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Evaluation of variable-rate nitrogen recommendation of winter wheat based on SPAD chlorophyll meter measurement

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Abstract To develop a time-Specific and time-critical spatial variable rate nitrogen application (VRN) method and to overcome the limitations of traditional field sampling methods, this study focused on the relationship between SPAD chlorophyll meter readings and nitrogen content in leaves in order to determine the amount of nitrogen fertilisation required for agricultural objectives. Field experiments were conducted in three wheat growth duration stages from 2003 to 2006. Grain yields and soil NO_3-N contents were measured in all plots. Our results indicated that VRN technology reduced wheat yield spatial variability. The benefits of VRN included low soil residual NO_3-N content and NO_3-N leaching potential, suggesting that VRN technology based on SPAD readings can potentially reduce groundwater pollution and therefore protect our limited environmental resources.

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INTRODUCTION

Variable rate nitrogen application (VRN) can help crop growers site-specifically apply economically optimised nitrogen rate (EONR) at locations within a field. It has both environmental and economic benefits because it can potentially reduce residual N in soils at the end of growing season and consequently lower the potential of N leaching into the water system (Dinnes et al. 2002). It should be noted that EONR for a whole field is not necessarily equal to the mean of EONR for its subsections (Bullock et al. 2002). Thus, the real-time VRN offers opportunities to increase crop yield at a reduced amount of N fertiliser application (NFA). As increased revenue and the saving of NFA exceeds the costs of VRN, this technology will become more acceptable to crop growers.

There are many methods for site-specific fertilising reported (Haar et al. 1999; Peters et al. 1999; Schwarz et al. 2001; Wenkel et al. 2001). Although grid soil sampling can provide an accurate basis for variable rate fertiliser application maps, the cost and labour associated with the sampling for accurate mapping may make it unrealistic and unfeasible in execution (Fleming et al. 2000). To reduce the expense of grid soil sampling, Fleming et al. (2000) proposed the idea of management zones of equal soil quality. As a portable, non-destructive and lightweight device designed to estimate foliar chlorophyll, the SPAD-502 chlorophyll meter can be used to reduce the cost of grid soil sampling (Rodriguez & Miller 2000). Leaf chloroplasts contain 70% of leaf N concentration (Madakadze et al. 1999); thus, the amount of chlorophyll present in plant leaves is often well correlated with leaf N (Kantety et al. 1996; Bullock & Anderson 1998). For this reason, the SPAD meter is often used to improve N management and increase yields by predicting the N status

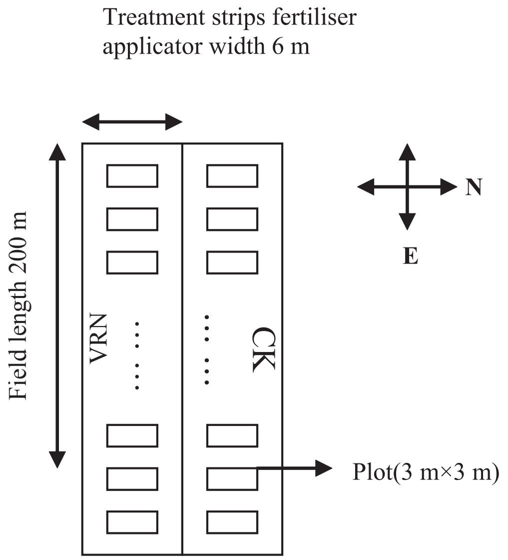

Fig. 1 Spatial distribution of experimental treatments.

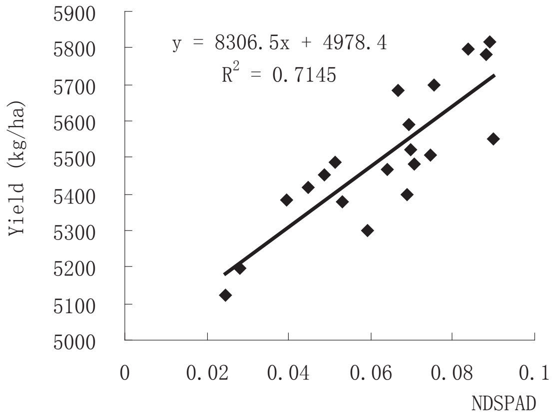

Fig. 2 The relationship between NDSPAD readings and yields of variable-rate.

of various crops and determining their fertilisation requirements. This instrument has been shown to be an easy and efficient method for detecting N status of barley (*Hordeum vulgare*) (Wienhold & Krupinsky 1999), corn (*Zea mays*) (Schepers et al. 1992), rice (*Oryza sativa*) (Peng et al. 1993), and wheat (*Triticum aestivum*) (Peltonen et al. 1995). The results suggested that SPAD could be successfully applied in crop N management.

