In-Season Optical Sensing Improves Nitrogen-Use Efficiency for Winter Wheat

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Optical sensor-based N management strategies are promising approaches to improve N-use efficiency (NUE) and reduce environmental pollution risk. The objective of this study was to evaluate an active optical sensor-based in-season N management strategy for winter wheat (*Triticum aestivum L.*) in the North China Plain (NCP). Initially, 10 field experiments were conducted at four villages in NCP in the 2004/05, 2005/06, and 2006/07 growing seasons to evaluate the in-season N requirement prediction developed by Oklahoma State University. Then the N application rates, winter wheat grain yield, NUE, economic returns, residual N content after harvest and apparent N loss were compared among three different management systems on a total of 16 farmer fields in 2005/2006 and 14 farmer fields in 2006/2007. The systems included a sensor-based system, a soil test-based approach crediting soil residual mineral N (N_{min}) to different depth at different growth stages, and common farmer practices. Averaged across site-years, the sensor-based, soil N_{min}–based N management strategies, and farmer practices produced similar grain yields but used 67, 88, and 372 kg N ha^{-1}, respectively. Nitrogen-use efficiencies were 61.3, 51.0, and 13.1% for the three methods of N recommendations, correspondingly. Their residual N content in the soil and apparent N loss were 115, 122, and 208 kg N ha^{-1}, and 4, 15, and 205 kg N ha^{-1}, respectively. The optical sensor-based N management strategy is relatively easy to use, has better potential to improve NUE and economic returns, and reduces residual soil N content and apparent N loss than other methods currently used in the NCP.

Abbreviations: CK, check; Con, conventional N fertilization; GDD, growth degree days; INSEY, in-season estimated yield; NCP, North China Plain; NDVI, normalized difference vegetation index; N_{min}, soil residual mineral N; NUE, nitrogen use efficiency; Opt, optimized N fertilization; PNG_{YPN}, predicted non-N limiting grain N uptake; PNG_{YP0}, predicted grain N uptake without additional N; RI, response index; YPN, non-N limiting yield potential; YPO, yield potential without additional N.

China is the world's largest producer and consumer of commercial N fertilizers (Smil, 2002), accounting for about 30% of the world total (Zhu and Chen, 2002). Excessive N application to crops raises the potential risk for loading reactive N into the environment and incurs unnecessary additional expense for producers. This is particularly the case within intensive agricultural regions of the NCP, where unjustified N-fertilization and irrigation have resulted in significant N leaching or denitrification during the winter wheat growing season (Chen et al., 2005; Li et al., 2007). The grain yield per unit applied N in the NCP decreased from 46 kg grain kg^{-1} N at an application rate of 174 kg N ha^{-1} yr^{-1} in 1978 to 21 kg grain kg^{-1} N at an application rate of 592 kg N ha^{-1} yr^{-1} in 1998 (Fang et al., 2006). Nitrogen contamination of water bodies has become an environmental and social issue threatening crop production and human health (Zhang et al., 1996; Liu et al., 2005). Technologies and methods for effective N fertilizer management are urgently needed in this area.

To advance crop N management in this region, Chen et al. (2006) developed an improved soil test-based in-season N management strategy that credits soil residual mineral N (N_{min}) to reduce N application rates without decreasing grain yield. This strategy has been evaluated for winter wheat in the NCP over 121 site-years using on-farm experiments. Using the N_{min} strategy, an average of 196 kg N ha^{-1} was saved without any significant wheat grain yield reduction as compared with the typical farmer's fertilization practice (Cui et al., 2008). However, it is not practical to apply this soil test-based management strategy to large areas for in-season site-specific N management due to labor, time, and expense limitations.

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Research and technological advances in the field of crop canopy sensing have greatly enhanced our ability to use remote sensing instruments for improved N management. Although many researchers have investigated the relationships between spectral vegetation indices or reflectance at particular wavelengths with various agronomic parameters (Bronson et al., 2003; Hansen and Schjoerring, 2003; Elwadie et al., 2005; Read et al., 2002), only limited studies have been performed for practical applications of N fertilizer based on crop canopy sensing (Stone et al., 1996; Zillmann et al., 2006).

Raun et al. (2001) successfully predicted in-season yield potential at critical growth stages for winter wheat using normalized difference vegetation index (NDVI) obtained with an active canopy sensor. This predictability was further improved by using in-season estimated yield (INSEY), where the NDVI measurement was divided by the number of days with growth degree days (GDD) > 0 from planting to sensing (Lukina et al., 2001). Consequently, a canopy sensor-based in-season N prediction algorithm was developed. The first step was to predict yield potential without additional N (YP0) using the INSEY yield prediction formula. The second step was to calculate the N response index (RI, the ratio of NDVI from the non-N limiting strip to NDVI from unfertilized wheat (Mullen et al., 2003). Non-N limiting yield potential was calculated as: (YPN = YP0 x RI). The corresponding predicted grain N uptake without additional N (PNG_{YP0}) and non-N limiting (PNG_{YPN}) field was calculated by the average percentage of N in grain multiplied by YP0 and YPN. The sensor-based fertilizer N recommendation is accomplished by subtracting PNG_{YP0} from PNG_{YPN}, then dividing by an assumed NUE to obtain the in-season topdressing N rate. Nitrogen fertilization based on this algorithm increased NUE more than 15% as compared with traditional practice (Raun et al., 2002).

Collectively, N_{min}–based N management strategies in practical N application and the relationship to environmental effects has been well studied (Scharf and Alley, 1993, 1994; Jaynes et al., 2004; Hong et al., 2007). Considering the advances made toward improving NUE for wheat using active sensing techniques, there are few studies in the literature that address its use for intensive and high-input agricultural production in Asia, especially its potential of reducing soil residual N content after harvest and apparent N loss. The objectives of this study were to evaluate the optical sensor-based in-season N management strategy for winter wheat developed by Raun et al. (2002) in an intensive agricultural region of NCP and to compare sensor-based N-management with a soil N_{min} based in-season N management strategy and common farmer practices with respect to agronomic, economic, and environmental effects.

MATERIALS AND METHODS

Overview of Experiments and Site Descriptions

Our study was composed of two different experiments administered in the NCP. One experiment was the evaluation of the optical sensor-based in-season N management strategy for winter wheat developed by Raun et al. (2002) while the other experiment utilized the results of the sensor-based N-management to predict N application rates. The predicted N rates were then compared with N rates recommended using a soil N_{min} based in-season N management strategy and with commonly used farmer practices. Comparisons were made among recommended N application rates, grain yields, net economic returns, and NUE for the different management strategies. Additionally, N balance and apparent N loss were compared among the different management strategies with respect to agronomic, economic, and environmental effects.

