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New spectral indicator assessing the efficiency of crop nitrogen treatment in corn and wheat

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ABSTRACT

To reduce environment pollution from cropping activities, a reliable indicator of crop N status is needed for site-specific N management in agricultural fields. Nitrogen Nutrition Index (NNI) can be a valuable candidate, but its measurement relies on tedious sampling and laboratory analysis. This study proposes a new spectral index to estimate plant nitrogen (N) concentration, which is a critical component of NNI calculation. Hyperspectral reflectance data, covering bands from 325 to 1075 nm, were collected using a ground-based spectroradiometer on corn and wheat crops at different growth stages from 2005 to 2008. Data from 2006 to 2008 was used for new index development and the comparison of the new index with some existing indices. Data from 2005 was used to validate the best index for predicting plant N concentration. Additionally, a hyperspectral image of corn field in 2005 was acquired using an airborne Compact Airborne Spectrographic Imager (CASI), and the corresponding plant N concentration was obtained by conventional laboratory methods on selected area. These data were also used for validation. A new N index, named Double-peak Canopy Nitrogen Index (DCNI), was developed and compared to the existing indices that were used for N detection. In this study, DCNI was the best spectral index for predicting plant N concentration, with R^2 values of 0.72 for corn, 0.44 for wheat, and 0.64 for both species combined, respectively. The validation using an independent ground-based spectral database of corn acquired in 2005, yielded an R^2 value of 0.62 and a root-mean-square-error (RMSE) of 2.7 mg N g^{-1} d.m. The validation using the CASI spectral information, DCNI calculation was related to actual corn N concentration with a R^2 value of 0.51 and a RMSE value of 3.1 mg N g^{-1} d.m. It is concluded that DCNI, in association with indices related to biomass, has a good potential for remote assessment of NNI.

1. Introduction

Optimizing fertilization strategy is critical to meet crops' temporal and spatial requirements of nitrogen (N) while protecting the environment and maintaining farm profitability. For a rainfed crop, N supply is likely the most important factor that can be managed to promote crop productivity (Tremblay, 2004). Since N supply and uptake depends on soil conditions, weather and plant characteristics, N fertilizer requirements change in space and time (Gupta et al., 1997; Mamo et al., 2003). To ensure productivity, crop growers usually supply more N in the fields (Schröder et al., 2000). N supplied in excess can cause many environmental problems, such as greenhouse gas (N_2O) emission (Sehy et al., 2003; Dambreville et al., 2008) and surface and ground water contamination (Jaynes et al., 2001; Zhao et al., 2007). Hence, residual soil mineral N after harvest (as an indicator of potential nitrate leaching during fall and winter) increases substantially at N rates higher than optimum (Sogbedji et al., 2000).

Many studies have suggested that N use efficiency can be enhanced by supplying minimal N to meet the limited requirements of the crop at its early developmental stages and saving most of N for a later application (topdressing) just before the period of rapid, exponential crop growth (Sowers et al., 1994; López-Bellido et al., 2005). At that latter point in time, the crop itself can be used as an indicator of its potential requirement for fertilizer N, provided that an adequate indicative parameter can be used. In many crops, the Nitrogen Nutrition Index (NNI) has been shown as an adequate N

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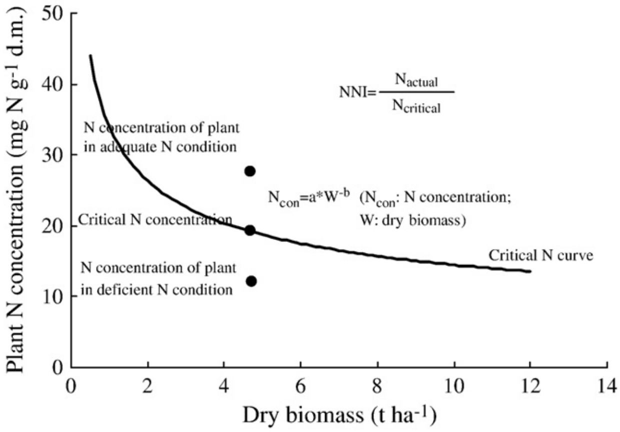

Fig. 1. Definition of NNI.

status indicator for this purpose (Justes et al., 1994; Plénet & Lemaire, 2000; Ziadi et al., 2008). NNI proceeds from a measurement of plant N concentration (expressed on dry matter basis) and a comparison with a critical N concentration at a given biomass level (Fig. 1). The critical N concentration is defined as the minimum N concentration necessary to achieve maximum growth. However, the determination of NNI by traditional method is very time-consuming, and cannot be done throughout the vegetative growth period in practical farm conditions (Lemaire et al., 2008). As an alternative, Lemaire et al. (2008) suggested remote sensing measurements as a surrogate way to determine this critical parameter, since such measurements are not invasive and can be repeated several times during the growth period. If plant N concentration and dry biomass (expressed on a land area basis) can be accurately estimated using remote sensing techniques, NNI can be calculated in a spatially detailed manner.

Remote sensing technology has been documented as a powerful tool for in-situ measurements of many crop parameters, such as leaf area index (LAI), leaf chlorophyll content, leaf water content and canopy cover, especially through spectral indices (Moran et al., 1994; Rondeaux et al., 1996; Haboudane et al., 2004; Thomas et al., 2008). The reflectance and transmittance spectra of dried ground leaves were found to be related to leaves' N concentration (Curran, 1989; Fourty et al., 1996), with N absorption features at 1510 nm, 1730 nm, 1940 nm, 1980 nm, 2060 nm, 2180 nm, 2240 nm, 2300 nm, and 2350 nm. However, field management cannot be conducted based on those findings, because remote sensors usually collect data over green vegetation rather than dry vegetation. In green vegetation, N absorption features are obscured by strong water absorption bands centered at 1450 nm and 1940 nm (Kokaly & Clark, 1999).

Considering the linkage between N and chlorophyll in green leaves (Boochs et al., 1990; Madakadze & Madakadze, 1999), the spectral features of chlorophyll in visible and red-edge bands have been used as indicators of crop N (Lamb et al., 2002; Reyniers & Vrindts, 2006). Many N indicators were proposed by researchers using these features (Reyniers et al., 2006; Zhu et al., 2008). However, most of them contributed to N content (expressed on a surface area basis) estimation, only a few have focused on designing spectral indices to predict N concentration in fresh plant materials. Hansen and Schjoerring (2003) randomly combined two bands of spectral in the formula of NDVI, and selected the one had high relationship with leaf N concentration as N concentration index. Cho and Skidmore (2006) provided a new technique for extracting the red edge position (REP) and used REP as detector of N concentration. However, REP is influenced both by chlorophyll and LAI (Lamb et al., 2002). The influence of LAI prevents the use of REP as a N concentration estimator. Eitel et al. (2007) found a good relationship between flag leaf nitrogen concentration and a combined index (MCARI/MTVI2, the ratio of modified chlorophyll absorption ratio index to the second modified triangular vegetation index).

