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Low-altitude aerial photography for optimum N fertilization of winter wheat on the North China Plain

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Abstract

Previous research has shown that site-specific nitrogen (N) fertilizer recommendations based on an assessment of a soil's N supply (mineral N testing) and the crop's N status (sap nitrate analysis) can help to decrease excessive N inputs for winter wheat on the North China Plain. However, the costs to derive such recommendations based on multiple sampling of a single field hamper the use of this approach at the on-farm level. In this study low-altitude aerial true-color photographs were used to examine the relationship between image-derived reflectance values and soil–plant data in an on-station experiment. Treatments comprised a conventional N treatment (typical farmers' practice), an optimum N treatment (N application based on soil–plant testing) and six treatments without N (one to six cropping seasons without any N fertilizer input). Normalized intensities of the red, green and blue color bands on the photographs were highly correlated with total N concentrations, SPAD readings and stem sap nitrate of winter wheat. The results indicate the potential of aerial photography to determine in combination with on site soil–plant testing the optimum N fertilizer rate for larger fields and to thereby decrease the costs for N need assessments.

Keywords: Greenness intensity; Image analysis; Nitrogen use efficiency; Sap nitrate; Wheat

1. Introduction

Increasing nitrate concentrations in the groundwater require improved nitrogen (N) fertilizer management in intensive winter wheat production systems of the North China Plain, where farmers apply high amounts of mineral N. Recent on-station research on a high fertility field in Dongbeiwang, near Beijing has shown that N application based on a comparison of the crop's N status (leaf nitrate) and the soil's N supply (testing of mineral N, Nmin) at three growth stages (sowing to regreening, regreening to booting and booting to harvest) allowed reductions of N application by 79 and 82% in the 1999/2000 and 2000/2001 seasons, respectively. Surprisingly, this dramatic reduction of N inputs did not lead to a decrease in crop growth and grain yield compared with farmers' N fertilization at 300 kg ha^{-1} of which half was applied as a basal dressing and half topdressed at booting (Chen, 2003).

A serious limitation for the use of a Nmin-based 'optimized' N fertilization at the farmers' level,

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however, is the need for time-consuming soil sampling and expensive Nmin analysis in a laboratory. Furthermore, even on the geomorphologically rather homogeneous loess formations of the North China Plain, variability in the soils' N status due to prior management decisions precludes representative testing for extensive areas. To overcome these constraints a complementary reflectance measurement of the crop canopy derived from high resolution aerial photographs may increase the scope of Nmin testing in predicting N needs for optimal crop growth.

However, such efforts have to take into account that diseases, insect damage and deficiencies in water and nutrients other than N will affect the greenness intensity of leaves (Jackson, 1986; Wildman, 1982). Therefore, the collection of ground truth data and the inclusion of known reference conditions within the photograph (Blackmer and Schepers, 1996) are necessary to verify in principle whether differences in canopy reflectance of winter wheat on the North China Plain indeed mirror differences in the soil's N supply.

Research in corn (*Zea mays* L.) shows that N deficient leaves reflect more light over the entire visible spectrum (400–700 nm) than N sufficient ones (Al-Abbas et al., 1974). Blackmer et al. (1994) reported good correlations between leaf reflectance in the visible part of the spectrum using chlorophyll meter readings, with leaf N and grain yield. Scharf and Lory (2002) successfully used aerial photography to predict the side-dressed N rate for optimum crop growth from the green or blue color spectrum at the V6–V7 growth stage of corn. On sandy Sahelian soils, notoriously low in phosphorus (P) and N, high resolution aerial photography was particularly useful to non-destructively estimate the above-ground dry matter of a spatially highly variable, herbaceous fallow vegetation and of pearl millet (*Pennisetum glaucum* L.). It also allowed to differentiate the effects of N fertilizer and stand density on three millet genotypes (Gerard and Buerkert, 1999, 2001; Gerard et al., 2001).

