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Optimum Nitrogen Fertilization of Winter Wheat Based on Color Digital Camera Images

L. Jia, X. Chen, and F. Zhang
Department of Plant Nutrition, China Agricultural University, Beijing, China

A. Buerkert
Institute of Crop Science, University of Kassel, Witzenhausen, Germany

V. Roemheld
Institute of Plant Nutrition, University of Hohenheim, Stuttgart, Germany

Abstract: Site-specific nitrogen (N) fertilizer management based on soil N_{min} (soil mineral N) and the plant N status (sap nitrate analysis and chlorophyll meter (SPAD) reading test) has been shown to be effective in decreasing excessive N inputs for winter wheat in the North China Plain, but the multiple sampling of soil and plants in individual fields is too time-consuming and costly for producers and farmers. In this study, a color digital camera was used to capture wheat canopy images at a specific growth stage to assess N needs. Treatments included a farmer's N treatment (typical farmer practice), an optimum N treatment (N application based on soil–plant testing), and four treatments without N (one to four cropping seasons without any N fertilizer input). Digital images were analyzed to get red, green, and blue color-band intensities for each treatment. Normalized intensities of the red, green, and blue color bands were well correlated with soil N_{min}, SPAD readings, sap nitrate concentration, and total N concentration of winter wheat. This research indicated the potential of using a digital camera as a tool combined with an improved N_{min} method to make N fertilizer recommendations for larger fields.

Keywords: Green intensity, image analysis, nitrogen-use efficiency, wheat

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Address correspondence to F. Zhang, Department of Plant Nutrition, China Agricultural University, Beijing 100094, China. E-mail: zhangfs@cau.edu.cn

INTRODUCTION

Nitrogen (N)–rate experiments have demonstrated that the N fertilizer needs of winter wheat can vary widely within fields under current production conditions in the North China Plain (Jia et al. 2000; Chen 2003). This variation can be caused by soil N supply and plant N demand. In the meantime, farmers often apply high amounts of N fertilizer (Chen et al. 2004) as "insurance" to get high grain yields. This may result in serious environmental problems such as groundwater nitrate contamination. To minimize the environmental pollution and economic losses, the need to develop an N recommendation method to reduce the N application rate while maintain a sustainable grain yield is a main task in the North China Plain.

The N_{min} method developed by Wehrmann et al. (1982) is based on the measured amount of mineral N [nitrate-N (NO_3-N) + ammonium-N (NH_4-N)] in the main rooting depth before N fertilizer application at selected growing periods. Recommendation rate of N fertilizer is calculated by the predicted N demand for the target yield minus the measured soil N_{min} value. An improved N_{min} method, which integrates soil–plant testing, has been tested in a Sino-German cooperative experiment in Dongbeiwang, Beijing, since October 1999 (Chen 2003; Chen et al. 2004).

As a nondestructive and rapid method, SPAD readings have been used to determine the N status in winter wheat (Fox, Piekielek, and Macneal 1994; Blackmer and Schepers 1995). The shortcomings of this method are that the SPAD chlorophyll meter only allows measurement of a small part of a leaf, and a large number of random observations are usually needed to obtain a representative value. Also, the measurements are always subject to operator bias in the selection of leaves for measurement. Furthermore, the collection of SPAD chlorophyll meter data is too time-consuming for the monitoring of large areas (Blackmer and Schepers 1995). The testing of sap nitrate in the basal stem has been found to reliably assess the N status of wheat (Geypens and Vandendriessche 1996). This method has been used to predict yield and grain quality of wheat in field trials (Handson and Sheridan 1992) but has not been widely accepted by farmers because of the complexity and time needed to collect and prepare samples for analysis of nitrate (Wollring, Reusch, and Karlsson 1998).

