage

The N status of winter wheat at shooting stage was significantly affected by the N treatments (Table 4). High N supply (initial soil Nmin + pre-plant N fertilization) led to high SPAD readings, aboveground biomass, shoot N concentration, stem sap nitrate concentration and total N uptake. The significant difference among the 5 pre-N treatments showed that the low N supply treatments of 1 and 2 were in the state of N deficiency, having lower aboveground biomass, SPAD readings, stem sap nitrate concentration and N uptake than the high N treatments of 4 and 5, which were in the state of over fertilization. The treatment 3 seemed to have optimum N status with relatively high SPAD readings and stem sap nitrate concentration.

Table 4. Nitrogen status of winter wheat at shooting stage

Items\Treatments	1	2	3	4	5
Nmin (0-90 cm)	56b	62b	82b	124a	112a
Chlorophyll meter readings (SPAD)	46.2c	48.2b	49.6a	50.1a	50.6a
Upland biomass (kg/ha)	852c	1137c	1273b	1543ab	1703a
Shoot N concentration (g/kg)	32.4c	32.7bc	33.8bc	36.6ab	37.8a
N uptake (kg/ha)	27.5d	36.9cd	43.5bc	57.0ab	63.6a
Stem nitrate Concentration (mg/kg)	1228c	1295c	1672b	1834ab	1955a

*Means with different letter are significant different at 0.05 level.

3.2 Correlations of vegetation indices with wheat N status at shooting stage

Significant correlations were found between NDVI, RVI and GNDVI with SPAD readings, stem sap nitrate concentration, aboveground biomass and nitrogen uptake at shooting stage (R^2 = 0.488-0.739) (Table 5). All of the single band reflectance of NIR, Red and Green had significant correlations with SPAD, stem sap nitrate concentration, biomass and N uptake (R^2 = 0.240-0.645), which were lower than those with VIs. Neither VIs nor single band reflectance used in this research could significantly explain wheat N concentration variation (R^2 = 0.008 – 0.397), but the high R^2 values with aboveground biomass (R^2 = 0.667-0.708) and nitrogen uptake (R^2 =0.678-0.739) suggested that VIs could still be used to explain N and growth status of wheat at shooting stage.

Table 5. Coefficient of determination (R^2) for wheat N status with single band digital value and vegetation indices derived from IKONOS satellite image at shooting stage

R2	SPAD	Stem sap nitrate	Biomass	N Content	N uptake
NIR	0.424*	0.434*	0.572*	0.291	0.615**
Red	0.645**	0.342*	0.501*	0.046	0.430*
Green	0.483*	0.352*	0.426*	0.008	0.329*
Blue	0.284	0.318	0.297	0.015	0.240
NDVI	0.707**	0.507*	0.704**	0.181	0.678**
GNDVI	0.647**	0.541*	0.708**	0.184	0.683**
RVI	0.686**	0.537*	0.667**	0.199	0.704**
OSAVI	0.678**	0.513*	0.707**	0.397*	0.739**

* *LSD*=0.05, ** *LSD*=0.01, number of observations = 20

3.3 Nitrogen uptake estimation of winter wheat for farmers' fields

The N uptake of the winter wheat at shooting stage for farmers' fields in Xili, Shizhang, Xujia and Xizhangliu were predicted using the relationships developed with the experimental data (Figure 2). The estimated N uptake values using any of the four vegetation indices were all significantly correlated with measured values. Considering the normally farmers N application rate of 277-441 kg/ha in this region, the RMSE for NDVI and OSAVI were acceptable (26.6-27.4 kg/ha) while the RMSE for RVI and GNDVI were too high (42.2 – 61.0 kg/ha) to be acceptable by the farmers. Compared with the other vegetation indices used in this research, OSAVI was the best for nitrogen uptake prediction (closest to 1:1 line), while N uptake predicted with RVI and GNDVI were either higher or lower than measured values at the state of high N uptake. The results suggested that NDVI and OSAVI derived from IKONOS satellite image could be used for monitoring and estimating of wheat growth and nitrogen status.