This study focuses on the development of a spectral index to assess plant N concentration, which is one important component for NNI determination. The objectives of this study were: i) to develop a new N concentration index by studying the relationship between reflectance in visible and near infrared bands and plant N concentrations; ii) to compare selected existing spectral indices to the one developed in this study using ground-measured spectra and corresponding plant N concentration measured in the laboratory; and iii) to validate the best spectral index for plant N concentration estimation using an independent database.

2. Materials and methods

2.1. Study sites and experimental design

The experiments were conducted over four years at three locations in the province of Quebec, Canada: the commercial operations of Ferme Landry and Associés located in St-Valentin (73°21′02.84″W, 45º05′21.20″N), the L'Acadie Experimental Farm (73°20′47.70″W, 45°17′43.30″N) of Agriculture and Agri-Food Canada's St-Jean-sur-Richelieu Research Station, and the commercial operation of Ferme Konkordia in St-Blaise-sur-Richelieu (73°18′45.60″W, 45°10′28.04″N). Fertilization treatments and sampling times were organized over several years with the objective of generating a variety of plant N concentrations. Table 1 shows the soil conditions at each site before sowing in different years.

In years of 2005, 2006 and 2007, fields were assigned to four treatments in a randomized block design with four replications in St-Blaise-sur-Richelieu and St-Valentin. Fertilization treatments consisted of 30 kg N ha^{-1} at sowing and different amounts of N at topdressing (Table 2). In St-Blaise-sur-Richelieu experimental field, the spring wheat (*Triticum aestivum* L), cultivar “AC Barrie”, was sown on May 11th 2005 at a density of 3,600,000 plants ha^{-1}. The plot size was 300 m × 15 m. Topdressing was done at Zadoks growth stage 43 (Zadoks et al., 1974) with N ranging from 0 kg N ha^{-1} to 90 kg N ha^{-1} for the different treatments (Table 2). In addition, 3-m-wide N-saturated strips, supplied with 120 kg N ha^{-1} at the beginning of the season, were placed between the treatments. In St-Valentin, the corn (*Zea mays*) cultivar “Dekalb DKC 4627BT” was used for the three years (2005, 2006 and 2007). The corn was sown on May 12th 2005, May 9th 2006, and May 3th 2007 respectively at a density of 79,000 plants ha^{-1}. Plot size was 180 m × 22.5 m in 2005 and 260 m × 6.75 m in 2006 and 2007. Topdressing was done at V5 (Ritchie et al., 1993) (2005), V6 (2006), and V5–V6 (2007) with a fertilizer N supply ranging from 0 kg N ha^{-1} to 158 kg N ha^{-1} in 2005 and 2006 (Table 2), and from 0 kg N ha^{-1} to 135 kg N ha^{-1} in 2007 (Table 2). In addition, 4.5-m-wide zero-N strips with 0 kg N ha^{-1} at sowing and N-saturated strips with 250 kg N ha^{-1} at sowing were also placed lengthwise (not randomly) in the fields. At the L'Acadie Experimental Farm in 2008, six treatments were established in a randomized block design with four replications. The corn, cultivar “Pioneer 38A24 (non

Table 1
Soil status of each site before sowing in different years.

Site	St-Valentin			L'Acadie	St-Blaise-sur-Richelieu
Year	2005	2006	2007	2008	2005
Previous crop	Corn	Corn	Corn	Corn	Corn
Soil texture (0–30 cm)	Fine sandy to clay loam			Clay loam	Fine sandy loam and a loam
Soil pH ($CaCl_2$)	6.2	6.1	6.6	7.3	5.9
Organic matter (%)	3.2	3.3	3.9	3.7	4.4
NO_3–N (mg kg^{-1}) (0–30 cm)	6	12	2	2	7
Available P (mg kg^{-1}) (Mehlich III)	22	65	27	71	39
Available K (mg kg^{-1}) (Mehlich III)	115	97	117	121	62

Table 2
Treatments design of each site in different years.

Site	Year	N treatment
St-Valentin	2005	N1: 30 kg ha^{-1} at sowing + 0 kg ha^{-1} at topdressing, N2: 30 kg ha^{-1} at sowing + 53 kg ha^{-1} at topdressing, N3: 30 kg ha^{-1} at sowing + 105 kg ha^{-1} at topdressing, N4: 30 kg ha^{-1} at sowing + 158 kg ha^{-1} at topdressing, and two saturated strips with 250 kg ha^{-1} at sowing and one zero-N strip.
	2006	Same as 2005
	2007	N1: 30 kg ha^{-1} at sowing + 0 kg ha^{-1} at topdressing, N2: 30 kg ha^{-1} at sowing + 45 kg ha^{-1} at topdressing, N3: 30 kg ha^{-1} at sowing + 90 kg ha^{-1} at topdressing, N4: 30 kg ha^{-1} at sowing + 135 kg ha^{-1} at topdressing, and one saturated strip with 250 kg ha^{-1} at sowing and one zero-N strip.
L'Acadie	2008	N1: 0 kg ha^{-1} at sowing + 0 kg ha^{-1} at topdressing, N2: 225 kg ha^{-1} at sowing + 0 kg ha^{-1} at topdressing, N3: 0 kg ha^{-1} at sowing + 180 kg ha^{-1} at topdressing, N4: 45 kg ha^{-1} at sowing + 68 kg ha^{-1} at topdressing, N5: 113 kg ha^{-1} at sowing + 0 kg ha^{-1} at topdressing, N6: 20 kg ha^{-1} at sowing + 93 kg ha^{-1} at topdressing.
St-Blaise-sur-Richelieu	2005	N1: 30 kg ha^{-1} at sowing + 0 kg ha^{-1} at topdressing, N2: 30 kg ha^{-1} at sowing + 30 kg ha^{-1} at topdressing, N3: 30 kg ha^{-1} at sowing + 60 kg ha^{-1} at topdressing, N4: 30 kg ha^{-1} at sowing + 90 kg ha^{-1} at topdressing, and two saturated strips with 120 kg ha^{-1} at sowing.

Bt) 2900 UTM", was planted on May 12th 2008 at a density of 79,000 plants ha^{-1}. The plot size was 16 m × 3 m. Topdressing was done at the V6–V7 growth stage. Nitrogen was applied in the range of 0 kg N ha^{-1} to 225 kg N ha^{-1} at sowing and 0 kg N ha^{-1} to 180 kg N ha^{-1} at topdressing for the different treatments (Table 2).