In recent years, more and more attention has been focused on the color analysis to detect N status of crops. The color intensity of leaves is related to their N status at certain growth stages. Nitrogen-deficient corn reflects more light over the entire visible spectrum than N-sufficient corn (Al-Abbas et al. 1974; Blackmer, Schepers, and Varvel 1994). Differences in reflectance are usually greatest at wavelengths from 550 to 600 nm (Blackmer, Schepers, and Varvel 1994; McMurtrey et al. 1994). These reflectance differences are associated with differences in chlorophyll concentrations in leaves (Hong et al. 1997).

Scharpf and Lory (2002) reported utilizing a color-analysis method to predict the N needs of maize and showed good potential for using this method to determine N top-dressing rates on a large scale. On the other hand, it was found that digital camera could be a better image-acquisition tool because it is easy to obtain digital images and easy to transfer images to a computer for analysis. A digital camera with the relative color-image analysis method showed potential for use as a tool to detect the N status of winter wheat (McMurtrey et al. 1994). In this article, we evaluated the use of a digital camera and digital-image processing method to make N fertilization recommendations for winter wheat at the shooting stage.

MATERIALS AND METHODS

Experiment Background

A field experiment comprising a winter wheat/summer maize double-cropping system, which involves planting and harvesting of one wheat and one maize crop within 1 year, was conducted at the Dongbeiwang Experiment Site, near Beijing, China. The experiment was a $3 \times 2 \times 3$ factorial split–split block experiment with four replications, which contained (i) three methods of irrigation (suboptimal irrigation as a control, a farmer's irrigation method as farmer practice, and optimized irrigation based on soil water measurement) as main plots of 60×30 m; (ii) two straw levels [with straw (straw recycling) and without straw (without straw recycling)] as subplots of 60×15 m; and (iii) three levels of N application as subsubplots of 20×15 m (control, farmer's N fertilization, and optimized N fertilization). Farmer's N fertilization consisted of 150 kg N ha^{-1} applied as ammonium bicarbonate (NH_4HCO_3) before sowing and an additional 150 kg N ha^{-1} as urea at booting, which is a typically practice of local farmers. The optimized N fertilization treatment took the soil mineral N (N_{min}) in the soil profile before sowing, at regreening, and at booting as well as yield goal into consideration to determine target N value (split for three growth stages from sowing to the regreen stage, regret to shooting stage, and shooting to harvest stage). A more detailed description of this experiment was reported by Jia et al. (2004).

In the 2000/2001 winter wheat growing season, 6 of the 18 treatments with different N rates with optimized irrigation and without straw recycling were selected to evaluate the use of color images to make N fertilizer recommendation (Table 1).

Winter Wheat Management

The 2000/2001 winter wheat (Jingdong 8) was sown at a seeding rate of 187 kg ha^{-1} with a row spacing of 15 cm on October 13, 2000, and harvested in mid-June 2001. Fifty-five kg P ha^{-1} was applied as triple

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

No.	N fertilization	N_{min} before sowing	Basal N	Top-dressed N at regreening	Top-dressed N at shooting
1	4 seasons w/o fertilization	26	0	0	0
2	3 seasons w/o fertilization	31	0	0	0
3	2 seasons w/o fertilization	34	0	0	0
4	1 seasons w/o fertilization	41	0	0	0
5	Traditional fertilization	203	150	0	150
6	Optimized fertilization	49	0	18	47

superphosphate (TSP) to all plots before sowing. During the 2000/2001 winter wheat growing season, 6 contrasting treatments, including 4 multi- or one-season no-N treatments, optimized N treatment, and farmer's N treatments, were selected for the measurements reported here.

SPAD readings were read at shooting (184 days after sowing (DAS)) and booting stages (201 DAS) using a SPAD 502 chlorophyll meter (Minolta Co., NY) to randomly measure the 30 first fully expanded leaves to get an averaged value for each plot. Aboveground biomass was harvested from a 1-m^2 sampling area per plot, dried to constant weight at 70°C, and analyzed for total N content with Kjeldahl methods for both growth stages. At the shooting stage, sap nitrate concentration of wheat was tested using an Rqflext meter and sap nitrate strips (Geypens and Vandendriessche 1996; Liu et al. 2003).