The experiments were conducted at two locations, Beijing and Huimin County, both located in the NCP. The climate in the NCP is warm-temperate sub-humid continental monsoon, with cold winters and hot summers. Less rainfall occurs during the winter wheat growing season. To achieve high grain yields, farmers in this region irrigate their wheat three to four times with well and/or canal irrigation water from the Yellow River. The average annual precipitation in Beijing was 602 mm from 1960 to 2000 and approximately 75% of that occurred between June and August, which is outside the growing season for winter wheat. Figure 1 shows the total rainfall and mean monthly temperature of Huimin County during the 3-yr study. The temperature was comparable in these 3 yr. The precipitation from October to May was 93, 131, and 108 mm for wheat growing seasons of 2004/05, 2005/06 and 2006/07, respectively. The main crops in this area are wheat (*Triticum aestivum L.*), maize (*Zea mays L.*), and cotton (*Gossypium hirsutum L.*). The winter wheat-summer maize rotation is the main cropping system and accounts for approximately 66% of the total cultivated area.

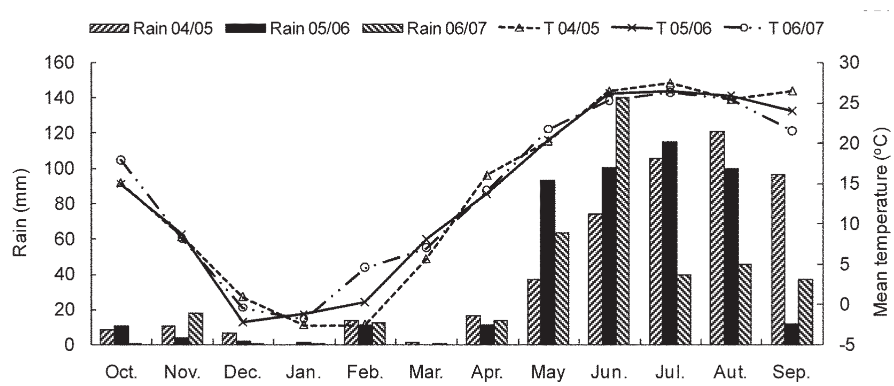

Fig. 1. Monthly total rainfall (Rain) and mean temperature (T) for three growing seasons (2004/2005, 2005/2006, and 2006/2007) in Huimin County, Shandong Province, China.

Evaluation Experiments

The purpose of the evaluation experiments was to establish a model between NDVI and grain yield. The model was developed by different site-year N level experiments and used to recommend N rates in the subsequent year. Ten ongoing long-term soil fertility field experiments were utilized for the evaluation which was conducted from October 2004 to May 2007 for three wheat seasons at two locations. The first location had one experiment located in Dongbeiwang Village near Beijing while the second location had nine experiments in Huimin County (Exp. 2–10) in Shandong Province. Both locations were representative of typical soil and crop management in the NCP. Soil texture at the experimental field in Beijing was loamy and fine-loamy in Huimin County. The soil chemical properties of the 10 fields used in the evaluation experiment are shown in Table 1. The experimental fields were selected with a low nitrate content (0- to 30-cm soil layer) using nitrate strip analysis to ensure the likelihood of a response to applied N. All experiments consisted of a randomized complete block design with four replications. Planting dates were from the 5th to 16th of October with harvest dates ranging between the 8th and 13th of June in each year.

Experiment 1 was an ongoing long-term soil fertility experiment. Three N rates including no N as check (CK), optimized N fertilization (Opt), and conventional N fertilization (Con), were applied from 1999 to 2006. Six treatment rates for Exp. 2 were: CK, Opt − 30 kg N ha^{-1}, Opt,

Table 1. Soil chemical properties (0- to 30-cm soil layer) and winter wheat varieties for the 10 fields used in the evaluation experiment.

Exp.	Site	Variety	Year	Organic matter	Total N	Mineral N (0–30 cm)	Mineral N (0–90 cm)	Olsen-P	NH_4OAC-K†
				——g kg^{-1}——		——kg ha^{-1}——		——mg kg^{-1}——	
Experiment	Village								
1	Dongbw	Jingdong8	04/05	21.4	1.17	36	76	34.6	145
2	Suncz	Weimai8	04/05	10.9	0.70	60	154	27.1	79
3	Suncz	Kenong9204	04/05	10.8	0.68	61	152	31.5	75
4	Jiexx	Lumai23	04/05	13.1	0.84	44	144	30.1	146
5	Xizl	Lumai23	04/05	12.6	0.81	30	96	45.3	215
6	Xizl	Lumai23	04/05	12.7	0.78	38	134	30.2	153
7	Xizl	Kenong9204/Lumai23	05/06	14.5	0.90	25	72	18.8	194
8	Xizl	Weimai8	05/06	13.8	0.79	45	105	24.2	202
9	Xizl	Kenong9204/Lumai23	06/07	14.1	1.08	57	121	20.3	154
10	Xizl	Weimai8	06/07	14.3	0.88	25	69	29.9	171

†Ammonium acetate extractable K.

Opt + 30 kg N ha^{-1}, Opt + 60 kg N ha^{-1} and Con. The optimized N fertilization rates were calculated according to a method advanced by Chen et al. (2006). In this method, optimization of N for winter wheat was based on plant N demands depending on a crop target yield and soil mineral N (N_{min}) supply (i.e., NO_3–N + NH_4–N) of three growth periods. The three growth periods were from sowing to regreening, regreening to shooting, and shooting to harvest. Soil N_{min} was tested in the effective rooting depths for the three different growth periods. The effective rooting depths were 0 to 30 cm for the sowing to regreening growth period, 0 to 60 cm for the regreening to shooting growth period, and 0 to 90 cm for the shooting to harvest growth period. The Con was based on local farmers' practices. Generally, for the Beijing suburb (i.e., Exp. 1), the Con treatment consisted of an application of 150 kg N ha^{-1} at preplant and an application of 150 kg N ha^{-1} as top-dressing at the Feekes Growth Stage 6 (Large, 1954). For Huimin County (i.e., Exp. 2–10), the Con treatment consisted of applications of 103 kg N ha^{-1} preplant and 266 kg N ha^{-1} at Feekes Stage 4 as top-dressing.

The N fertilizer treatments for Exp. 3 through 7 were CK, Opt, 40% of Opt, 70% of Opt, 130% of Opt, and Con. Experiment 8 was conducted as a split-plot design. Nitrogen was applied at five rates (0, 25, 50, 75, 100 kg N ha^{-1}) before planting. At Feekes Growth Stage 6, each plot was divided into two parts: one received N topdressing and the other did not. The topdressing N rate was determined based on an improved N_{min} method (Chen et al., 2006). Experiment 9 used the same N fertilizer treatments as described for Exp. 3 to 7, while Exp. 10 used the same treatment structure as Exp. 8. All experimental plots received 120 kg P_2O_5 ha^{-1} as triple super-phosphate and 90 kg K_2O ha^{-1} as potassium sulfate before planting. Urea was the N source for all experiments.