2.2. Data acquisition

During the growing season, ground sampling campaigns were conducted to monitor crop biophysical and biochemical parameters and corresponding canopy spectra. Sampling locations were determined using a stratified systematic unaligned sampling scheme and geo-locations were achieved with a differential global positioning system (DGPS) device (Pathfinder Pro XRB, Trimble, Sunnyvale, CAL). In 2005, 2006 and 2007, ground spectral measurements and field sampling at each point were performed 15 to 19 days after topdressing (depending on the weather conditions) at growth stages between V8 and VT (Table 3). In 2008, two field campaigns corresponding to the V5–V6 and V6–V7 corn growth stages were conducted before topdressing. In addition, a hyperspectral image was acquired on July 11th, 2005 over the St-Valentin experimental site at growth stage V9 of corn just before the field campaign, using a Compact Airborne Spectrographic Imager (CASI) hyperspectral sensor flown by the Earth Observations Laboratory of York University, Toronto, Canada.

2.2.1. Remote sensing data

Canopy spectra of corn and wheat were acquired at geo-referenced points with an Analytical Spectral Devices (ASD) spectroradiometer (Analytical Spectral Devices, Boulder, CO), which recorded reflectance between 325 nm and 1075 nm with a sampling interval of 1.6 nm and a resolution of 3.5 nm. Measurements were taken during cloud-free periods, between 10 a.m. and 2 p.m. in order to minimize the change in the illumination conditions. A white Spectralon reference panel (Labsphere, North Sutton, NH) was used under the same illumination conditions to convert the spectral radiance measurements to reflectance. Ten scans were measured at each point, and averaged to produce final canopy spectra.

The hyperspectral CASI image had 2-m spatial resolution and 72 channels covering the visible and near-infrared portions of the solar spectrum from 408 nm to 947 nm. First, the collected CASI was processed to at-sensor radiance using calibration coefficients determined in laboratory by the Earth Observations Laboratory, York University. The CAM5S atmospheric correction model (O'Neill et al., 1997) was then used to transform the at-sensor radiance to absolute ground reflectance. A flat field calibration (Goetz & Srivastava, 1985) was used to remove the residual atmospheric effects from hyperspectral reflectance image cubes. After radiometric correction, the image was geo-corrected using a two-step process. The images were first geo-corrected using ITRES automated geo-correction software (ITRES Research Limited, Calgary, Alberta, Canada), and later geo-referenced again with the orthoengine procedure of PCI software (PCI, Toronto, Ontario, Canada) using ground measured locations of the GPS targets seen in the image.

Table 3
Mean values of plant N concentration (mg N g^{-1} d.m.), SPAD, and LAI of corn and wheat at different corn growth stages and N fertilizer levels and years.

Crop type	Year	Growth stage	Treatment	$N_{con}^{\#}$	SPAD	LAI
Corn	2005	V9#	A1	19.6a	36.2a	1.66a
			A2	22.2b	42.5b	1.81a
			A3	23.9c	43.2b	2.07a
			A4	24.6c	44.1b	2.06a
	2006	V10#	B1	13.0a	33.5a	1.68a
			B2	16.4b	37.1ab	1.57a
			B3	18.5c	40.3b	1.73a
			B4	18.7c	40.4b	1.70a
	2007	V8#	C1	19.7a	48.7a	1.74a
			C2	22.3b	49.5a	1.57a
			C3	23.2b	52.5b	1.69a
			C4	23.5b	51.7b	1.66a
	2008	V5–V6&	D1	18.4a	33.8a	0.39a
			D2	19.1a	38.3ab	0.54a
			D3	24.1b	43.3b	0.55ab
			D4	25.9c	49.8c	0.78b
			D5	28.6c	54.6c	0.97b
		V6–V7&	D1	14.5a	33.3a	0.49a
			D2	12.6a	34.1a	0.80ab
			D3	14.1a	42.4b	1.14b
			D4	24.9b	53.8c	1.33b
			D5	26.6c	56.5c	1.52b
Wheat	2005	Zadoks 47#	E1	13.3a	40.6a	3.18a
			E2	13.6a	39.6a	2.98a
			E3	16.5b	42.0ab	3.40a
			E4	18.0b	43.7b	3.58a

# Denotes measurements taken after topdressing; & denotes measurements taken before topdressing.
Different letters following the values denotes significant differences at 0.05; A1 denotes 30 + 0 treatment [numbers prior to the + symbol means amount of N (kg N ha^{-1}) applied at sowing, and numbers after the + symbol denotes the amount of N applied at topdressing.] The same convention holds for the following treatments: A2 = 30 + 53; A3 = 30 + 105; A4 = 30 + 158; B1 = 30 + 0; B2 = 30 + 53; B3 = 30 + 105; B4 = 30 + 158; C1 = 30 + 0; C2 = 30 + 45; C3 = 30 + 90; C4 = 30 + 135; D1 = 0 + 0; D2 = 20 + 93; D3 = 45 + 68; D4 = 113 + 0; D5 = 225 + 0; E1 = 30 + 0; E2 = 30 + 30; E3 = 30 + 60; E4 = 30 + 90.

2.2.2. Crop biophysical and biochemical variables

Crop biophysical and biochemical variables were measured at the corresponding spectral sampling points: 1) leaf area index (LAI) using a Plant Canopy Analyzer (LAI-2000, LI-COR, Lincoln, NE); 2) plant N concentration using procedures described below; 3) chlorophyll using a handheld chlorophyll meter (SPAD-502, Minola Osaka Company, Ltd., Japan).

For the measurements of plant N concentration, an area of 1.5 m^2 for corn and of 0.2 m^2 for wheat were sampled above ground level using pruning scissors, and the samples were then mechanically shredded. A subsample of approximately 500 g was dried at 70 °C in a forced-draft oven for 7 d, ground to pass though a 1 mm sieve in a Wiley mill, and stored at room temperature before analysis. The material was digested according to the method developed by Isaac and Johnson (1976) and the N concentration was measured on a

QuickChem 8000 Lachat autoanalyzer (Zellweger Analytics, Milwauk, WI) using the Lachat method 15-501-3 (Lachat Instruments, 2005). The samples collected in 2005, 2006 and 2007 were analyzed by the Soils and Crops Research and Development Center, Agriculture and Agri-Food Canada, while those collected in 2008 were analyzed with a TRAACS 800 colorimeter (Bran+ Lubbe, Hamburger, German) by the Horticulture Research and Development Center, Agriculture and Agri-Food Canada.

2.3. Spectral indices

Spectral indices considered to be good candidates for estimating plant N concentration were tested. Included were indices specifically aimed at N estimation [N content and N concentration] as well as some indices aimed at chlorophyll estimation [chlorophyll content and chlorophyll concentration] (Table 4). In addition, a new N concentration index, the Double-peak Canopy Nitrogen Index (DCNI), was developed in this study, as explained below.