Digital Photograph and Image Processing

At the shooting stage, digital images were acquired using an Olympus 2100UZ color digital camera, taken at 1.5 m above ground level with an angle of 60° to the wheat canopy. All the images were taken between 12:00 to 13:00 at sunny days with a relatively stable sun angle to eliminate the effect of sunlight on image quality. A white plate was used to make color balance. Images with a resolution of 1024 × 768 pixels were transferred to a computer in TIFF format.

Images were analyzed using the Histogram function of Adobe Photoshop®. Three separate image parts without soil background were selected as studied parts in each image to minimize the soil background effect on color analysis. Mean values of each channel for red (R), green (G), and blue (B) were recorded as the color intensity.

RESULTS

Soil–Plant Analysis to Optimize N Fertilization

For the optimum N treatments, no nitrogen fertilizer was applied before sowing because of the high amount of residual N_{min} after maize harvest, and 18 kg ha^{-1} and 47 kg ha^{-1} N were applied at regreening and shooting stages, respectively. The farmer's N treatments were fertilized 150 kg ha^{-1} N preplant and 150 kg ha^{-1} as top-dressing at the shooting stage in the 2000/2001 crop season.

As shown in Table 2, at the shooting stage, the shoot biomass of optimum N treatments was not significantly different from the farmer's N treatments. Shoot total N concentration was at a high level even though significant differences could be found in the optimized, farmer's N, and no-N treatments. The stem nitrate concentration of farmer's N treatment was significantly higher than optimized and no-N treatments, but no significant difference was found between optimized N treatment and one-season no-N treatment.

At harvest, the aboveground biomass, grain yield, straw yield, and total N uptake of aboveground biomass were not significantly different between optimized and farmer's N treatments, but both were significantly higher than no-N treatments. The net N recovery for optimized N treatment was 66%, significant higher than the 18% of farmer's N treatments. Compared with the farmer's N treatments, the optimum N treatments had a similar yield while saving 78% of N fertilizer. This suggests the optimum N strategy was agronomically and environmentally sound and the optimum N fertilization treatment met the crop's N requirements.

Correlations between Digital Imaging and Winter Wheat N Status

The correlations between normalized green intensity and N status of winter wheat at shooting and booting are shown in Table 3. There were significant correlations found among $G/(R+G+B)$ and plant total N content, SPAD readings, and stem sap nitrate concentration at shooting and booting stages. This suggests that the $G/(R+G+B)$ could be used to monitor the N status of wheat at the two growth stages. The highly significant relationship between $G/(R+G+B)$ and grain yield suggested that the normalized green intensity could predict the grain yield.

The distribution figure of the normalized green intensity of different N treatments is shown in Figure 1. For the no-N treatments, the $G/(R+G+B)$ varied from 0.420 to 0.443, but was significantly higher

Table 2. Nitrogen (N) fertilizer application, N status of wheat at booting, and wheat yield a harvest for the selected treatments in the 2000/2001 season at Dongbeiwang, Beijing, China

Parameter	Treatment number 1	2	3	4	5	6
N supply (kg ha^{-1})						
N_{min} at 0–0.9 m before sowing	26	31	34	41	203	49
Basal N fertilization[a]	0	0	0	0	150	0
Top-dressing at regreening[b]	0	0	0	0	0	18
Top-dressing at shooting[c]	0	0	0	0	150	47
Total N fertilization[d]	—	—	—	—	300	65
N status of winter wheat at booting						
N_{min} at 0–0.9 m at booting (kg ha^{-1})	—	—	—	45	287	63
Total N concentration (%)	2.41d[g]	2.81c	2.87c	3.42b	3.98a	3.58b
Stem nitrate concentration (mg L^{-1})	429d	737cd	957bc	1147bc	3828a	1416b
Chlorophyll meter readings (SPAD)	37.4d	40.1c	40.9bc	41.2bc	44.0a	43.0ab
Upland biomass (kg ha^{-1})	1703a	1545a	1604a	1734a	1819a	1684a
N uptake before shooting (kg ha^{-1})	29.8c	43.4c	46.1c	59.2b	72.4a	60.3b
Harvest data						
Shoot dry matter (kg ha^{-1})	7472c	6928c	7524c	8191b	10139s	9847s
Grain yield[e] (kg ha^{-1})	3321b	3192b	3452b	3598b	4356a	4447a
Straw yield (kg ha^{-1})	4151c	3736c	4072c	4593b	5783a	5400a
N uptake (kg ha^{-1})	79b	71b	88b	87b	141a	129a