Comparison Experiments

The purpose of the comparison experiments was to compare N rates recommended using the GreenSeeker sensor (N-tech Industries, Ukiah, CA) with application rates obtained using a soil N_{min} based in-season N management strategy and with commonly used farmer practices. Sixteen farmers' fields were selected randomly with cooperating farmers as comparison experiments at Huimin County in 2005/2006. Fourteen of those 16 fields were utilized in 2006/2007 because two of the farmers planted cotton instead of wheat. Table 2 summarizes the soil fertility of the 16 fields. Each field was designed with 4 N treatments, no N as check (CK), N recommendation based on N_{min} (Opt1), N recommendation based on GreenSeeker sensor (Opt2) and conventional N

Table 2. Soil chemical properties (0- to 30-cm soil layer) and winter wheat varieties for the 16 fields used in the comparison experiment.

Exp.	Site	Variety	Year	Organic matter	Total N	Mineral N (0–30 cm)	Mineral N (0–90 cm)	Olsen-P	NH_4OAc-K†
				——g kg^{-1}——		——kg ha^{-1}——		——mg kg^{-1}——	
Experiment	Village								
1	Liubt	Weimai8	05/06	11.7	0.73	21	51	10.8	210
2	Liubw	Lumai23	05/06	15.2	0.93	49	182	8.2	187
3	Mabl	Lumai23	05/06	11.1	0.69	39	112	9.4	191
4	Wangbh	Weimai8	05/06	12.7	0.91	31	118	15.8	202
5	Wangg	Lumai23	05/06	15.1	0.91	23	65	14.3	210
6	Wanghh	Weimai8	05/06	13.3	0.86	30	77	23.7	198
7	Wanghs	Weimai8	05/06	15.1	0.93	59	215	9.6	202
8	Wangjx	Weimai8	05/06	15.3	0.91	74	213	19.3	198
9	Wangpy	Lumai23	05/06	13.8	0.60	36	91	29.1	214
10	Wangsx	Weimai8	05/06	12.7	0.77	39	89	18.7	175
11	Wangxf	Lumai23	05/06	13.6	0.85	29	76	19.5	218
12	Wangxm	Weimai8	05/06	13.0	0.86	38	114	13.9	175
13	Zhangdxb	Weimai8	05/06	17.4	1.05	65	159	22.0	222
14	Zhangdxn	Lumai23	05/06	16.5	0.98	41	162	32.1	210
15	Zhangxh	Weimai8	05/06	16.9	0.92	49	123	21.6	222
16	Zhangxx	Weimai8	05/06	15.6	0.94	50	132	16.6	183

†Ammonium acetate extractable K.

fertilization (Con, farmer practice managed by farmers themselves). We used different farmers' fields as replications. The plot area was 75 m^2 for Opt1 and Opt2 and 150 m^2 for CK and Con. The phosphate and potassium rates for each plot were the same as the evaluation experiments.

The sensor-based N rate recommendation of Opt2 was obtained by subtracting the predicted plant N uptake in area without additional N from the predicted N uptake in the non-N limiting reference strip (often referred as the N-rich strip) in each field, then dividing by an NUE factor (usually about 0.4 in the optimum N rate using the local application method). Due to preplant N fertilizer applied by farmers in local villages and high soil N_{min} before sowing, we regarded Con treatment as the non-N limiting reference strip in each field. It was slightly different from the algorithm developed by Raun et al. (2002 and 2005) because it was calculated by subtracting PNG_{YP0} from PNG_{YPN} without forage N uptake due to its low value in local areas.

NDVI Measurements

About 3 to 4 m^2 winter wheat was selected randomly in the center of each plot and was sensed by holding a GreenSeeker active sensor approximately 0.6 to 1.0 m above the canopy and walking the same speed in each plot. The Feekes Growth Stage 4 to 7 was sensed in all plots and the sensor path was parallel to the seed rows or the beam of light was perpendicular to the seed row. The GreenSeeker Hand Held optical reflectance sensor uses active radiation from red (650 ± 10 nm) and near infrared (770 ± 15 nm) band independent of solar radiations. The device uses built-in software to calculate NDVI directly and generates 10 NDVI determinations per second.

Normalized sensor readings were calculated to neutralize variability in spectral canopy reflectance resulting from differences in site conditions. The normalized NDVI readings were obtained by dividing sensor readings of each plot by that of the plot which received the highest N rate in the same experiment (Flowers et al., 2003).

Plant and Soil Measurements

Aboveground biomass was collected by randomly clipping 100 by 30 cm vegetation from scanned plants following sensing in each plot. All plant samples were oven dried at 70°C to constant weight then weighed, ground, and Kjeldahl-N was determined. Plant samples were taken at Feekes Growth Stages 4, 5, 6, and 7. The plant N uptake (N uptake) was determined by multiplying plant N concentration by dry biomass. The normalized plant N concentration and uptake were calculated by dividing plant N concentration and plant N uptake by plant N concentration and plant N uptake of the plot which received the highest N rate in the same experiment. For determination of grain yield, a 1 × 1 m area in the middle of each plot was hand harvested, dried at 70°C to constant weight, then weighed.

To analyze N_{min} of the soil, soil samples were taken at preplant, Feekes 4 (only for Exp. 7 and 8 in 2005/06), Feekes 6, Feekes 10 (only for Exp. 7 and 8 in 2005/06), and after harvesting. Five soil cores were collected from each sub-plot in 30-cm increments (depth varied with growth stage). Soil NH_4–N and NO_3–N in the fresh soil samples were extracted with 0.01 mol L^{-1} $CaCl_2$, then analyzed using the Continuous Flow Analyzer (TRAACS 2000, Bran and Luebbe, Germany).

Statistical Analysis

The standard deviation (SD), mean and coefficient of variation (CV, %) of NDVI, whole-plant N concentration and N uptake were calculated using Microsoft Excel (Microsoft Corporation, Redland, CA) for each evaluation experiment. The coefficient of determination (R^2) relating sensor readings with plant N concentration and uptake corresponding to linear formula were calculated using PROC REG (SAS Inst., 2001).

Nitrogen-use efficiency was calculated by the method as shown in the following formula (Liu et al., 2003):

$$\text{NUE}(\%)=\frac{(\text{N uptake in fertilized treatment}-\text{N uptake in unfertilized treatment})}{\text{amount of N fertilizer}}\times 100$$

The amount of apparent N loss was calculated before sowing and after harvesting according to the balanced model (N inputs = N outputs), which equals to the difference between N inputs and sum of N uptake and residual N_{min} (Liu et al., 2003; Olfs et al., 2005). Net economic returns were the difference between grain sales and N fertilizer costs using wheat grain prices of \$0.2 kg^{-1} in 2006 and \$0.24 kg^{-1} in 2007, and N price of \$0.5 kg^{-1} for both years.