Reflectance in red-edge region has always been considered important in relationships with biochemical or biophysical parameters (Cho & Skidmore, 2006). Two or more peaks have been reported in derivative reflectance spectra of the red edge (Zarco-Tejada et al., 2002; Clevers et al., 2004; Lemaire et al., 2004; Smith et al., 2004). In this study, the first derivative spectra were extracted from field measured ASD data using first-difference transformation with a 1-nm step, and then smoothed using Savitzky–Golay method (Savitzky & Golay, 1964) with a second-order polynomial and a nine-band window. As shown in Fig. 2, two main peaks were observed in the corn and wheat database, confirming the findings in the literature: first peak was located around 700 nm and the second was located between 715 and 731 nm. It can be observed that the height of the first peak increased relatively to the second peak as the plant N concentration decreased. To measure N concentration, we proposed to track the relative change of these two peaks. In derivative spectra, the ratio of average value of all points within 670 nm to 700 nm bands to the averaged value of all points within 700 nm to 720 nm bands varies with the changes in two peaks' relative heights. The difference between two points in the original reflectance spectra divided by their distance is equal to the averaged value of all the points between these two points in the corresponding derivative spectra. Therefore, the formula $(R_{720}-R_{700})/(R_{700}-R_{670})$ can be used to characterize the change in these two peaks in derivative spectra. $R_{720}-R_{670}$ was incorporated to the denominator of $(R_{720}-R_{700})/(R_{700}-R_{670})$ to minimize LAI influence and increase its sensitivity to changes in plant N concentration (Fig. 3). To compensate for the influence of background, a constant (n) was introduced along with $R_{720}-R_{670}$ using the concept suggested by Huete (1988). The formula for plant N concentration detection becomes $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+n)$ (where n is a constant). A Matlab 7.0 program was made to select the best n value. It calculated the value of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+n)$ by setting n from -1 to 1 with 0.01 steps, and the correlation between $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+n)$ and corn plant N concentration was investigated using corn data in the years of 2006, 2007 and 2008. As a result, 0.03 was considered as the best value for n. To examine the effects of inserting 0.03 on the performance of the index, two aspects were considered. Firstly, to assess the effects of different soil types on the index variability, 25 spectra from soil spectral library of ENVI 4.5 software were collected. They covered a wide variety of soil types with a very large range of soil reflectance (Table 5). The PROSPECT-SAILH model (Jacquemoud & Baret, 1990; Verhoef, 1984) was used to simulate spectral responses under different soil spectra and Chlorophyll concentration (30, 40, 50,

Table 4
Summary of spectral indices studied in this paper.

Index	Name	Formula	Developed by
Nitrogen indices			
VI_{opt}	Optimal vegetation index	$(1+0.45)((R_{800})^2+1)/(R_{670}+0.45)$	Reyniers et al. (2006b)
$NDVI_{g-b}$[#]	Normalized difference vegetation index green–blue[#]	$(R_{573}-R_{440})/(R_{573}+R_{440})$	Hansen and Schjoerring (2003)
RVI I[#]	Ratio vegetation index I[#]	R_{810}/R_{660}	Zhu et al. (2008)
RVI II[#]	Ratio vegetation index II[#]	R_{810}/R_{560}	Xue et al. (2004)
NRI	Nitrogen reflectance index	$(R_{800}/R_{550})_{target}/(R_{800}/R_{550})_{reference}$	Bausch and Duke (1996)
MCARI/MTVI2	Combined index	MCARI/MTVI2 MCARI: $(R_{700}-R_{670}-0.2(R_{700}-R_{550}))(R_{700}/R_{670})$ MTVI2:$1.5(1.2(R_{800}-R_{550})-2.5(R_{670}-R_{550}))/\text{sqrt}((2R_{800}+1)^2-(6R_{800}-5\text{sqrt}(R_{670}))-0.5)$	Eitel et al. (2007)
REP-LE[#]	Red edge position: linear extrapolation method[#]	Based on linear extrapolation of two straight lines through two points on the far-red and two points on the NIR flanks of the first derivative reflectance spectrum of the red edge region. REP is defined by the wavelength value at the intersection of the straight lines	Cho and Skidmore (2006)
DCNI[#]	Double-peak canopy nitrogen index[#]	$(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$	This study
Chlorophyll indices			
MCARI	Modified chlorophyll absorption ratio index	$(R_{700}-R_{670}-0.2(R_{700}-R_{550}))(R_{700}/R_{670})$	Daughtry et al. (2000)
TCARI	Transformed chlorophyll absorption in reflectance index	$3((R_{700}-R_{670})-0.2(R_{700}-R_{550})(R_{700}/R_{670}))$	Haboudane et al. (2002)
TCARI/OSAVI	Combined Index II[#]	TCARI/OSAVI TCARI: $3((R_{700}-R_{670})-0.2(R_{700}-R_{550})(R_{700}/R_{670}))$ OSAVI: $1.16(R_{800}-R_{670})\ /\ (R_{800}+R_{670}+0.16)$	Haboudane et al. (2002)
MTCI	MERIS terrestrial chlorophyll index	$(R_{750}-R_{710})/(R_{710}-R_{680})$	Dash and Curran (2004)
R–M[#]	Red model[#]	$R_{750}/R_{720}-1$	Gitelson et al. (2005)
CCI	Canopy chlorophyll index	D_{720}/D_{700}	Sims et al. (2006)
REP-LI[#]	Red edge position: linear interpolation method[#]	$700+40(R_{re}-R_{700})/(R_{740}-R_{700})$ R_{re}: $(R_{670}+R_{780})/2$	Guyot et al. (1988)
Other indices			
NDVI	Normalized difference vegetation index	$(R_{800}-R_{670})/(R_{800}+R_{670})$	Rouse et al. (1974)
RVI	Ratio vegetation index	R_{800}/R_{670}	Pearson and Miller (1972)

[#] Denotes named by this study; D_i denotes derivative reflectance at band i (nanometer); R_i denotes reflectance at band i (nanometer).

