Title

Evaluating red edge vegetation indices for estimating winter wheat N status under high canopy coverage condition

Authors

Li, Fei
Miao, Yuxin
Gnyp, Martin L.
et al.

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Introduction

Dynamic monitoring of plant N status using remote sensing under high canopy coverage conditions is critical for high yield crop management and environmental protection. Selection of bands plays an important role in deriving plant N information of crop canopy using remote sensing technology (Hansen and Schjoerring, 2003). The red light reflectance does not change much with chlorophyll pigment content when it is higher than 150 mg m^{-2} (Gitelson et al., 2003; Steele et al., 2008a) and red absorption in plant pigments saturates (Hatfield et al., 2008). N plays an important role in forming photosynthetic pigment-proteins complexes including chlorophyll a and b (Blackburn, 2007). Sufficiency and deficiency of N significantly affect plant chlorophyll content and crop growth. As a result, red band-based indices would rapidly saturate, even with low N content (Flowers et al., 2003), leaf area index (LAI) and biomass (Serrano et al., 2000; Thenkabail et al., 2000).

Red edge, as the inflection point of the strong red absorption to near infrared reflectance, includes the information of both crop N and growth status. The reflectance around red edge is sensitive to wide range of crop chlorophyll content, N content, LAI and biomass (Hatfield et al., 2008; Mutanga and Skidmore, 2007; Steele et al., 2008b). Recently, Cho and Skidmore (2006) developed a new technique for extracting red edge position. The method was validated by deriving leaf N concentration of different plants. Subsequently, they tested the method under different conditions (Cho et al., 2008). Also, some published results have indicated that normalized and simple ratio indices composed of red edge bands were able to extract N information of canopy and leaf across plants and environmental conditions (Sims and Gamon, 2002; Zarco-Tejada et al., 2001). However, most of the measurements were conducted in laboratories or under controlled conditions. Some results were validated by using radiative transfer model (Wu et al., 2008) at both leaf and canopy levels. However, limited studies were conducted to evaluate these indices for estimating plant N uptake and concentration of winter wheat under high canopy coverage directly under on-farm conditions. Therefore, the objective of this study was to identify the best performing red edge parameters under high canopy density in farmers' fields.

Materials and methods

The experiments were conducted in Shandong Province, the North China plain (NCP) and the climate is warm-temperate subhumid continental monsoon, with cold winters and hot summers. The precipitation from October to May was 131 and 108 mm for wheat growing seasons of 2005/06 and 2006/07, respectively. The annually average temperature in 2006 and 2007 was 13.7 and 14.1 °C, respectively.

Six 200 × 200 m fields in four villages were selected with cooperative farmers. Each field was managed by different farmers according to their common practices. Canopy spectral reflectance was measured using the ASD Hand-held Fieldspec optical sensor (Analytical Spectral Devices, Inc., Boulder, CO, USA) from Feekes growth stages 7 to 10.5. We selected the data set from Feekes growth stage 7 to 9, when the wheat canopy fully covered fields.

Following each spectral measurement, the corresponding 100 by 30 cm above-ground vegetation was destructively cut for biomass and N concentration measurement. In all, 83 plant samples involving 29, 24, 30 samples at three fields in 2006 and 115 plant samples involving 28, 41, 46 samples at three fields in 2007 were collected from Feekes growth stages 7 to 9, respectively. All plant samples were oven dried at 70 ^{o}C to constant weight and then weighed, ground, and their Kjeldahl-N determined.

In this study, we selected 6 red edge indices related to plant N or chlorophyll estimation (Table 1). Four indices (ZTM, ND705, R-M and TCARI/OSAVI(705, 750)) are based on benchmark of normalized and simple ratio. An important difference from traditionally indices is that the selected bands in these indices are all locate around red edge. Two indices (REIP and REP) were selected to calculate the position of red edge. The red edge position for REIP is based on linear four-point interpolation technique and it uses four wavebands (670, 700, 740 and 780 nm) (Guyot and Baret, 1988). The calculation of REP is based on linear extrapolate technique developed by Cho and Skidmore (2006). Before calculation, we used a wavelet filter to smooth the first derivative spectra. Then, sensitivity analysis was conducted to obtain optimum bands combination (Cho and Skidmore, 2006).

Table 1 Spectral vegetation indices tested in this study.

Index	Definition	Reference
Zarco-Tejada&Miller(ZTM)	R_{750}/R_{710}	Zarco-Tejada et al. (2001)
ND705	$(R_{750}-R_{705})/(R_{750}+R_{705})$	Sims and Gamon (2002)
R-M	$(R_{750}/R_{720})-1$	Gitelson et al. (2005)
TCARI/OSAVI(705, 750)	TCARI/OSAVI(705, 750)	Wu et al. (2008)
REIP	$700+40*\{[(R_{670}+R_{780})/2]-R_{700}\}/(R_{740}-R_{700})$	Guyot et al. (1988)
REP	-(c1-c2)/(m1-m2)	Cho and Skidmore (2006)

m1/c1 and m2/c2 represent the slope and intercept of straight line through two point on the far red (680-700 nm) and two point on near infrared (720-760 nm) of the first derivative reflectance spectrum.

Results and discussion

Different from other selected indices in this paper, the calculation of the red edge index REP requires sensitivity analysis to find optimal band combinations. Gathered all data from two years, we plotted the contour maps of coefficients of determination (R^2) between plant N uptake and concentration and red edge position calculated by linear extrapolate method (Fig. 1). The results indicated that the far red bands in 683-687 nm range combined with near infrared bands in 725-730 nm range yielded the highest correlation with plant N uptake across years and stages (Fig. 1, left). For plant N concentration, the best performing bands focused on far red in 713-716 and near infrared bands in 727-740 (Fig. 1, right). The highest R^2 correlated to plant N uptake and concentration was 0.357 ($p<0.01$) and 0.434 ($p<0.01$), respectively. This is acceptable under on-farm conditions. Based on the results, the most sensitive far-red and near-infrared band was 685 and 727 nm for plant N uptake, and 714 and 738 nm for plant N concentration.