RESULTS

Evaluation Experiments

The NDVI values were obtained for all 10 experiments representing typical wheat production in the NCP (Table 3). The NDVI ranged between 0.18 and 0.80 at Feekes Growth Stage 4 to 5 and between 0.27 and 0.86 at Feekes 6 to 7. The physiological Feekes Growth Stages in winter wheat was described by Large (1954). Feekes 4 is the beginning of the erection of the pseudo-stem when the leaf sheaths begin to lengthen. In Feekes 5, the pseudo-stem formed by sheaths of leaves is strongly erected. During Feekes 6, the first node of the stem is visible at the base of the shoot and Feekes 7 is typified by the second node of the stem being formed and the next-to-last leaf is just visible. The Zero N treatment generally had the lowest NDVI values, plant total N concentration and plant N uptake. The highest N rates had the greatest NDVI for each experiment. The NDVI was better correlated with crop biomass than with N concentration (Sembiring et al., 1998). Plant N uptake was calculated as the product of crop N concentration and aboveground biomass. There was a better relationship between NDVI values and plant N uptake than between NDVI and plant N concentration at all growth stages (Table 3).

As the growth stage progressed, plant total N concentration decreased from Feekes Growth Stage 4 to 5 to Feekes Growth Stage 6 to 7 probably due to a dilution effect (Justes et al., 1994). The correlations between NDVI and plant N concentration were significant for 7 out of 10 experiments at Feekes Growth Stages 4 to 5 and 6 out of 8 experiments at Growth Stages 6 to 7. These partial correlations do not support that NDVI is a good estimator of plant N concentration. However, all of the individual NDVI values were significantly related to plant N uptake. This suggests that plant N uptake could be estimated by sensing, which agrees well with the findings of Stone et al. (1996). Lukina et al. (2001) reported that NDVI was an excellent predictor of early-season plant N uptake for nine trials that covered 3 yr, two varieties, a range of planting and sensing dates, and three physiological stages of growth. Similar to the study by Lukina et al. (2001), our study showed the relationship between NDVI and N uptake was reliable regardless of varieties, growth stages and experimental sites. Additionally, biomass was highly correlated with plant N uptake. The coefficients of determination (R^2) between biomass and N uptake was 0.89 in Feekes Growth Stage 4 to 5 and 0.83 in Feekes Growth Stage 6 to7 for all evaluation experiments.

When all experimental data were combined for each growth stage, compared with individual experiments, there were no

Table 3. Mean values (± SD) for the NDVI values, biomass, whole-plant N concentration and plant N uptake and root mean standard error (RMSE) and determination coefficient (R^2) for the relationship between biomass, plant N concentration, uptake and NDVI values at Feekes Growth Stage 4 to 7 in 2005, 2006, and 2007 in the evaluation experiment.

Experiment	n	NDVI	Biomass			Plant N concentration			Plant N uptake		
		Mean (SD) †	Mean (SD)	RMSE	R^2	Mean (SD)	RMSE	R^2	Mean (SD)	RMSE	R^2
			——kg ha^{-1}——			——g kg^{-1}——			——kg N ha^{-1}——		
Feekes growth stage 4–5											
1	12	0.448 (0.125)	786 (178)	108	0.67**	42.0 (7.4)	2.6	0.89**	34 (12)	4	0.87**
2	24	0.568 (0.034)	1838 (381)	293	0.44**	35.9 (4.7)	3.3	0.53**	71 (19)	13	0.52**
3	24	0.564 (0.035)	2027 (285)	236	0.34**	31.2(4.4)	3.0	0.56**	64 (15)	9	0.65**
4	24	0.551 (0.052)	1511 (272)	149	0.71**	35.9 (3.9)	3.4	0.30**	55 (14)	9	0.58**
5	24	0.586 (0.049)	1501 (265)	167	0.62**	33.3 (2.8)	2.3	0.33*	50 (11)	6	0.72**
6	24	0.484 (0.057)	1348 (142)	101	0.52**	32.8 (3.0)	2.1	0.54*	44 (7)	4	0.73**
7	48	0.318 (0.091)	576 (178)	119	0.60**	41.3 (2.2)	2.2	0.01	25 (9)	6	0.55**
8	20	0.350 (0.060)	490 (149)	133	0.25*	38.4 (2.2)	2.0	0.16	18 (7)	5	0.36**
9	48	0.675 (0.090)	1567 (378)	360	0.11*	40.4 (2.0)	1.8	0.21**	64 (17)	15	0.15*
10	20	0.508 (0.057)	1187 (423)	233	0.71**	39.3 (2.6)	2.2	0.32*	47 (19)	10	0.72**
All	268	0.508 (0.141)	1281 (575)	363	0.60**	37.4 (6.3)	4.9	0.01	48 (22)	13	0.64**
Normalized all,%	268	92.1 (11.2)	85.3 (19.7)	16.1	0.34**	94.9 (7.9)	6.8	0.25**	81.4 (22.4)	17.1	0.43**
Feekes growth stage 6–7											
1	12	0.654 (0.218)	2892 (1171)	378	0.91**	25.6 (7.1)	2.2	0.91**	81 (47)	18	0.87**
2	24	0.827 (0.019)	2986 (408)	316	0.43**	24.6 (2.1)	2.0	0.18*	74 (15)	12	0.39**
3	24	0.834(0.020)	3806 (900)	684	0.45**	29.1 (2.9)	2.4	0.38*	112 (33)	24	0.51**
4	24	0.818 (0.024)	3802 (845)	730	0.29**	25.8 (3.0)	2.7	0.21*	100 (30)	25	0.32**
7	48	0.486 (0.124)	1300 (432)	349	0.36**	31.3 (3.4)	2.8	0.36**	41 (17)	12	0.50**
8	20	0.549 (0.088)	1302 (423)	307	0.50**	34.6 (3.3)	2.8	0.35*	47 (18)	9	0.75**
9	48	0.726(0.070)	1922 (432)	401	0.16**	39.0 (2.8)	2.6	0.19*	76 (20)	18	0.19**
10	20	0.696 (0.049)	1955 (418)	370	0.26*	38.1 (2.3)	2.2	0.13	75 (19)	17	0.25*
All	220	0.684 (0.159)	2986(418)	735	0.58**	32.0 (6.2)	6.2	0.00	72 (33)	21	0.58**
Normalized all,%	220	95.7 (11.7)	82.9 (21.5)	17.9	0.31**	92.8 (10.2)	8.6	0.30**	78.1 (25.4)	18.9	0.41**

* Significant at the 0.05 probability level.

** Significant at the 0.01 probability level.

† SD, Standard deviation.

significant correlations between NDVI values and whole-plant N concentration (Table 3). This indicates that factors like climate, sites, and cultural conditions affected NDVI values in addition to N fertilization variations. Thus, it is not advisable to use NDVI to estimate plant N concentration at different sites and years. The problem appeared to be avoided by normalizing all data using reference plots (plots receiving the highest N rate) for each experiment. Normalization improved the prediction of plant N concentration at Feekes Growth Stage 4 to 5 ($R^2 = 0.25$) and Feekes Growth Stage 6 to 7 ($R^2 = 0.30$). However, similarly to the studies of Flowers et al. (2003), normalization did not enhance the prediction of plant N uptake.