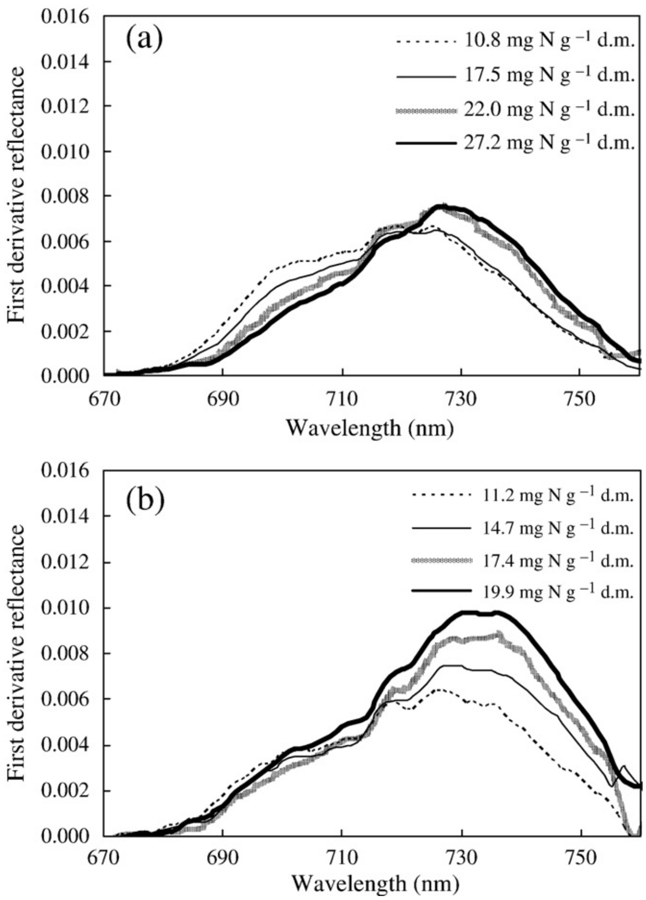

Fig. 2. Red edge first derivative curves for corn and wheat (Savitzky–Golay smoothing method was used to smooth the derivative curves). (a) Corn with four levels of plant N concentration: 10.8, 17.5, 22.0, and 27.2 mg N g^{-1} d.m. (b) Wheat with four levels of plant N concentration: 11.2, 14.7, 17.4, and 19.9 mg N g^{-1} d.m.

and 60 μg cm^{-2}) levels, while LAI value was set to 1.5. The values of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$ and $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$ were calculated from the simulated spectra. Table 6 shows the results of the influence of different soil types on the index variability. Under the same chlorophyll level, the values of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$ appeared to be more scattering than the values of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$ along with variety of soil spectra and the difference was significant. Secondly, under the condition of non-full cover, the measured reflectance above vegetation canopy is always comprised by the soil reflectance and vegetation reflectance. The change of LAI determines the effect of soil optical properties on measured vegetation reflectance. Thus, to assess the effect of different LAI on the index variability, The PROSPECT-SAILH model was used to simulate the spectral response under different levels of LAI (0.2, 0.5, 1, 2, 3, 4, 5, and 6) and chlorophyll concentration (30, 40, 50, and 60 μg cm^{-2}), along with the reflectance spectra of a yellow loam soil as constant background. The values of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$ and $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$ were calculated from the simulated spectra. The results of the effect of different LAI on the index variability were given in Table 7. Under the same chlorophyll level, the values of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$ seemed to be more scattering than the values of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$ along with variety of LAI. The difference was also significant Therefore, the formula of Double-peak Canopy Nitrogen Index (DCNI) became $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$.

2.4. Data analysis

First, as chlorophyll and LAI dominate spectral features in the visible and near infrared bands, the relationship among SPAD values (indicator of chlorophyll level), LAI and plant nitrogen concentrations was investigated to determine the principal spectral features of variables that facilitated N concentration prediction. Second, wheat data from 2005 and corn data from 2006, 2007 and 2008 were used to estimate the relationships between spectral indices and plant N concentration. The correlations between indices and LAI were also examined to show the influence of LAI on estimation of plant N concentration. During this process, the correlation analysis was first performed. When a significant correlation ($p<0.01$) was present between indices and plant N concentration or LAI, linear, exponential, power, and logarithmic models were tested for regression analysis. The R^2 values and corresponding $RMSE_{cal}$ values of the best model were reported in Table 9. $RMSE_{cal}$ were calculated from predicted and actual values of samples using Eq. (1). Among the indices, those with the highest R^2 and the lowest $RMSE_{cal}$ were considered as the best. Finally, the best indices were validated using 2005 ASD spectroradiometer data and CASI imagery with corresponding plant N concentration. The R^2 and $RMSE_{val}$ values were used to assess performances. $RMSE_{val}$ values were calculated from predicted and actual values of samples in the independent database, using Eq. (1). ENVI 4.5 software (ITT Visual Information Solutions, Boulder, Colorado, USA) was used to process the image.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (x'_i - x_i)^2}{n}} \quad (1)$$

(x' is the predicted value of sample i; x is the actual value of sample i; n is the total sample number).

3. Results and analysis

3.1. Relationships between SPAD, LAI and plant N concentration

As water absorptions obscure N absorption features in the shortwave bands, it is hard to detect plant N concentration from N absorption features in this part of the electromagnetic spectrum. It is pertinent to use reflectance in the visible and red-edge bands for N concentration estimation based on the good relationship between chlorophyll concentration and plant N concentration. As the visible and near infrared reflectance are dominated by LAI and chlorophyll absorption features, the relationship among SPAD, LAI and plant N concentration was assessed, using our corn and wheat database. Significant correlations were found between SPAD and plant N concentration for corn, wheat and the combined database (Table 8 and Fig. 4). Cartelat et al. (2005) also found a significant correlation ($r=0.97$) between chlorophyll concentration and N concentration in wheat. In this study, LAI had a weak relationship with plant N concentration for corn or combined database, while the relationship was significant for wheat (Table 8). As the crop grows, from planting to biophysical maturity, crop N and chlorophyll concentration decrease as its biomass and LAI increase (Plénet & Lemaire, 2000) (Table 3, year 2008). Within a given growth stage, plant N concentration and LAI change consistently, along with the variation of available N in field (Table 3). It follows that, on one hand, plant N concentration presents a significant relationship with both LAI and chlorophyll in the wheat, of which the database had a single growth stage. On the other hand, plant N concentration presented a significant relationship only with chlorophyll when different growth stages were existed in the dataset (corn or combined databases). Therefore, it can be concluded that: 1) the spectral feature of chlorophyll can be used for N concentration prediction; 2) the