The objective of this experiment is to develop formulae for site-specific N recommendations using foliar SPAD measurements in winter wheat, to predict yield and crop quality of winter wheat, and to evaluate the economic benefits and feasibility of VRN in winter wheat production.

MATERIALS AND METHODS

Experimental setups

Field experiments were conducted during wheat growth duration stages from 2003 to 2006 at the Xiaotangshan Precision Agriculture Experimental Station, Changping District, Beijing (40°18′29″N to 40°18′32″N, 116°44′02″ E to 116°44′22″E). Winter wheat (*Triticum aestivum*) cultivar (‘Jingdong-8’) was used in this study.

The treatments were laid out in a completely randomised block design with all plots measuring 3 × 3 m. The uniform N rate treatment, which was chosen as the check treatment (CK), received the same gross fertilisation rate as the VRN treatment (Fig. 1). There were 20 plots of VRN and of CK, respectively. In-season SPAD readings were used to modulate the additional N rate during early growth stages of the plant since leaf SPAD readings indicated significant linear responses with respect to plant NO_3. All nitrogen fertiliser was applied at the Feek 5 growth stage.

SPAD readings of winter wheat in the variable-rate plots were measured at Feek 5 growth stages during 2003–04, in order to determine the amount of additional N. The N application formula is as follows:

Normalised difference SPAD (NDSPAD): NDSPAD = $(SPAD_2 - SPAD_1)/(SPAD_2 + SPAD_1)$ (1)

where $SPAD_2$ is SPAD readings of the second newly full expanding leaf; $SPAD_1$ is SPAD readings of the first newly full expanding leaf.

The relationship between target grain yield (TGY) and NDSPAD is shown in Fig. 2.

$$TGY = 8306.5NDSPAD + 4978.4 \quad (R^2 = 0.7145) \qquad (2)$$

The relationship between grain N uptake (GNU) and TGY is shown in Fig. 3.

$$GNU = 0.0706TGY - 204.17 \quad (R^2 = 0.6602) \qquad (3)$$

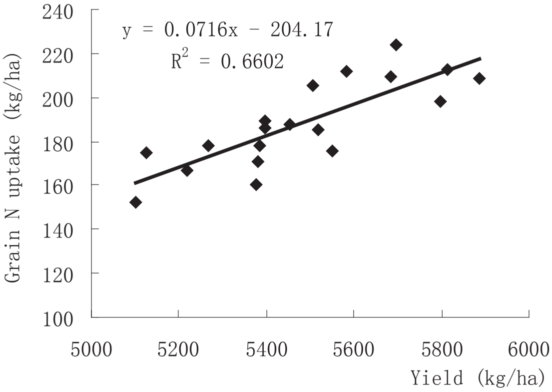

Fig. 3 The relationship between grain N uptake and yields with variable rates of N application.

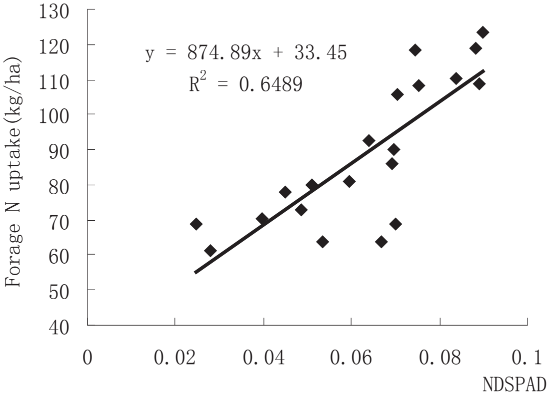

Fig. 4 The relationship between forage N uptake and NDSPAD with variable rates of N application.

Table 1 Average field-level measured and predicted yields for Experiments B and C[1].

Experiment	Measured yield (kg ha^{-1})	Predicted yield (kg ha^{-1})	Error (%)
Experiment B	5411	5543	2.44
Experiment C	5492	5541	0.89
Average	5451	5542	1.66

[1]Experiment A was conducted from 2004 to 2005, Experiment C was conducted from 2005 to 2006.

The relationship between foliar N uptake (FNU) at the Feek 5 growth stage is shown in Fig. 4.

Using NDSPAD to calculate foliar uptake (FNU) at the Feek 5 growth stage:

$$FNU = 874.89NDSPAD + 33.45 \quad (R^2 = 0.6489) \qquad (4)$$

Fertiliser N requirement (FNR):FNR = (GNU – FNU)/(0.46 × 0.5) (5)

where 0.46 is N percentage of urea fertiliser, and 0.5 is N use efficiency.