Establishment of Yield Prediction Formula

Yield potential is an important factor in most N management strategies. If yield potential could be predicted before topdressing, a more accurate topdressing N rate would be determined. The relationship between measured yield and NDVI for six experiments is shown in Fig. 2 at local topdressing time. Most farmers applied topdressing N from Feekes Growth Stages 4 to 6 in the NCP. The application time was slightly different in different villages. Thus, regression analysis showed the relationship between harvested yield and NDVI was not a continuous curve due to NDVI being determined at different growth stages (Fig. 2). The harvested yields were highly correlated with NDVI at both sensing dates (three experiments at

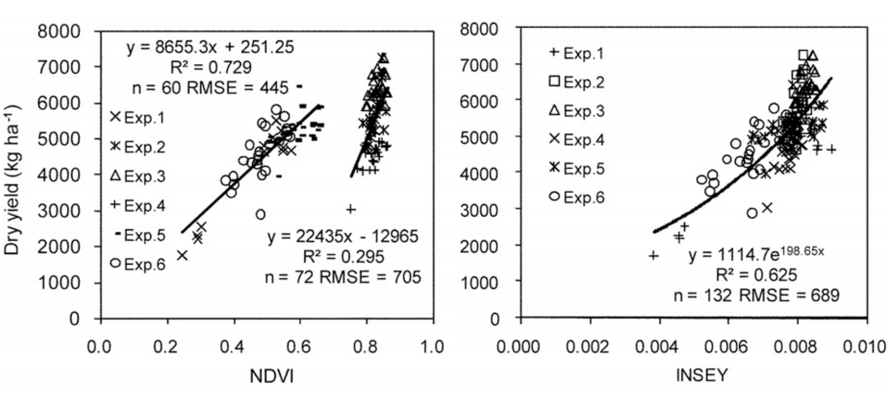

Fig. 2. The relationship between grain yields and Normalized difference vegetation index (NDVI) and in-season estimated yields (INSEY) at Feekes Growth Stage 4 and 6 in 2005.

Feekes 4 and others at Feekes 6) but with different slopes and intercepts (Fig. 2). However, similar to the findings of Raun et al. (2001 and 2002), in-season estimated yields (INSEY, normalized NDVI using the number of days when GDD > 0) improved the yield potential prediction (Fig. 2). The GDD was calculated by the formula: GDD = $(T_{min} + T_{max})/2 - 4.4°C$, where T_{min} and T_{max} are minimum and maximum daily temperatures, respectively. As a method, INSEY normalized NDVI measurements across various cultural and climatic conditions (Teal et al., 2006). Figure 3 illustrated a significant exponential relationship between grain yield and INSEY in 3 yr. This suggests that INSEY can predict the yield potential of winter wheat in the NCP. Therefore, a topdressing N rate can be accurately estimated using the model developed in this region.

Comparison Experiments

Across all fields and years, the N application rates generated from the sensor-based strategy (Opt2 treatment) varied from 30 to 136 kg N ha^{-1} with a mean of 94 kg N ha^{-1} in 2006 and 40 kg N ha^{-1} in 2007. These application rates were not significantly different from N_{min} based recommendations (Opt1 treatment) (Table 4). In contrast, farmers applied 191 to 543 kg N ha^{-1} with a mean application rate of 432 kg N ha^{-1}. The conventional rates were on average 317 and 338 kg N ha^{-1} more than Opt1 and Opt2 treatments in 2006, and 303 and 324 kg N ha^{-1} more in 2007. However, farmer's conventional applications did not increase grain yield compared with Opt1 and Opt2 treatments, except for one field in 2006.

On average, the yields of Opt1, Opt2, and Con treatment were not significantly different, but all were significantly higher than the check. As expected, the NUE was significantly higher for both optimized N fertilization treatments compared with conventional N fertilization in both 2006 and 2007 (Table 4). Compared with Con N treatment, the Opt1 and Opt2 treatments saved an average of $164 and $132 ha^{-1} in 2006, and $95 and $120 ha^{-1} in 2007 on fertilizer N cost, respectively. This indicates there is a great potential for maintaining the same yields while decreasing N rates by using a new technology to manage fertilizer use in the NCP.

Nitrogen Balance in the Wheat–Soil System

Nitrogen balance in crop-soil systems is a useful tool to estimate the fate of fertilizer N and its environmental risk. As illustrated in Table 5, N input in the Con treatment was significantly higher than that in Opt1 and Opt2 treatments in two consecutive years. As a result, the residual mineral N contents (N_{min} 0- to 90-cm soil depth) at harvesting time for Con was 241 kg N ha^{-1} in 2006 and 175 kg N ha^{-1} in 2007, while those under optimized N fertilization practices were significantly lower compared with Con.

The mean apparent N loss was only 32 and 18 kg N ha^{-1} for Opt1 and Opt2 treatment during 2005/2006 growing season and no apparent N loss occurred in 2006/2007. Conversely, the apparent N losses from Con treatment were 227 kg N ha^{-1} in 2005/2006 and 182 kg N ha^{-1} in 2006/2007. The apparent N losses augmented with increased N application rates (Fig. 4). It is obvious that fertilization not based on crop needs greatly influenced apparent N loss and residual soil N_{min} content.

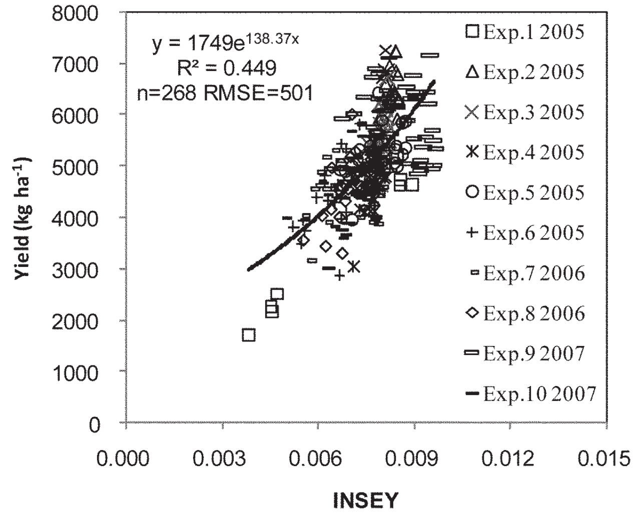

Fig. 3. Relationship between grain yields and in-season estimated yields (INSEY) using all 10 locations from 2005 to 2007.

DISCUSSION

Normalized NDVI values using reference plots receiving sufficient N application greatly improved the relationships between NDVI and plant N concentration but not the relationships between NDVI and plant N uptake, since N uptake was already strongly correlated with NDVI across fields, varieties and years. This indicates that plant N uptake was a more reliable indicator of N status of winter wheat and can be estimated by an optical sensor such as GreenSeeker.