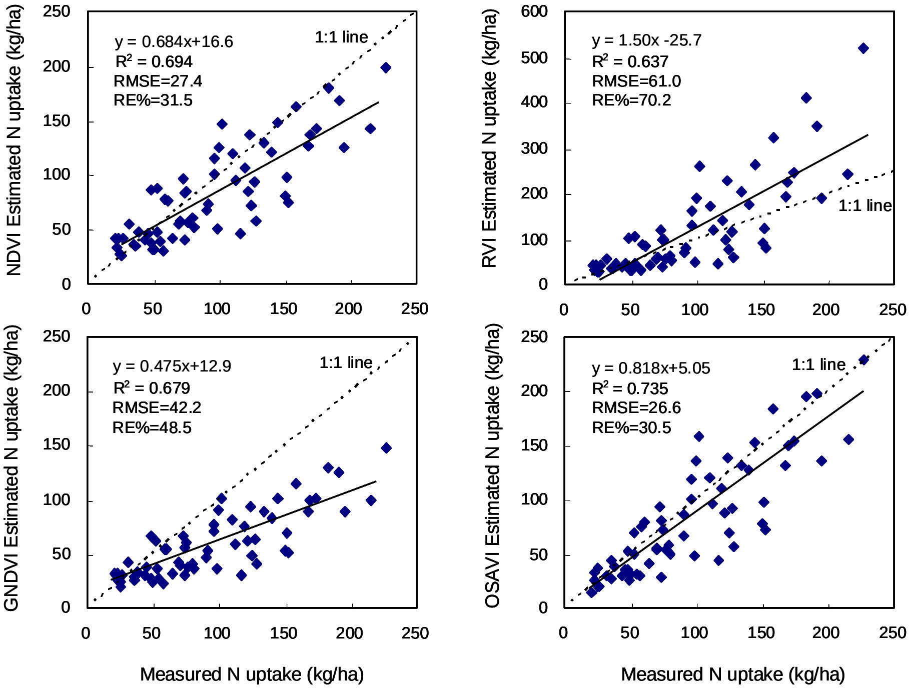

Figure 2. Comparison of the accuracy of the measured N uptake at shooting stage with predicted N uptake in the farmer's field (RMSE = root mean square error; RE% = relative error; number of observations = 84)

4 Discussion:

A very important approach to precision N management is to detect crop N status during the growing season and use this information to guide in-season N management. Traditional soil-plant analysis methods, such as SPAD, biomass, shoot N concent and soil Nmin, are either destructive or too time- and money-intensive for regional investigation. High resolution multispectral satellite imagary provides a promising solution for non-destructive and fast estimation of crops growth and N status. The vegetation indices used in this research all showed significant correlations with wheat N status indicators of SPAD readings, stem sap nitrate concentration, upland biomass and nitrogen uptake, but not with shoot N concentration. These results differ from earlier findings by Shou et al.[19] and Wright et al.[17], which showed that vegetation indices derived from Quickbird satellite image had significant correlations with shoot N concentration. An explanation of the low correlations of IKONOS image with shoot N concentration is that rapid wheat aboveground biomass increase at shooting stage causes unstable changes of the shoot N concentration when field measurements and satellite image were taken. Measurements at later growing stages and corresponding image acquisition may have a better relationship. More studies are needed to test this hypothesis.

The successful estimation of the nitrogen uptake in overfertilized farmers' fields, rather than in control experiments[27-30], supported the idea suggested by Shou et al.[19] to use high resolution satellite image combined with in-site soil-plant analysis at small reference fields to monitor regional nitrogen status of winter wheat in North China Plain.

The fast development of the satellite technologies have made the acquisition of high spatial and spectral resolution satellite images become cheaper and easier than before. In recent years, some researchers have considered hyperspectral sensors to monitor rice nitrogen status and nutrients disorder[31] and satellites with radar systems (SAR) to study soil and crop moisture[32-33] and forest biomass [34](Austin et al., 2003). Although more sensors have been used in monitoring vegetation growth status than before, satellite images for agriculture uses still face many challenges, such as clouds or dust which interfere the acquisition or quality of the image, low spectral resolution in explaining the canopy and canopy reflectance disorders caused by other factors except nutrients, etc. A possible solution to this problem is multi-source remote sensing data fusion. For example, high spatial resolution IKONOS or Quickbird satellite images combined with high spectral resolution EO-1 Hyperion and soil-plant analysis may provide better explanations for crop canopy nutrient disorders. In such studies, plots with optimum N management should be included to provide reference values. This may allow the development of site-specific fertilizer recommendation maps as described by Scharf and Lory[12]. Further researches are needed to verify this idea and develop a robust system that will allow farmers to access these data to improve their management decisions.

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