In view of the pressing need to optimize N input in Chinese winter wheat, the objective of this study was to examine the potential of low-altitude aerial photography as a predictive tool for N fertilizer recommendations based on a comparison between simple reflectance readings and a conventional soil–plant diagnosis of the crop's actual N status.

2. Materials and methods

2.1. The experiment

The winter wheat/summer maize double cropping experiment used for this study was established in October 1999. It consisted of a 3 × 2 × 3 factorial field trial in which three methods of irrigation were arranged as main plots, two straw levels (±recycling) as sub-plots, and three levels of N application as sub-sub-plots of 20 m × 15 m. The latter comprised an unfertilized control and treatments of farmers' N fertilization and 'optimized' N fertilization. Farmers' N application as typically practiced in the North China Plain consisted of 150 kg N ha^{-1} applied as NH_4HCO_3 before sowing and an additional 150 kg N ha^{-1} as urea at booting. The optimized N fertilization treatment took into consideration the Nmin target values (at three growth stages) for the target yield and the Nmin level in the soil profile before sowing, at regreening and at booting. A more detailed description of this experiment was reported by Jia et al. (2004). During the 2001/2002 winter wheat growing season eight treatments with contrasting N treatments but all with optimized irrigation and without straw recycling were selected in each of the four experimental replicates (Table 1).

2.2. Collection and processing of data

At booting of winter wheat on 11 April 2001 high resolution aerial images were taken with a remotely controlled 24 mm × 36 mm Nikon F601 camera from a helium-filled balloon at 300–450 m above ground (Buerkert et al., 1996). For further processing in Adobe Photoshop® 4.0 images were scanned with a MicroTek ArtixScan2500 at a resolution of 2000 dpi. Each pixel had a depth of eight bits ranging from 0 to 255 for red (R), green (G) and blue (B). Subsequently, in each plot three to five image segments were selected to represent the variation in reflectance of the crop canopy captured. From these the medians of the absolute intensity values for red, green and blue pixel bands were calculated.

Regardless of the band all medians were normalized as follows given the on-going debate about possible bias in absolute and normalized color values or color ratios used to derive a crop's N status from color film

Table 1
Initial soil mineral nitrogen (Nmin in kg ha^{-1}) at 0–0.9 m and N application rate (kg ha^{-1}) in selected treatments at Dongbeiwang, Beijing, China

No.	N fertilization	Nmin before sowing[a]	Basal N	Topdressed N at regreening	Total N supply before booting
1	Six seasons w/o fertilization	43	0	0	43
2	Five seasons w/o fertilization	39	0	0	39
3	Four seasons w/o fertilization	56	0	0	56
4	Three seasons w/o fertilization	45	0	0	45
5	Two seasons w/o fertilization	55	0	0	55
6	One season w/o fertilization	64	0	0	64
7	Farmers' fertilization	669	150	0	819
8	Optimized fertilization	142	0	37	179

[a] 'Native' soil N plus fertilizer N applied before the season.

(McMurtrey et al., 1994; Blackmer et al., 1994; Daughtry et al., 2000; Scharf and Lory, 2002):

1. normalized redness intensity: $NRI = R/(R + G + B)$;
2. normalized greenness intensity: $NGI = G/(R + G + B)$;
3. normalized blueness intensity: $NBI = B/(R + G + B)$.

Finally, for each of the three normalized colors, relative values were calculated by dividing plot values by those of the respective averages of high N plots. All measurements were compared with the following indicators of the N status in winter wheat at booting: readings from a Minolta SPAD®-502 chlorophyll meter, sap nitrate concentrations, leaf total N concentrations and total N supply (Nmin + fertilizer N input).

For analysis of soil Nmin and total N at regreening (156 days after sowing (DAS)) and booting (184 DAS) five cores were collected from each plot and pooled at 0–30, 30–60 and 60–90 cm depth intervals. All samples were sieved, extracted with 0.01 M $CaCl_2$ and analyzed for NH_4^+ and NO_3 by continues flow analyzer TRAACS 2000 (Bran and Luebbe, Norderstedt, Germany).