(*continued*)

Table 2. Continued

Parameter	Treatment number					
	1	2	3	4	5	6
Net N recovery[f](%)	—	—	—	—	18	66

[a]The soil N_{min} at 0–30 cm for optimum N fertilization treatments before the 2000/2001 wheat sowing was higher than 30 kg N ha^{-1}; there was no basal N fertilization for optimum N treatments in this crop season.

[b]The N_{min} target from regreening to booting was 90 kg ha^{-1}. Because most roots grew in the 0- to 60-cm soil layer, the $N_{min0\text{-}60}$ at the regreening stage was considered for optimum N treatments.

[c]The N_{min} target from shooting to harvest was 110 kg ha^{-1}. Because most roots grew in the 0- to 90-cm soil layer, the $N_{min0-90}$ at the regreening stage was considered for optimum N treatments.

[d]Total N fertilization = N fertilization before sowing + top-dressing at regreening + top-dressing at booting.

[e]Dry matter.

[f]Net N recovery % = [(Total N uptake — Total N uptake of control plots w/o N application for the current season)] + Total N fertilization × 100.

[g]Means with a different letter are significantly different using an $LSD_{0.05}$.

than those of the optimum N treatment, which varied from 0.410 to 0.424, and for the farmer's N treatment, which varied from 0.381 to 0.407. This suggests that a shooting $G/(R+G+B)$ of less than 0.408 indicated N surplus, whereas a $G/(R+G+B)$ between 0.408 and 0.423 indicated an optimum N supply and a $G/(R+G+B)$ of more than 0.423 indicated N deficiency.

Table 3. Correlations between normalized green intensity with some N status parameters of wheat at shooting and booting stage in 2000/2001

Relationship	R (Shooting stage)	R (Booting stage)
$G/(R+G+B)$—Plant N concentration (%)	-0.583^a	-0.701^b
$G/(R+G+B)$—SPAD	-0.511^a	-0.617^b
$G/(R+G+B)$—Stem nitrate cont.	-0.789^b	No data
$G/(R+G+B)$—Upland biomass	-0.352	-0.762^b
$G/(R+G+B)$—Grain yield	—	-0.772^b

Notes. N fertilizer was applied at the shooting stage, so the correlations of $G/(R+G+B)$ with grain yield were calculated only at booting.

[a]LSD = 0.05.

[b]LSD = 0.01.

n.s. = no significance.

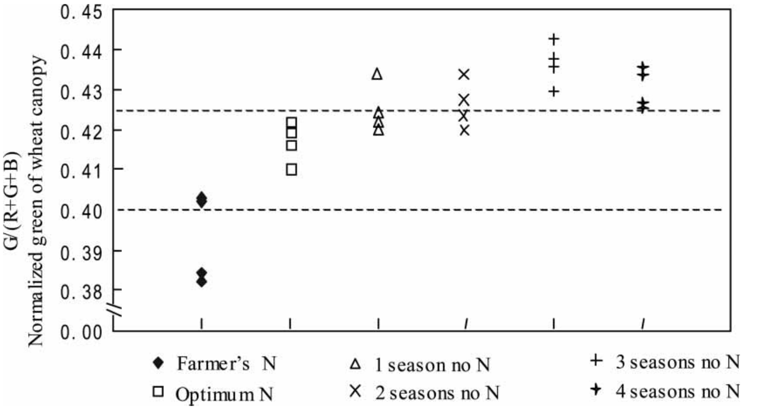

Figure 1. Distribution of relative green intensity of different N treatments on the wheat canopy.