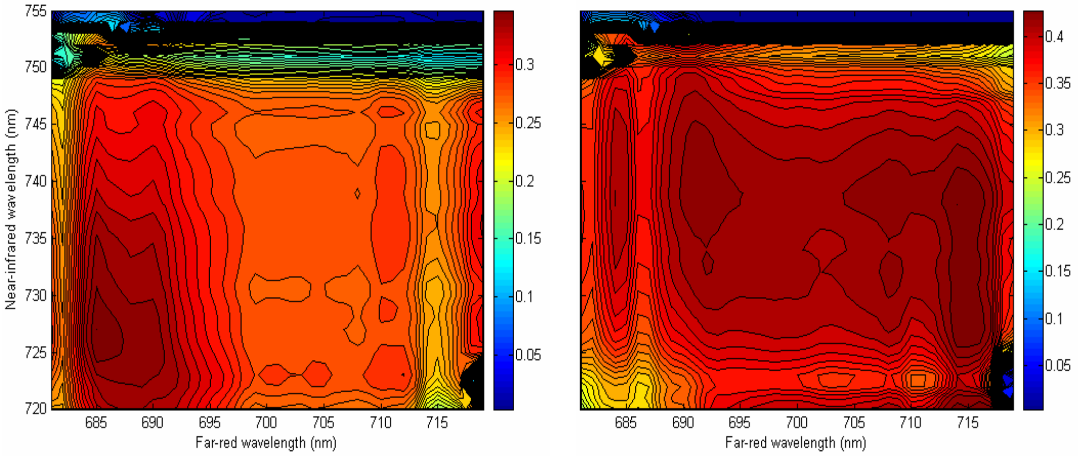

Fig. 1. Contour maps indicating the sensitivity of red edge positions calculated by linear extrapolate method using fixed bands from 680 to 760 nm. The maps showed the coefficients of determination (R^2) between red edge position and plant N uptake (left) and plant N concentration (right).

Plant N uptake and concentration are important indicators of winter wheat plant nitrogen status. Due to the difference of winter wheat varieties used, growing stages and management levels for different farmers, plant N concentration varied from 15.9 to 44.8 g kg^{-1}, and plant N uptake from 58 to 247 kg N ha^{-1} (Table 2).

Table 2 Descriptive statistics of the data used in this study.

year	n	Plant N concentration (g kg^{-1})			Plant N uptake (kg N ha^{-1})		
		range	median	CV, %	range	median	CV, %
2006	83	15.9-37.9	24.7	16.6	58-226	145	26.9
2007	115	24.0-44.8	32.4	13.0	91-247	174	23.6
All	198	15.9-44.8	29.3	19.1	58-247	159	26.6

In order to find promising red edge indices, the linear relationships between plant N uptake, plant N concentration and red edge indices used were established across developing stages and years. Table 3 shows the coefficients of determination (R^2) of these linear models. Results indicated that the R^2 between plant N uptake and red edge indices was higher than that between plant N concentration and red edge indices in 2006 and 2007. However, it was different for data combined across two years. This is probably due to variations of climate conditions in the two years, which affected the N concentration in plants. The high coefficient of variation (CV) in combined data against single year resulted in higher R^2 between red edge indices and plant N concentration for all data of two years. For red edge indices, the red edge position based REIP and REP indices performed better in estimating plant N uptake and concentration than normalized and simple ratio based indices. Especially for REP, the selection of optimum bands in estimating plant N status was obtained by using sensitivity analysis. The prediction potential will be improved with data collected under wider range of on-farm conditions.

Table 3 Coefficients of determination (R^2) for relationships between red edge indices and plant N uptake and concentration at high canopy coverage.

Indices	2006		2007		All combined	
	Plant N uptake	Plant N concentration	Plant N uptake	Plant N concentration	Plant N uptake	Plant N concentration
(ZTM)	0.195^{**}	0.130^{**}	0.418^{**}	0.010	0.329^{**}	0.381^{**}
ND705	0.179^{**}	0.141^{**}	0.390^{**}	0.010	0.285^{**}	0.385^{**}
R-M	0.173^{**}	0.160^{**}	0.441^{**}	0.005	0.331^{**}	0.394^{**}
TCARI/OSAVI(705, 750)	0.183^{**}	0.112^{**}	0.370^{**}	0.028	0.336^{**}	0.322^{**}
REIP	0.285^{**}	0.142^{**}	0.464^{**}	0.001	0.380^{**}	0.405^{**}
REP	0.411^{**}	0.233^{**}	0.272^{**}	0.009	0.357^{**}	0.440^{**}

TCARI/OSAVI(705, 750) = $3*[(R_{750}-R_{705})-0.2*(R_{750}-R_{550})(R_{750}/R_{705})]/[(1+0.16)(R_{750}-R_{705})/(R_{750}+R_{705}+0.16)]$

Conclusion

This study evaluated different red edge vegetation indices for estimating winter wheat nitrogen status under high canopy coverage conditions in farmers' fields at Huimin County, Shandong Province, China, across 2006 and 2007. Compared with plant N concentration, plant N uptake was easier to estimate across years and growing stage for winter wheat. REP was a promising red edge index for estimating plant N uptake and concentration. More studies are needed to further validate these indices at different growth stages and more diverse on-farm conditions.

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