Plant SPAD readings were taken at booting on 17 April as an average of the uppermost fully expanded leaves from 30 randomly selected plants per plot. At the same time, the above-ground plant dry matter was determined on 1 m^2 and analyzed for total N using Kjeldahl digestion. At booting, the nitrate concentration of the plant sap was tested with a Reflect Meter (Merck Co., Darmstadt, Germany) and at maturity three separate sub-samples (each of size 3 m^2) were harvested to determine grain and straw yield for each plot.

3. Results

3.1. Soil–plant analysis to optimize N fertilization

At booting shoot biomass in farmers' treatment plots was significantly higher than in optimum and no N ones (Table 2). Shoot N concentrations in both optimum and farmers' N plots were high, even though there were significant differences between these treatments. Stem tissue nitrate concentration for winter wheat with farmers' N rates was significantly higher than with optimized or zero N treatments (Table 2). There was no significant difference in chlorophyll meter (SPAD) readings between optimum and farmers' N treatments. For plants in plots without N, however, total N supply from the soil seemed to be very low. At harvest stage, farmers' and optimally fertilized wheat had similar grain and straw yields and shoot N uptake, which were significantly higher than for plots without N (Table 2).

Over the entire season, the fertilizer input for optimum N treatments amounted to 98 kg ha^{-1} leading to a 67% reduction of fertilizer N compared with farmers' N application at 300 kg ha^{-1} (Table 2). The nitrogen use efficiency (NUE) for optimum N

Table 2
Nitrogen (N) fertilizer application, N status of wheat at booting and wheat yield at harvest for the selected treatments in the 2001/2002 season at Dongbeiwang, Beijing, China (see Table 1 for a description of treatments)

	Treatment number							
	1	2	3	4	5	6	7	8
N supply (kg ha^{-1})								
Soil Nmin at 0–0.9 m before sowing	10	6	8	8	10	12	84	12
Basal N fertilization[a]	0	0	0	0	0	0	150	0
Topdressing at regreening[b]	0	0	0	0	0	0	0	37
Topdressing at booting[c]	0	0	0	0	0	0	150	61
Total N supply[d]	–	–	–	–	–	–	300	98
N status at booting								
Soil Nmin at 0–0.9 m at booting (kg ha^{-1})	–	–	–	–	–	51	444	49
Total soil N concentration (mg kg^{-1})	–	–	–	–	–	26.1 c	37.7 a	32.1 b
Stem nitrate concentration (mg l^{-1})	72 c	86 c	94 c	105 c	146 c	340 c	2945 a	1845 b
Chlorophyll meter readings (SPAD)	30.5 c	32.0 c	33.0 c	32.1 c	35.0 c	38.8 c	45.7 a	42.5 ab
Shoot biomass (kg ha^{-1})	–	–	–	–	–	1855 b	2261 a	1850 b
N uptake before booting (kg ha^{-1})	–	–	–	–	–	48 c	84 a	60 b
Harvest data								
Shoot dry matter (kg ha^{-1})	4805 c	4805 c	5631 bc	5188 bc	6139 b	7210 b	10495 a	10620 a
Grain yield[e] (kg ha^{-1})	1803 c	1774 c	2179 bc	1991 c	2478 bc	2845 b	3888 a	4249 a
Straw yield (kg ha^{-1})	3003 c	3031 c	3452 bc	3197 bc	3661 bc	4364 b	6607 a	6371 a
N uptake (kg ha^{-1})	42 c	41 c	55 bc	50 bc	65 b	75 b	139 a	123 a
NUE[f] (%)	–	–	–	–	–	–	21	49

Means in a row with a different letter are significantly different using an $LSD_{0.05}$.