Table 4. Distribution of wheat canopy G/(R + G + B) under different N treatments

Treatments	G/(R + G + B)	Average	N status	N fertilization[a] (kg · ha⁻)
Conv. N	0.381~0.407	0.394	Surplus	0
Optimum N	0.410~0.424	0.419	Optimum	50
Without N	0.420~0.443	0.429	Deficient	70~90

[a]Top-dressing rate at shooting stage.

Considering the N status of winter wheat at the shooting stage, the farmer's N treatments were in N surplus state and the crop did not need N top-dressing; the optimum N treatment was in a good growth state and needed 48 kg ha^{-1} N top-dressing in this experiment to reach the targeted yield; and for the no-N treatments, the winter wheat was in an N stress state. Because of long-time N stress from sowing to shooting stage, the wheat needed N top-dressing to achieve the targeted grain yield. Considering the N_{min} of no-N treatments and optimum N treatments before sowing and the N top-dressing rate at the regreening stage for optimum treatments, the N top-dressing rate for no-N treatments should be 81 kg ha^{-1} (Table 4).

DISCUSSION

The normalized green intensity of the wheat canopy decreased as the N status of the crop increased, which is consistent with previous research on corn

(Blackmer, Schepers, and Varvel 1994; Scharpf and Lory 2002) and wheat (Jia et al. 2004). More research on this method is still needed to determine its reliability in assessing the N status of winter wheat on the North China Plain. Many factors may affect the canopy reflectance value; for example, soil reflectance, the cloudiness of a particular day, and the angle of view from which an image is taken are known as potential errors affecting the comparability of reflectance measurement over time and space. Also, plant disease or nutrient disorders not related to the crop's N status will affect the light reflectance (Gerard et al. 1997). Detailed spectrum studies have been shown in principle to be able to distinguish between these different causes for spectral reflectance changes of leaves (Graeff, Steffens, and Schubert 2001); such an approach needs further verification under field conditions. At the same time, some other ratios such as $R/(R+G+B)$ and $B/(R+G+B)$ should be studied to find whether they are suitable for N status estimation, although these two ratios were not significantly correlated with N status changes in this study (data not shown).

Normalized green intensity values of optimized N treatments and farmer's N treatments were very close in this study, which showed the $G/(R+G+B)$ ratio could not separate the high fertilization with optimized N well, although it could clearly recognize the N stress status from N surplus and N optimized states. Another problem that hampered the use of the light-reflectance method in the farmer's field is the different growth stages because of different sowing dates and tillage managements, which introduces large variation because of different wheat varieties or growth stage. This should be considered when using canopy light reflectance to estimate the N status of wheat in farmer's field, and it should be integrated with other field survey methods such as soil–plant testing. Further research should consider the digital image processing data with soil and plant testing data together to produce a map for fertilizer recommendation as described by Scharpf and Lory (2002).

With the rapid development of image acquisition and storage technologies, digital cameras can get higher and higher resolution pictures and store more image data than before. With some easily refits, commercial digital cameras could easily get near-infrared (NIR) images, which provide more useful information about the crops than the natural color pictures. The trend toward digital-image-based crop growth status investigation systems will likely grow in the future.

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REFERENCES

Al-Abbas, A.H., Barr, R., Hall, J.D., Crane, F.L., and Baumgardner, M.F. (1974) Spectra of normal and nutrient-deficient maize leaves. *Agron. J.*, 66: 16–20.

Blackmer, T.M. and Schepers, J.S. (1995) Use of a chlorophyll meter to monitor nitrogen status and schedule fertigation for corn. *J. Proc. Agric.*, 8: 56–60.