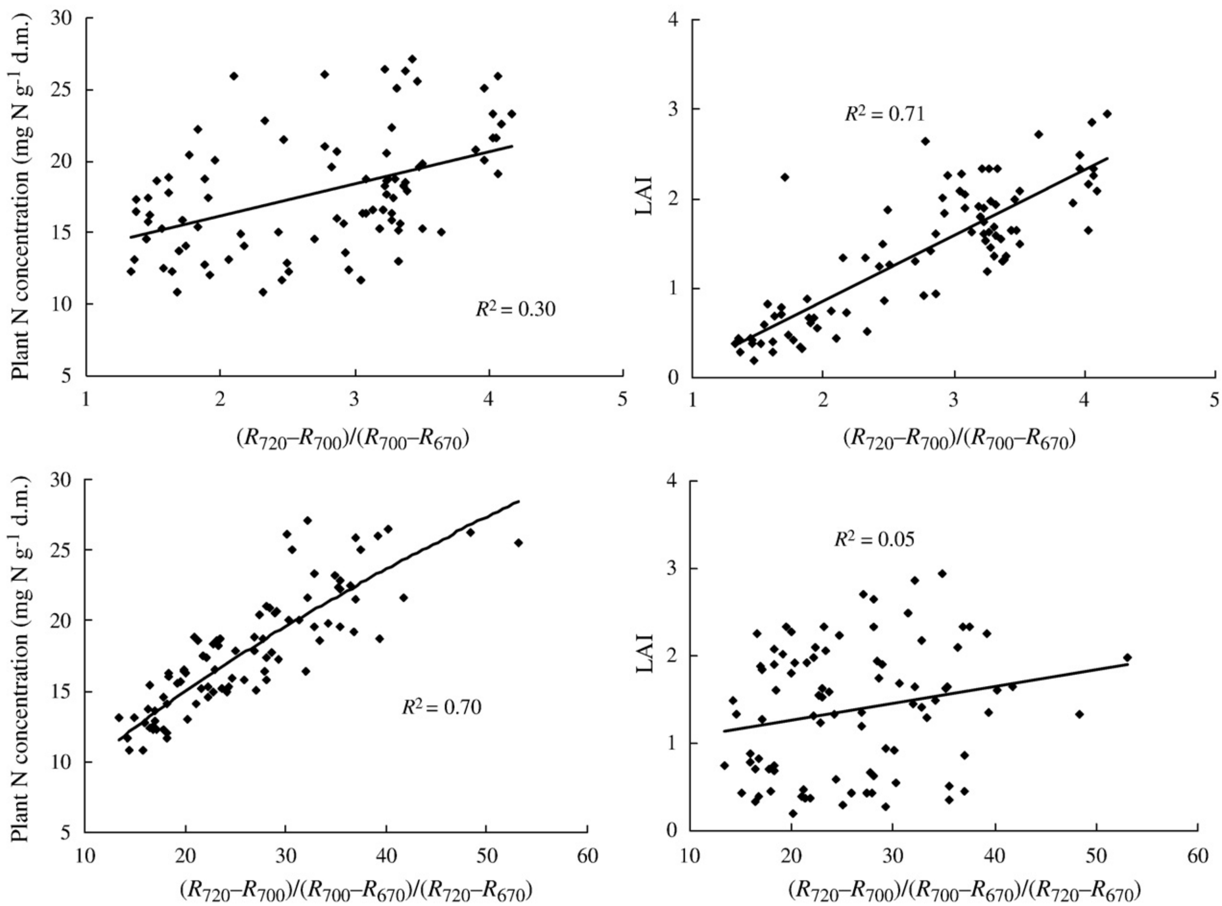

Fig. 3. The effects of insert $R_{720}-R_{670}$ to the denominator of $(R_{720}-R_{700})/(R_{700}-R_{670})$ on its ability to predict corn plant N concentration.

Table 5
Description of the 25 soil samples collected from soil spectral library of ENVI 4.5 software. Their reflectance in Red (670 nm) and Near-Infrared (800 nm) wavelengths were expressed.

Soil sample number	Soil type	Reflectance	
		670 nm	800 nm
1	Very dark grayish brown soil	0.24	0.34
2	Grayish brown loam soil	0.19	0.28
3	Dark grayish brown silty loam soil	0.11	0.17
4	Pale brown silty loam soil	0.29	0.36
5	Dark brown fine sandy loam soil	0.14	0.21
6	Gray silty clay soil	0.13	0.19
7	Reddish brown fine sandy loam soil	0.28	0.34
8	Reddish brown fine sandy loam soil	0.24	0.32
9	Brown sandy loam soil	0.16	0.25
10	Brown to dark brown gravelly loam soil	0.12	0.18
11	Brown to dark brown gravelly fine sandy loam soil	0.16	0.21
12	Brown silty loam soil	0.27	0.33
13	Brown loamy fine sand soil	0.22	0.30
14	Brown fine sandy loam soil	0.29	0.35
15	Brown fine sandy loam soil	0.24	0.31
16	Gray/dark brown extremely stoney coarse sandy soil	0.11	0.18
17	Dark reddish brown organic-rich silty loam soil	0.16	0.28
18	Very dark grayish brown loam soil	0.12	0.18
19	Dark reddish brown fine sandy loam soil	0.28	0.36
20	Brown to dark brown sand soil	0.22	0.27
21	Brown to dark brown loamy sand soil	0.25	0.32
22	Very dark grayish brown loam soil	0.17	0.27
23	Brown to dark brown sandy loam soil	0.25	0.32
24	Dark yellowish brown micaceous loam soil	0.30	0.37
25	Brown sandy loam soil	0.17	0.23

spectral feature of LAI is a confounding factor for the remote estimation of plant N concentration at different growth stages of a crop.

3.2. Regression analysis results between spectral indices and corn plant N concentration

To be a good estimator of plant N concentration, a spectral index should be well correlated with N concentration and must show low

Table 6
Results of the effects of different soil types on indices variability. The PROSPECT-SAILH model was used to simulate spectra under different soil spectra and chlorophyll concentration (30, 40, 50, 60 μg cm^{-2}) levels. Then, the value of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$ and $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$ were calculated from simulated spectral data and used to make the table below. The PROSPECT-SAILH model parameters were the following: $C_W=0.0015$ cm, $C_m=0.0035$ g cm^{-2}, $N=1.41$, LADF = spherical, sun zenith angle = 21.5°, sensor viewing angle = 0°, fraction of incoming radiation = 1 and LAI = 1.5.

Chlorophyll level (μg cm^{-2})	$(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$			$(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$			Paired-samples *T* test of CV
	Mean	Std	CV	Mean	Std	CV	
30	11.29	1.04	9.21%	9.54	0.74	7.76%	**
40	15.13	1.40	9.25%	12.59	0.98	7.78%	**
50	19.50	1.92	9.84%	15.99	1.31	8.19%	**
60	24.59	2.58	10.49%	19.82	1.74	8.78%	**

** Denotes significant at 0.01 level; Std means standard deviation; CV means coefficient of variation.

Table 7
Results of the effects of different LAI on indices variability. The PROSPECT-SAILH model was used to simulate spectra under different LAI (0.2, 0.5, 1, 2, 3, 4, 5, 6) and chlorophyll concentration (30, 40, 50, 60 μg cm^{-2}) levels. Then, the value of $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$ and $(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$ were calculated from simulated spectral data and used to make the table below. The PROSPECT-SAILH model parameters were the following: $C_W=0.0015$ cm, $C_m=0.0035$ g cm^{-2}, $N=1.41$, LADF = spherical, sun zenith angle = 21.5°, sensor viewing angle = 0°, fraction of incoming radiation = 1 and a yellow loam soil spectra.