The sensor-based fertilizer N recommendation of Opt2 was calculated using the algorithm by Raun et al. (2002, 2005). An important difference between our study and those conducted by Raun et al. (2002, 2005) was that in our study the conventional farmer's practice was regarded as an N-rich strip (which is consid-

Table 4. Mean values (± SD, standard deviation) for N application rate, grain yield, net economic return and nitrogen use efficiency (NUE, %) for the comparison experiment fields in 2006 and 2007.

Treatment	N applied	Grain yield	Net economic return†	NUE
	kg N ha^{-1}	kg DM ha^{-1}	$ ha^{-1}	%
2006 (*n* = 16)				
Check	0	3914 (480) b	783 ± (96) b	–
Opt1‡	115 (46) b¶	5119 (984) a	967 (194) a	47.2 (16.3) a
Opt2§	94 (25) b	4909 (1005) a	935 (193) a	51.8 (16.9) a
Con#	432 (59) a	4952 (785) a	803 (166) b	14.4 (5.9) b
2007 (*n* = 14)				
Check	0	5151 (636) b	1236 (153) c	–
Opt1	61 (33) b	5905 (578) a	1387 (146) ab	54.7 (35.2) a
Opt2	40 (9) b	5966 (648) a	1412 (157) a	70.8 (38.9) a
Con	312 (51) a	6034 (612) a	1292 (154) bc	11.7 (4.5) b

† Net economic return was calculated as the difference between the return on wheat grain yield and the cost of N fertilizer. Wheat grain prices of $0.20 kg^{-1} in 2006 and $0.24 kg^{-1} in 2007 were used in the calculations while an N price $0.5 kg^{-1} was used in both years.

‡ Opt1, Optimized N fertilization based on soil test.

§ Opt2, Optimized N fertilization based on sensor.

¶ Within each column, different letters indicate significant difference by LSD at the 5% level.

Con, Conventional fertilization based on farmers' practice.

Table 5. Nitrogen balance (kg N ha^{-1}) in the comparison experiment fields as affected by different strategies of N fertilizer management.

Treatment	2005/2006				2006/2007			
	No N	Opt1†	Opt2‡	Con§	No N	Opt1	Opt2	Con
A. N input								
Fertilizer N	0	115 b¶	94 b	432 a	0	61 b	40b	312 a
0–90 cm soil N_{min} preplant	126	126	126	126	172	172	172	172
Apparent N mineralization	93	93	93	93	72	72	72	72
Total input	219 c	334 b	313 b	651 a	245 c	305 b	285 b	556 a
B. N output								
Plant N uptake	123 b	173 a	170 a	183 a	163 b	194 a	192 a	199 a
0–90 cm soil N_{min} at harvest	96 c	129 b	125 bc	241 a	81 c	115 b	104b	175a
Total output	219 c	302 b	295 b	424 a	245 c	308b	296 b	374 a
Apparent N loss (A-B)	0	32 b	18 b	227 a	0	–3b	–11 b	182 a

† Opt1, Optimized N fertilization based on soil test.

‡ Opt2, Optimized N fertilization based on sensor.

§ Con, Conventional fertilization based on farmers' practice.

¶ Within each row, different letters indicate significantly difference by LSD at the 5% level.

ered non N-limiting) and the response index was calculated using the NDVI of the Con treatment divided by NDVI of Opt2. The soil N supply (soil N_{min} + fertilizer N) in the 0- to 90-cm profile of Con treatment in farmer's fields reached 205 kg N ha^{-1} in 2005 and 261 kg N ha^{-1} (data not shown) in 2006 before sowing confirming N was not limiting for those fields. Therefore, the sensor-based N management could be used to optimize yields and fertilizer rate if farmers apply no N or a lower rate of N preplant. This in-season prediction of yield potential for winter wheat can reduce cost and minimize N loss. However, more experiments should be performed to improve the yield prediction formula and validate its reliability and suitability at other regions in the NCP or possibly outside of NCP.

Roelcke et al. (2004) showed that lowering N fertilizer application rates by 30 to 40% compared with farmers' practice led to significant decreases in N surpluses, but only to slight or insignificant changes in grain yields and economic returns. In our study, over the 16 demonstration farmers' fields in 2 yr, N application rates for Opt1 and Opt2 on average were reduced by 317 and 338 kg N ha^{-1} in 2005/2006 and 251 and 272 kg N ha^{-1} in 2006/2007 compared with farmer's practice, thus reducing N loss and increasing economic returns. This was accomplished without a yield reduction. Similar to the findings of Cui et al. (2008) and Zhao et al. (2006), when N rates applied by farmers exceeded the optimum N supply (soil-test based), wheat grain yield was not significantly increased, while apparent N losses and soil residual N increased significantly. Generally, the optimum N rates should be <200 kg N ha^{-1} to achieve potential yields and approximately 40% of N fertilizer can be saved from current farmer practices in the NCP (Fang et al., 2006). Based on those studies and field results of our study, it appears there is an urgent need to reduce N application rates in this intensive agricultural region of the NCP. However, the soil-test based N management strategy requires frequent soil sampling and analysis and is not possible with current soil testing availability. It is probably a good tool for use in demonstration fields at the regional scale to convince farmers to reduce unnecessary N fertilization (Chen et al., 2006). In contrast to the soil-test based approach, the optical sensor-based approach does not require sampling and can be implemented easily. Overall, the optical sensor-based approach seems to be a better alternative for recommending topdressing N rates for winter wheat in this area.

In the intensive agricultural production region of NCP, some farmers are unwilling to take any risk of N deficiency or yield reduction, due to increased grain price and relative low N prices. Therefore, most farmers apply more N than the crop needs based on their personal experiences rather than research findings. Recently, studies have shown the annual N fertilizer inputs for some producers reached as high as 500 to 600 kg N ha^{-1} (Ju et al., 2006; Fang et al., 2006). Survey results from 4 villages, including 69 farmers, showed N application rates ranged from 58 to 535 kg N ha^{-1} with a median of 375 kg N ha^{-1} for winter wheat production (Li et al., 2008). The concentrated summer rainfall under the monsoon climate of the NCP combined with high N application rates, especially in the winter wheat growing season, has led to reactive N leaching to the groundwater (Liu et al., 2005; Li et al., 2007). Zhang et al. (1996) found over half of the 69 locations had groundwater nitrate content exceeding 50 mg L^{-1}. It is obvious that the adoption of new techniques like crop reflectance sensors is important in this area. Such techniques can diagnose N needs at the subfield scale. In this study, the active sensor method displayed promising potential to predict optimized N rate. Similar to the method based on soil testing, to some extent, it was able to regulate the N_{min} content of crop root zone to a rational range (Fig. 5). The residual soil N_{min} content at harvesting was 125 kg N ha^{-1} in 2006 and 104 kg N ha^{-1} in 2007, which approximates the baseline standard of 100 kg N ha^{-1} for environmental safety established in Europe (Schleef and Kleihanss, 1994). Compared with farmers' practice, sensor-based N management strategy decreased residual soil N_{min} content at harvesting by 48.1 and 40.7% in 2006 and 2007, respectively. Also, sensor-based and soil N_{min}–based N management strategies were effective demonstrations to