[a] The soil Nmin 0–30 cm for optimum N fertilization treatment (treatment 8) before the 2001/2002 wheat sowing was lower than for the 30 kg N ha^{-1} treatment because of the high amount of irrigation before sowing. No pre-sowing N application occurred given the high wheat growth of the last three seasons.

[b] The Nmin target from regreening to booting was 90 kg ha^{-1}. Because at the regreening stage most roots grew in the 0–60 cm soil layer, the $Nmin_{0–60}$ was used as the criterion for N application.

[c] The Nmin target from regreening to booting was 110 kg ha^{-1}. Because at the regreening stage most roots grew in the 0–90 cm soil layer, the $Nmin_{0–90}$ was used as the criterion for N application.

[d] Total N supply = N fertilization before sowing + topdressing at regreening + topdressing at booting.

[e] Dry matter.

[f] $$\text{N fertilizer use efficiency (NUE) (\%)} = \frac{\text{total N uptake} - \text{total N uptake of control plots w/o N application for the current season}}{\text{total N supply}} \times 100$$

treatments was at 49% more than twice as high as that of farmers' N treatments (21%).

3.2. Relationship between variables derived from aerial photographs and plant–soil diagnosis

There were no significant correlations between absolute color values and total shoot N concentration, SPAD readings or sap nitrate at booting. However, significant negative linear correlations were found between relative values for the red, green and blue color intensities of the wheat canopy and total shoot N concentration, SPAD readings and sap nitrate concentration; there were no correlations with shoot biomass. The normalized redness intensity (NRI) was negatively correlated with all conventional N status indices, whereas these were positively correlated with the normalized greenness and blueness intensities (Table 3).

The NRI for the farmers' N treatment varied from 0.240 to 0.254 but was significantly lower than for the optimum N treatment which varied between 0.259 and 0.336 and for the unfertilized controls which varied between 0.333 and 0.371. This suggests that a booting NRI of <0.256 indicated N surplus, while a NRI between 0.256 and 0.334 indicated an optimum N supply, and an NRI of >0.334 indicated N deficiency (Fig. 1).

Table 3
Correlations between relative and normalized color intensities with total shoot N concentration, SPAD readings, sap nitrate concentration and shoot biomass of winter wheat at booting (Dongbeiwang, Beijing, China)

Pearson correlations (*r*)	Relative value			Normalized value		
	Red	Green	Blue	Red	Green	Blue
Total shoot N concentration	−0.764**	−0.693**	−0.704**	−0.791**	0.642*	0.739**
SPAD value	−0.839**	−0.800**	−0.825**	−0.785**	0.712**	0.671**
Sap nitrate concentration	−0.904**	−0.823**	−0.810**	−0.883**	0.824**	0.727**
Shoot biomass	ns[a]	ns	ns	ns	ns	ns

[a] Not significant.
* $P < 0.05$.
** $P < 0.01$.

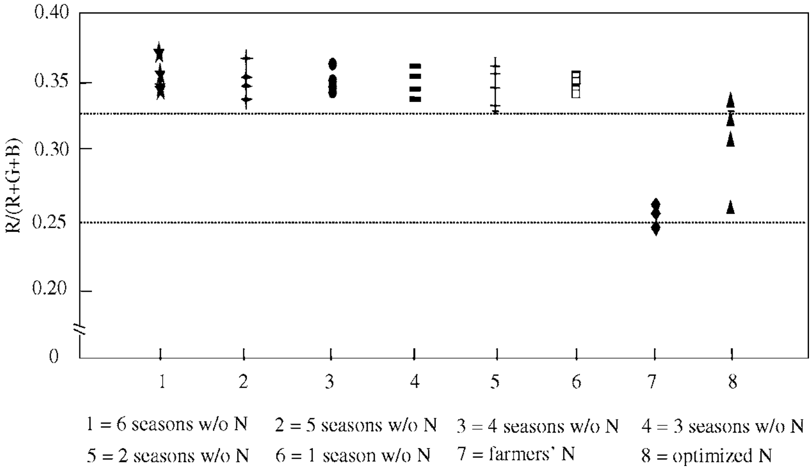

Fig. 1. Distribution of normalized red reflectance intensity (NRI = $R/(R + G + B)$) derived from images of winter wheat canopies at booting which were subjected to different N application rates.