Chlorophyll level (μg cm^{-2})	$(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670})$			$(R_{720}-R_{700})/(R_{700}-R_{670})/(R_{720}-R_{670}+0.03)$			Paired-samples T test of CV
	Mean	Std	CV	Mean	Std	CV	
30	14.44	4.87	0.34	11.24	1.73	0.15	**
40	19.00	5.10	0.27	14.66	1.44	0.10	**
50	24.34	5.04	0.21	18.57	0.96	0.05	**
60	30.60	4.56	0.15	23.06	0.79	0.03	**

** Denotes significant at 0.01 level; Std means standard deviation; CV means coefficient of variation.

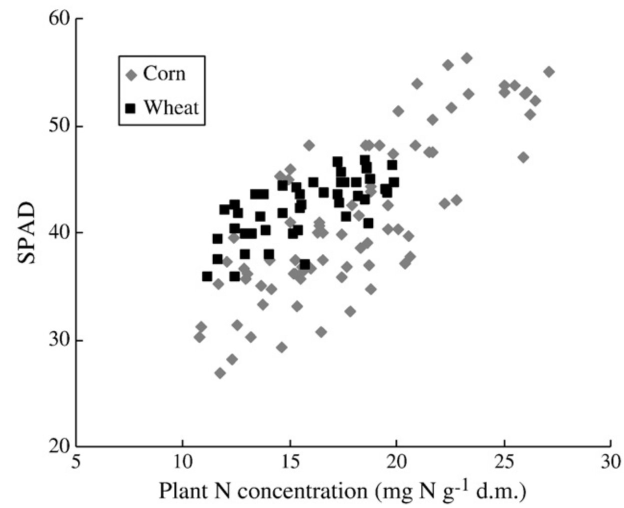

Fig. 4. Correlative relationships between plant nitrogen concentration (mg N g^{-1} d.m.) and SPAD obtained from corn data of years 2006 to 2008 and wheat data of year 2005.

sensitivity to other confounding factors (Daughtry et al., 2000). In this study, the best relationships with corn N concentration were achieved by the DCNI, and the ratio of the Transformed Chlorophyll Absorption in Reflectance Index to Optimization of Soil-adjusted Vegetation Index (TCARI/OSAVI). The regression equations of DCNI and TCARI/OSAVI had R^2 values of 0.72 and 0.66 and corresponding $RMSE_{cal}$ values of 2.3 and 2.4 mg N g^{-1} d.m., respectively (Table 9). LAI showed limited influence ($0.18 \leq R^2 \leq 0.29$). Nitrogen Reflectance Index (NRI), the ratio of Modified Chlorophyll Absorption Ratio Index to the second Modified Triangular Vegetation Index (MCARI/MTVI2), Transformed Chlorophyll Absorption in Reflectance Index (TCARI), and Canopy Chlorophyll Index (CCI) all exhibited a moderate relationship with corn plant N concentration. The regression equations have R^2 value between 0.31 and 0.56 and corresponding $RMSE_{cal}$ between 2.8 and 3.4 mg N g^{-1} d.m. LAI also had a moderate influence (R^2 between 0.30 and 0.49). The other indices showed low or no correlation with corn plant N concentration and most of them showed high sensitivity to LAI.

For clarity purpose, only relationships between the best spectral indices and plant N concentration are shown in Fig. 5. The best regression model for DCNI was obtained with a power function. It presented positive relationship with corn plant N concentration and did not saturate over the range from 10 mg N g^{-1} d.m. to 28 mg N g^{-1} d.m. TCARI/OSAVI and MCARI/MTVI2 were negatively related to N concentration, and the best regression models were from the exponential function. The slope of the regression line for DCNI was indicative of high sensitivity to changes of N concentration. In the range from 10 to 20 mg N g^{-1} d.m., both TCARI/OSAVI and MCARI/MTVI2 well relate to N concentration with sharp slopes. However, above 20 mg N g^{-1} d.m., they showed saturation which makes them barely suitable for the detection of high N concentration.

Table 8
Correlative relationships between plant nitrogen concentration and LAI and SPAD (*r* was expressed) using corn data of years 2006, 2007, and 2008 and wheat data of year 2005.

	Corn[$] ($n=88$)			Wheat[#] ($n=46$)			Corn and wheat[&] ($n=134$)		
	N_{con}	SPAD	LAI	N_{con}	SPAD	LAI	N_{con}	SPAD	LAI
N_{con}	1.00			1.00			1.00		
SPAD	0.81**	1		0.70**	1.00		0.73**	1.00	
LAI	0.20	0.44**	1	0.52**	0.65**	1.00	0.00	0.40**	1.00

n denotes number of sample; ** denotes significant at 0.01 level; N_{con} donotes plant nitrogen concentration; $ denotes corn database containing data from different growth stage of corn; # denotes wheat database containing data from one growth stage of wheat; & denotes combined database include all corn and wheat data.

3.3. Regression analysis results between spectral indices and wheat plant N concentration

Compared with other indices, MCARI/MTVI2, DCNI and TCARI/OSAVI yielded relatively good relationships with wheat plant N concentration. The R^2 values of the regression equations were 0.56 for MCARI/MTVI2, 0.44 for DCNI, and 0.40 for TCARI/OSAVI with $RMSE_{cal}$ of 1.7, 1.9 and 2.0 mg N g^{-1} d.m., respectively (Table 9). The R^2 values for DCNI and TCARI/OSAVI were lower for wheat than for corn. CCI also exhibited a weaker relationship with the N concentration of wheat than that of corn. The NRI performance was considerably lower for wheat than for corn. TCARI, $NDVI_{g-b}$, MTCI and REP-LI showed a level of correlation comparable to CCI for wheat, with R^2 values of regression equations in the range from 0.31 to 0.36 and corresponding $RMSE_{cal}$ values in the range from 2.0 to 2.1 mg N g^{-1} d.m. The other spectral indices did not show satisfactory results.

3.4. Regression analysis results between spectral indices and plant N concentration for both corn and wheat

Canopy structure parameters (leaf internal structure parameter, LAI, leaf angle distribution function[LADF]) strongly influence the performance of spectral indices aimed at predicting vegetation biophysical/biochemical attributes (Jacquemoud et al., 2000; Haboudane et al., 2008). Such parameters can affect the prediction accuracy of spectral indices used on a variety of species. Data from the two crops (corn and wheat) were combined to further assess the performance of the spectral indices, a method used in Haboudane et al. (2008). In this context, many spectral indices were unable to correlate with plant N concentration (Table 9). TCARI/OSAVI experienced a significant decrease in the relationship with plant N concentration but this was not the case for DCNI, MCARI/MTVI2 or TCARI, which had only slightly lower R^2 values of regression equations. Compared with other indices, DCNI, MCARI/MTVI2 and TCARI/OSAVI exhibited relatively good relationships with plant N concentration in the combined database. When plotted (Fig. 6), the points representing corn and wheat were grouped in parallel trends, but with a slightly overlap for TCARI/OSAVI and with higher values for

Table 9
Results of regression analysis between spectral indices and crop plant N concentration and LAI. Linear, logarithm, exponential, powder model were used to make fit. The results [R^2 and $RMSE_{cal}$ (mg N g^{-1} d.m.)] of best calibrated model were expressed in the table. Wheat data of year 2005 and corn data of years 2006 to 2008 were used.