Soil NO_3-N content

The soil NO_3-N content was analysed by using the UV spectrophotometric method.

Economic analysis

$$\text{Economic benefits} = Y \times Pc - N \times Pn \qquad (6)$$

where Y is wheat yield (kg/ha), Pc is the price of wheat (e.g., 1500 yuan/ton), N is nitrogen application rate (kg/ha), and Pn is the cost of nitrogen fertiliser (e.g., 1500 yuan/ton).

RESULTS AND ANALYSIS

Yield predictions

The N application formula gave very good results in predicting wheat yields, and the percentage error between the prediction and field measurements was 2.44% for Experiment B and 0.89% for Experiment C (Table 1). The 2-year field-level predicted yield was 5542 kg ha^{-1}, only 1.66%, or 92 kg ha^{-1}, off the average measured yield.

Spatial yield variability

Mean yield of VRN was greater than that of CK in 2 production years (Table 2). Variation coefficients were 12.62 and 13.78%, which were lower than those of CK (16.21 and 17.08%). This means that the VRF technology reduced yield variation. The maximum yield of all treatments in the 2 production years appeared in winter wheat with VRN application.

Optimum nitrogen rate and economic benefits

Economic benefits for VRN was computed using Eqn (6) and was then averaged over Experiment

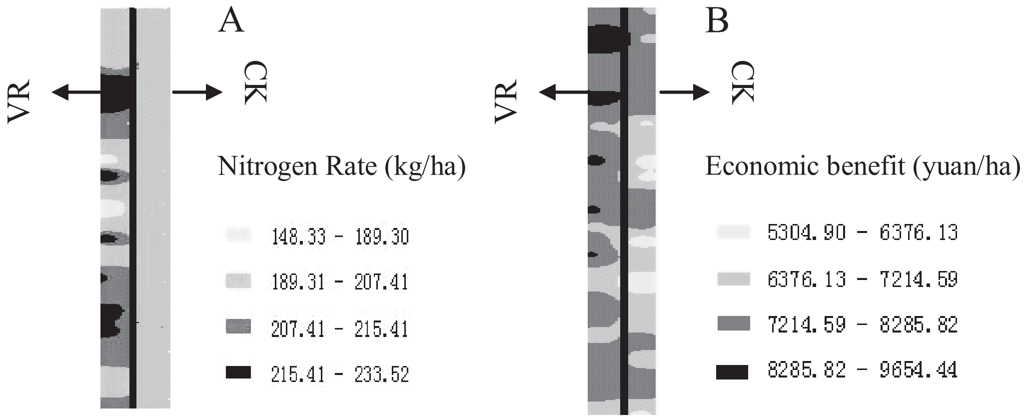

Fig. 5 Optimum variable nitrogen rate (A) for wheat and corresponding economic benefits (B) of plots.

Table 2 The mean yields, standard deviations and variation coefficients between variable-rate fertilisation and the control. SD, standard deviation; CV, coefficient of variation.

Experiment	Treatment	Mean yield (kg/ha)	SD	CV	Maximum (kg/ha)	Minimum (kg/ha)
Experiment B	VRN	5410.73	682.57	12.62	7123.00	4273.80
	CK	4609.88	747.06	16.21	5847.37	3362.79
Experiment C	VRN	5491.62	756.64	13.78	6967.83	4537.87
	CK	4977.56	850.20	17.08	6236.49	3381.56

B and Experiment C for each plot, to develop the average economic benefit for each nitrogen rate. Results show high spatial distribution of VRN for plots across the field (Fig. 5A). Economic benefits for each plot corresponding to the VRN and CK are illustrated in Fig. 5B.

The comparison of economic benefits for different levels of spatial distribution (Table 3) shows that VRN application is more economically effective than CK over Experiment B and Experiment C. There were 15 plots with yields ranging from from 7214.59 to 8285.82 yuan/ha, consisting of the 75% of total of economic benefits in VRN, but only nine plots in CK. However, cost for soil sampling and analysis were not included in the economic analysis.

Soil residual nitrate-nitrogen

One of the primary objectives of these studies was to evaluate the impact of VRN application on leachability potential of NO_3-N after harvest. Therefore, a substantial effort was made to determine root zone NO_3-N concentrations on a plot basis after harvest in late autumn. The N budget was not considered, nor did NO_3-N leach below 0.6 m, the greatest depth measured. However, the residual NO_3-N can provide an estimate of leachability potential, so it is comparable among the VRN and CK treatments. As Fig. 6 shows isotropic semi-variogrammatic parameters for soil residual NO_3-N for the VRN treatments have achieved significant difference in the 2 production years.