For farmers' N plots, Nmin at booting was 444 kg ha^{-1}, much higher than the target value of 110 kg ha^{-1} for optimum N treatments. Nmin at booting was 49 kg ha^{-1}, leading to supplementary application of 60 kg N ha^{-1} compared to 110 kg N ha^{-1} for unfertilized controls (Table 4).

4. Discussion

In this study which only comprised a single year and site relative light reflectances of the wheat canopy decreased with increasing crop N status. This is similar to previous results for corn (Blackmer et al., 1994;

Table 4
Normalized red reflectance intensity (NRI = $R/(R + G + B)$) derived from canopy images of winter wheat subjected to different rates of N application

Treatment	NRI range	Average	N status	N fertilization (kg ha^{-1})
Farmers' N	0.240–0.254	0.242	Surplus	0
Optimum N	0.259–0.336	0.307	Optimum	60
Without N	0.333–0.371	0.351	Deficient	110

Scharf and Lory, 2002). The negative correlations between relative reflectances of red, green and blue light derived from aerial photographs of the wheat canopy and total shoot N, sap nitrate concentration and SPAD readings were surprisingly high. To our knowledge such changes of the proportion of red, green and blue reflectances as induced by different levels of N application have not been reported previously. If confirmed by other studies on the North China Plain these results suggest that use of these or the G/R, G/B or R/B ratios might help to reliably assess the N status of winter wheat in this region.

The stem tissue nitrate concentration in the optimized N treatment was 1845 mg l^{-1}, only a little above the critical value of 1500 mg l^{-1} found previously for winter wheat at booting in the North China Plain (Li et al., 1997). For the high fertility field of this study the establishment of high N references plots was not necessary to effectively monitor the crop's N status. The data show that the color reflectance values for optimum N treatments were already close to those from high N treatments. This precluded the use of high N plots to derive the amount of N needed for N stressed crops.

Further research should be conducted to examine the relationship of image-derived reflectance intensities with plant and soil data. In such studies reference plots with a target N status should be included to obtain spectral reference values. This might allow production of a map with site-specific fertilizer recommendations such as described by Scharf and Lory (2002).

However, it should be stressed that a crop's total canopy reflectance can be affected by many factors such as the soil background reflectance, light intensity as influenced by the degree of cloudiness, the angle of view from which an image is taken and by the effects of diseases and nutrient disorders not related to the crop's N status (Gérard et al., 1997; Jia et al., 2004). While detailed spectral studies have shown that it may in principle be possible to distinguish between these different causes for spectral reflectance changes of leaves (Graeff et al., 2001) such an approach certainly needs further verification under field conditions.

Image resolution versus foot print of an image are other important factors to be considered when using aerial photography as a predictive tool in plant nutrition. Kite-based images may cover between a few 100 m^2 to several hectares (Buerkert et al., 1996) and at the higher end of this range have similar resolution problems as airplane-based photographs. Alternatively, some researchers have used a digital camera or a digital video to monitor crop growth from the air (Dymond and Trotter, 1997; Clarke, 1997).

With the rapidly increasing resolution and easier storage of digital data, the use of digital camera- or video-based systems to monitor and assess the N status of crops is likely to grow in the future, at least for ecologically sensitive areas which require close monitoring of N fluxes or for larger farms which can afford to use mechanized systems for site-specific nutrient management. For more detailed investigations in highly variable fields or to predict a crop's N status in a single homogeneous plot such approaches will likely be coupled with SPAD-based chlorophyll readings.

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