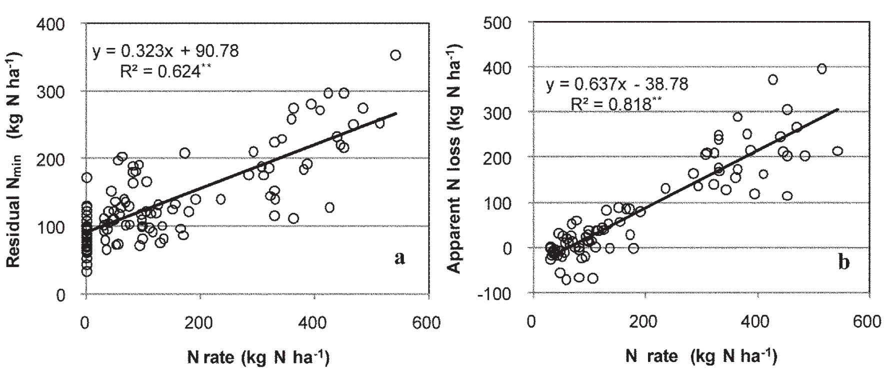

Fig. 4. Relationship between N application rate and (a) residual mineral N (N_{min} = NH_4–N + NO_3–N) in the 0- to 90-cm soil profile (b) apparent N loss in the 0- to 90-cm soil profile.

farmers and led to significant reductions in N application rate in farmer practice from 432 kg N ha^{-1} in 2005/2006 to 312 kg N ha^{-1} in 2006/2007 (Table 5). All of these confirm that there are great economic, environmental and social benefits from improved N management using a new technology in the NCP.

CONCLUSIONS

The relationship between NDVI and plant N uptake was much stronger than between NDVI and whole-plant N concentration across varieties, experiments, years, and growth stages. Normalizing NDVI with the number of days when GDD > 0 (INSEY) significantly improved grain yield predictions for winter wheat. Using INSEY to predict yield broadened the sensing window across different climatic and cultural conditions.

Compared with conventional farmers' practice, both the soil test and optical sensor-based N management strategies significantly reduced N application rates, residual N in the soil after harvest, and apparent N loss without significant decreases in grain yields. The optical sensor-based approach is promising for practical applications due to its nondestructive and timely measuring characteristics.

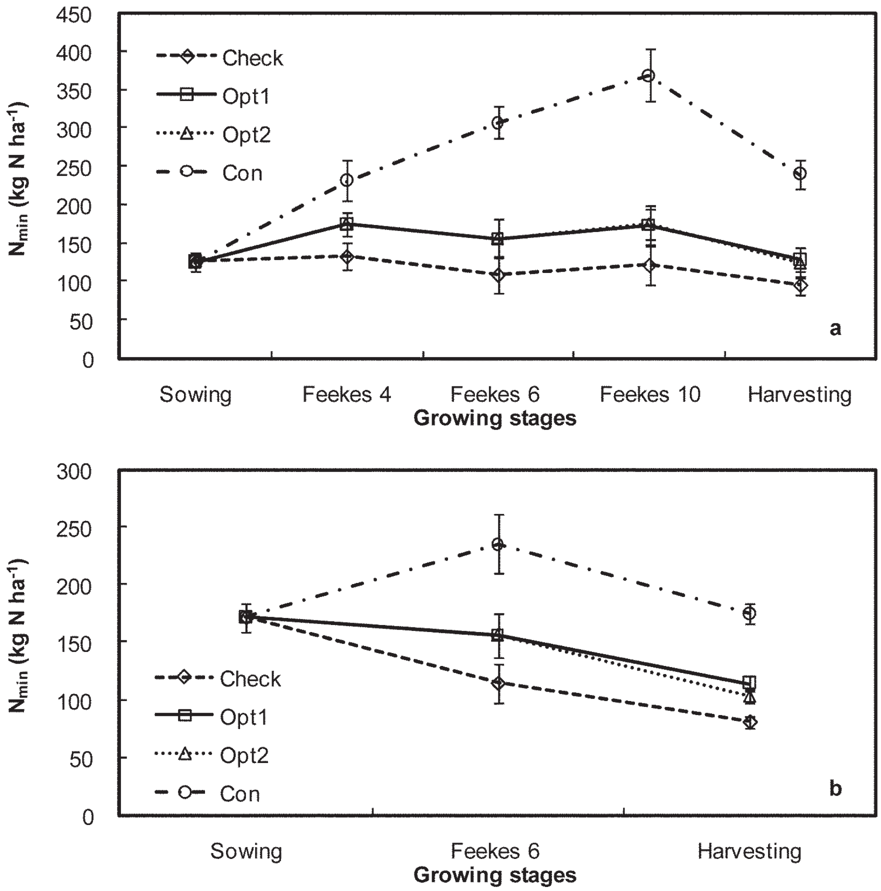

Fig. 5. Dynamics of 0- to 90-cm soil N_{min} under different strategies of N management on validation fields in (a) 2005/2006 growing season and (b) 2006/2007 growing season (Opt1, Optimized N fertilization based on soil test; Opt2, Optimized N fertilization based on sensor; Con, Conventional fertilization based on farmers' practice).

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REFERENCES

Bronson, K.F., T.T. Chua, J.D. Booker, J.W. Keeling, and R.J. Lascano. 2003. In-season nitrogen status sensing in irrigated cotton: II. Leaf nitrogen and biomass. Soil Sci. Soc. Am. J. 67:1439–1448.

Chen, J.Y., C.Y. Tang, Y. Sakura, J.J. Yu, and Y. Fukushima. 2005. Nitrate pollution from agriculture in different hydrogeological zones of the regional groundwater flow system in the North China Plain. Hydrogeol. J. 13:481–492.

Chen, X.P., F.S. Zhang, V. Römheld, D. Horlacher, R. Schulz, M. Böning-Zilkens, P. Wang, and W. Claupein. 2006. Synchronizing N supply from soil and fertilizer and N demand of winter wheat by an improved N_{min} method. Nutr. Cycling Agroecosyst. 74:91–98.

Cui, Z.L., F.S. Zhang, X.P. Chen, Y.X. Miao, J.L. Li, L.W. Shi, J.F. Xu, Y.L. Ye, C.S. Liu, Z.P. Yang, Q. Zhang, S.M. Huang, and D.J. Bao. 2008. On-farm evaluation of an in-season nitrogen management strategy based on soil N_{min} test. Field Crops Res. 105:48–55.

Elwadie, M.E., F.J. Pierce, and J. Qi. 2005. Remote sensing canopy dynamics and biophysical variables estimation of corn in Michigan. Agron. J. 97:99–105.

Fang, Q.X., Q. Yu, E.L. Wang, Y.H. Chen, G.L. Zhang, and J. Wang. 2006. Soil nitrate accumulation, leaching and crop nitrogen use as influenced by fertilization and irrigation in an intensive wheat–maize double cropping system in the North China Plain. Plant Soil 284:335–350.