Soil leaching nitrate-nitrogen patterns

Patterns of NO_3-N leaching in soil for VRN and CK are shown in Fig. 6. This generated interpolated maps of soil NO_3-N leaching for each treatment, which covered the extent of the entire study area. These illustrate that both treatments resulted in higher soil NO_3-N leaching in the east portion of the field. This was because this site is centre pivot irrigated. The separate interpolated maps of VRN and CK, particularly in Experiment B, indicated substantial soil NO_3-N leaching after harvest. It is evident that VRN decreased soil NO_3-N leaching.

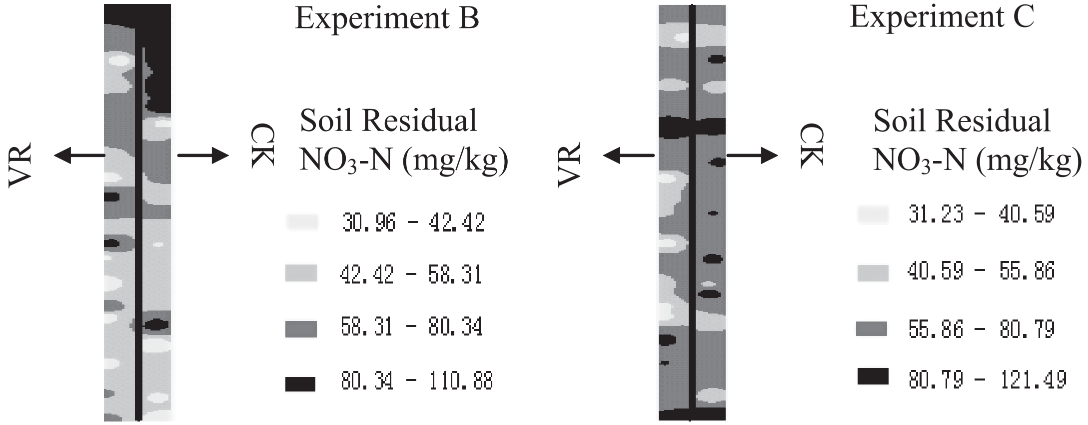

Fig. 6 Kriged maps of soil NO_3-N leaching for VRN and CK.

Table 3 Distribution of average economic benefits for plots in Experiments B and C of variable rate nitrogen (VRN) and check treatment (CK).

Net return (yuan/ha)	No. of plots		Percentage (%)	
	VRN	CK	VRN	CK
5304.90–6376.13	0	7	0	35
6376.13–7214.59	5	4	25	20
7214.59–8285.82	9	9	45	45
8285.82–9654.54	6	0	30	0

DISCUSSION

There is no doubt that the nitrogen management practices can be adopted by crop growers if the practices are affordable, accurate in fertilisation, easy to use, and environmentally friendly. The SPAD meter has been demonstrated and proved to be a viable and effective tool in developing and evaluating management recipes across a field.

The aimed yield is ascertained with different site leaf SPAD readings, which determine fertilisation according to yield and soil nutrition. This method can explore soil potential, apply fertiliser as needed, and potentially reduce environmental contamination. However, extensive research has shown that expected, potential, average, and actual yields are often very poorly correlated with the economically optimum N rate for a site. These phenomena have been observed across Ontario in Canada (Kachanoski et al. 1996), and states of Colorado (Fleming et al. 2000), Illinois (Harrington et al. 1998), Michigan (Everett & Pierce 1996), Minnesota (Davis et al. 1996), Missouri (Scharf et al. 2002) and Wisconsin (Vanotti & Bundy 1994) in the United States. More than 480 field studies in Ontario, Colorado, Illinois, Iowa, Michigan, Minnesota, and Wisconsin suggested that the variation in the recommended N rate explained less than 10% of the variation in the actual economically optimum N rate.

CONCLUSION

As demonstrated in this study, crop N requirement within a field can vary widely. There are differences in N fertiliser requirement for different NDSPAD in fields. As an effective tool, the SPAD meter was used to measure chlorophyll a. The results of this experiment indicated that VRN improved wheat yield and reduced the variability of wheat yield. The diversities of yield were reduced under relatively great variation of soil nutrient conditions in each plot, and we believe the experiment has demonstrated some economic benefits. Meanwhile, VRN may reduce the potential of water pollution, and therefore, better protect our limited environmental resources.

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