Blackmer, T.M., Schepers, J.S., and Varvel, G.E. (1994) Light reflectance compared with other nitrogen stress measurements in corn leaves. *Agron. J.*, 86: 934–938.

Chen, X. (2003) Optimization of the N fertilizer management of a winter wheat/summer maize rotation system in the Northern China Plain, PhD Dissertation, Hohenheim University: Stuttgart, Germany.

Chen, X., Zhou, J., Wang, X., Blackmer, A.M., and Zhang, F. (2004) Optimal rate of nitrogen fertilization for a winter wheat–corn cropping system in Northern China. *Commun. Soil Sci. Plant Anal.*, 35 (3–4): 583–597.

Fox, R.H., Piekielek, W.P., and Macneal, K.M. (1994) Using a chlorophyll meter to predict nitrogen fertilizer needs of winter wheat. *Commun. Soil Sci. Plant Anal.*, 25 (3–4): 171–181.

Gerard, B., Buerkert, A., Hiernaux, P., and Marschner, H. (1997) Non-destructive measurement of plant growth and nitrogen status of pearl millet with low-altitude aerial photography. *Soil Sci. Plant Nutri.*, 43: 993–998.

Geypens, M. and Vandendriessche, H. (1996) Advisory systems for nitrogen fertilizer recommendations. *Plant Soil*, 181 (1): 31–38.

Graeff, S., Steffens, D., and Schubert, S. (2001) Use of reflectance measurements for the early detection of N, P, Mg, and Fe deficiencies in *Zea mays* L. *J. Plant Nutr. Soil Sci.*, 164: 445–450.

Handson, P. and Sheridan, J. (1992) Rapid sap tests for better fertilizer management. In *Proceedings of the International Conference on Fertilizer Use in the Tropics*; Aziz, B. (ed.), Kuala Lumpur, 220–233.

Hong, S., Rim, S., Lee, J., and Kin, J. (1997) Remote sensing for estimating chlorophyll amount in rice canopies. In *Proceeding of International Geoscience and Remote Sensing Symposium*, IEEE International: Singapore, 89–91, IEEE International.

Jia, L., Chen, X., Zhang, F., Buerkert, A., and Roemheld, V. (2004) Use of digital camera to assess nitrogen status of winter wheat in the Northern China Plain. *J. Plant Nutr.*, 27: 441–450.

Jia, L., Chen, X., Zhang, F., Liu, H., and Wu, J. (2000) Study of optimum N supplying rate in winter wheat in Beijing area. *J. China Agricul. Univ.*, 6 (3): 67–73 (in Chinese with English abstract).

Liu, X., Ju, X., Zhang, F., and Chen, X. (2003) Nitrogen recommendation for winter wheat using N_{min} test and rapid plant tests in North China Plain. *Commun. Soil. Sci. Plant Anal.*, 34 (17–18): 2539–2551.

McMurtrey III, J.E., Chappelle, E.W., Kim, M.S., Meisinger, J.J., and Corp, L.A. (1994) Distinguishing nitrogen fertilization levels in field corn (*Zea mays* L.) with actively induced fluorescence and passive reflectance measurements. *Remote Sens. Environ*, 47: 36–44.

Scharpf, P.C. and Lory, J.A. (2002) Calibrating corn color from aerial photographs to predict sidedress nitrogen need. *Agron. J.*, 94: 397–404.

Wehrmann, J.H., Scharpf, C., Boehmer, M., and Wollring, J. (1982) Determination of nitrogen fertilizer requirements by nitrate analysis of the soil and plant. In Plant Nutrition, 1982, Proceedings of the Ninth International Plant Nutrition Colloquium, Warwick University, England; Commonwealth Agricultural Bureaux: Slough, U.K., 202–208.

Wollring, J., Reusch, S., and Karlsson, C. (1988) Variable nitrogen application based on crop sensing. In *Proceeding of Fertilizer Society*; York, UK 28, 423.