Flowers, M., R. Weisz, and R. Heiniger. 2003. Quantitative approaches for using color infrared photography for assessing in-season nitrogen status in winter wheat. Agron. J. 95:1189–1200.

Hansen, P.M., and J.K. Schjoerring. 2003. Reflectance measurement of canopy biomass and nitrogen status in wheat crops using normalized difference vegetation indices and partial least square regression. Remote Sens. Environ. 86:542–553.

Hong, N., P.C. Scharf, G. Davis, N.R. Kitchen, and K.A. Suddus. 2007. Economically optimal nitrogen rate reduces soil residual nitrate. J. Environ. Qual. 36:354–362.

Jaynes, D.B., D.L. Dinnes, D.W. Meek, D.L. Carlen, C.A. Cambardella, and T.S. Colvin. 2004. Using the late spring nitrate test to reduce nitrate loss within a watershed. J. Environ. Qual. 33:669–677.

Ju, X.T., C.L. Kou, F.S. Zhang, and P. Christie. 2006. Nitrogen balance and groundwater nitrate contamination: Comparison among three intensive cropping systems on the North China Plain. Environ. Pollut. 143:117–125.

Justes, E., B. Mary, J.M. Meynard, J.M. Machet, and L. Thelier-Huche. 1994. Determination of a critical nitrogen concentration dilution curve for winter wheat crops. Ann. Bot. (Lond.) 74:397–407.

Large, E.C. 1954. Growth stage in cereals. Plant Pathol. 3:128–129.

Li, F., M.L. Gnyp, L.L. Jia, Y.X. Miao, Z.X. Yu, W. Koppe, G. Bareth, X.P. Chen, and F.S. Zhang. 2008. Estimating N status of winter wheat using a handheld spectrometer in the North China Plain. Field Crops Res. 106:77–85.

Li, X.X., C.S. Hu, J.A. Delgado, Y.M. Zhang, and Z.Y. Ouyang. 2007. Increased nitrogen use efficiencies as a key mitigation alternative to reduce nitrate leaching in North China Plain. Agric. Water Manage. 89:137–147.

Liu, G.D., W.L. Wu, and J. Zhang. 2005. Regional differentiation of non-point source pollution of agriculture– derived nitrate nitrogen in groundwater in Northern China. Agron. Eco. Environ. 107:211–220.

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

Lukina, E.V., K.W. Freeman, K.J. Wynn, W.E. Thomason, R.W. Mullen, M.L. Stone, J.B. Solie, A.R. Klatt, G.V. Johnson, R.L. Elliot, and W.R. Raun. 2001. Nitrogen fertilization optimization algorithm based on in-season estimates of yield and plant nitrogen uptake. J. Plant Nutr. 24:885–898.

Mullen, R.W., K.W. Freeman, W.R. Raun, G.V. Johnson, M.L. Stone, and J.B. Solie. 2003. Identifying an in-season response index and the potential to increase wheat yield with nitrogen. Agron. J. 95:347–351.

Olfs, H.W., K. Blankenau, F. Brantrup, J. Jasper, A. Link, and J. Lammel. 2005. Soil-and plant-based nitrogen–fertilizer recommendations in arable farming. J. Plant Nutr. Soil Sci. 168:414–431.

Raun, W.R., G.V. Johnson, M.L. Stone, J.B. Sollie, E.V. Lukina, W.E. Thomason, and J.S. Schepers. 2001. In-season prediction of potential grain yield in winter wheat using canopy reflectance. Agron. J. 93:131–138.

Raun, W.R., J.B. Solie, G.V. Johnson, M.L. Stone, R.W. Mullen, K.W. Freeman, W.E. Thomason, and E.V. Lukina. 2002. Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agron. J. 94:815–820.

Raun, W.R., J.B. Solie, M.L. Stone, K.L. Martin, K.W. Freeman, R.W. Mullen, H. Zhang, J.S. Schepers, and G.V. Johnson. 2005. Optical sensor-based algorithm for crop nitrogen fertilization. Commun. Soil Sci. Plant Anal. 36:2759–2781.

Read, J.J., L. Tarpley, J.M. McKinnion, and K.R. Reddy. 2002. Narrow-waveband reflectance ratios for remote estimate of nitrogen status in cotton. J. Environ. Qual. 31:1442–1452.

Roelcke, M., Y. Han, K.H. Schleef, J.G. Zhu, G. Liu, Z.C. Cai, and J. Richter. 2004. Recent trends and recommendations for nitrogen fertilization in intensive agriculture in eastern china. Pedosphere 14:449–460.

SAS Institute. 2001. SAS user's guide: Statistics, Ver 9.2; Cary, NC

Scharf, P.C., and M.M. Alley. 1993. Spring nitrogen on winter wheat. II: A flexible multicomponent rate recommendation system. Agron. J. 85:1186–1192.

Scharf, P.C., and M.M. Alley. 1994. Residual soil nitrogen in humid region wheat production. J. Prod. Agric. 7:81–85.

Schleef, K.H., and W. Kleihanss. 1994. Mineral balance in agriculture in EU. Institute of farm economics, Federal Agricultural Research Centre, Brounchweig, Germany

Sembiring, H., W.R. Raun, G.V. Johnson, M.L. Stone, J.B. Solie, and S.B. Phillips. 1998. Detection of nitrogen and phosphorus nutrient status in winter wheat using spectral radiance. J. Plant Nutr. 21:1207–1233.

Smil, V. 2002. Nitrogen and food production: Proteins for human diets. Ambio 31:126–131.

Stone, M.L., J.B. Solie, W.R. Raun, R.W. Whitney, S.L. Taylor, and J.D. Ringer. 1996. Use of spectral radiance for correcting in-season fertilizer nitrogen deficiencies in winter wheat. Trans. ASAE 39:1623–1631.

Teal, R.K., B. Tubana, K. Girma, K.W. Freeman, D.B. Arnall, O. Walsh, and W.R. Raun. 2006. In-season prediction of corn grain yield potential using normalized difference vegetation index. Agron. J. 98:1488–1494.

Zhao, R.F., X.P. Chen, F.S. Zhang, H.L. Zhang, J. Schroder, and V. Röemheld. 2006. Fertilization and nitrogen balance in a Wheat-Maize Rotation System in North China. Agron. J. 98:938–945.

Zillmann, E., S. Graeff, J. Link, W.D. Batchelor, and W. Claupein. 2006. Assessment of cereal N requirements derived by optical on-the-go sensors on heterogeneous soils. Agron. J. 98:682–690.

Zhang, W.L., Z.X. Tian, N. Zhang, and X.Q. Li. 1996. Nitrate pollution of groundwater in northern China. Agron. Eco. Environ. 59:223–231.

Zhu, Z.L., and D.L. Chen. 2002. Nitrogen fertilizer use in China– contribution to food production, impacts on the environment and best management strategies. Nutr. Cycling Agroecosyst. 63:117–127.