Spectral index	Corn ($n=88$)				Wheat ($n=46$)				Corn and wheat ($n=134$)			
	N_{con}		LAI		N_{con}		LAI		N_{con}		LAI	
	R^2	$RMSE_{cal}$	R^2	$RMSE_{cal}$	R^2	$RMSE_{cal}$	R^2	$RMSE_{cal}$	R^2	$RMSE_{cal}$	R^2	$RMSE_{cal}$
Vi_{opt}	–	–	0.80	0.42	–	–	0.57	0.81	–	–	0.81	0.82
$NDVI_{g-b}$	0.11	3.9	0.25	0.63	0.36	2.1	–	–	0.19	3.5	0.17	1.38
RVI I	–	–	0.81	0.38	–	–	0.48	0.89	–	–	0.84	0.72
RVI II	0.09	3.9	0.81	0.39	0.17	2.3	0.47	0.87	–	–	0.85	0.70
NRI	0.31	3.3	0.42	0.64	–	–	0.47	0.86	0.10	3.4	0.52	1.23
MCARI/MTVI2	0.56	2.8	0.33	0.59	0.56	1.7	0.23	0.97	0.52	2.6	0.10	1.27
REP-LE	0.27	3.7	0.60	0.47	0.19	2.5	0.47	0.97	0.16	3.5	0.54	1.14
DCNI (this study)	0.72	2.3	0.18	0.69	0.44	1.9	0.15	1.02	0.64	2.3	0.05	1.56
MCARI	0.23	3.7	0.42	0.64	0.29	2.2	–	–	0.26	3.3	0.55	1.09
TCARI	0.34	3.4	0.30	0.68	0.34	2.1	–	–	0.33	3.1	0.26	1.35
TCARI/OSAVI	0.66	2.4	0.29	0.61	0.40	2.0	0.13	0.99	0.39	3.0	0.30	1.13
MTCI	0.25	3.6	0.73	0.43	0.34	2.1	0.48	0.87	0.17	3.5	0.67	1.03
R–M	0.14	3.8	0.83	0.35	0.29	2.2	0.54	0.85	0.04	3.7	0.82	0.81
CCI	0.32	3.4	0.49	0.56	0.31	2.1	0.29	0.97	0.26	3.3	0.39	1.29
REP-LI	0.26	3.6	0.69	0.52	0.35	2.0	0.55	0.83	0.08	3.8	0.76	1.05
NDVI	–	–	0.84	0.36	–	–	0.48	0.89	–	–	0.83	0.81
RVI	–	–	0.81	0.39	–	–	0.46	0.89	–	–	0.84	0.72

– means there is no significant ($p<0.01$) correlation between the two variables.

corn. In contrast, there was clear overlapping of corn and wheat for DCNI and MCARI/MTVI2. This suggests that DCNI and MCARI/MTVI2 are well correlated to plant N concentration in both wheat and corn, and could be considered as potential species-independent N estimators. At least, they should be appropriate indices for N concentration indicator for corn and wheat.

3.5. Validation using corn data from 2005

Based on the above findings, only N prediction equations of DCNI and MCARI/MTVI2 were validated using the independent corn database (2005).

3.5.1. Validation results based on ASD spectra

Predicted corn plant N concentrations for 2005 were calculated at each GPS point using established regression equations (Section 3.2). The relationships between actual N concentration and predicted N concentration were investigated (Fig. 7) with R^2 values to be 0.62 and 0.49 and the corresponding $RMSE_{val}$ values to be 2.7 mg N g^{-1} d.m. and 4.9 mg N g^{-1} d.m. for DCNI and MCARI/MTVI2, respectively. In general, DCNI expressed better performance.

3.5.2. Validation results based on CASI image

To further validate our results, the DCNI and MCARI/MTVI2 values were calculated from CASI hyperspectral image, and the predicted plant N concentrations were obtained from the established equations. Then the predicted plant N concentrations at specific GPS points were extracted from the image. The determination coefficients (R^2) between predicted plant N concentration and measured plant N concentration for DCNI and MCARI/MTVI2 were 0.51 and 0.40 with the corresponding $RMSE_{val}$ values to be 3.1 mg N g^{-1} d.m. and 5.0 mg N g^{-1} d.m.. The results were not as good as those generated from ASD spectra in 2005. This was likely due to factors such as geo-referencing errors, atmospheric correction uncertainty, and spatial and spectral resolutions. Generally, CASI estimated DCNI still performed better than MCARI/MTVI2.

A map of CASI-predicted plant N concentrations based on DCNI is shown in Fig. 8(a). Fig. 8(b) shows the amount of applied N and the corresponding mean N concentration of corn GPS points in each plot. The numbers, representing the mean N concentration in the 16 plots [Fig. 8(b)], are clearly related to corn plant N concentrations in the Fig. 8(a). The three strips on the map correspond to zero-N strip and saturated-N strips, and they can be seen explicitly in the map. The strip with yellow tone that splits the field longitudinally in half is the zero-N strip (0 kg N ha^{-1} at sowing). The other two strips with blue tones are the saturated N strips (250 kg N ha^{-1} at sowing). They correspond to the first and third longitudinal lines in the field. The presence of the zero-N strip and the saturated N strips (Samborski et al., 2009) in the experimental design and the fact that their respective N concentrations are coherent with those of the other N treatments is a clear demonstration that N supply was the predominant factor in the variation of DCNI levels. Our results showed the potential of using DCNI in combination with hyperspectral imagery to map the variation of plant N concentration in a corn field.

4. Discussion

4.1. Plant N content vs. NNI

Plant N content, expressed on a land area basis, is the product of plant N concentration and dry biomass. It can be used to indicate N status of crop in the same growth stage. However, it is not suitable for discriminating crop N status from different growth stages. N unlimited crop at an earlier growth stage, containing high N concentration and low dry biomass, may have the same plant N content as compared to N limited crop at a later growth stage, containing low N concentration and high dry biomass. Thus, growth stage must be taken into account when N content is used to make crop N diagnosis. However, it is difficult to determine the growth stage of a crop in a spatial detailed manner when the available N and other soil conditions vary substantially within the field. As mentioned in the introduction, NNI distinguishes the contribution of plant N concentration and dry biomass for crop N status estimation, and is therefore more accurate than N content. Lemaire et al. (2008) defined NNI as the specific (varies only with nitrogen nutrition), sensitive (reacts rapidly to any change in plant N nutrition status), memorable (can give information about the history of the stand), predictive (can infer future elements of crop behaviors) tool for crop N diagnosis.

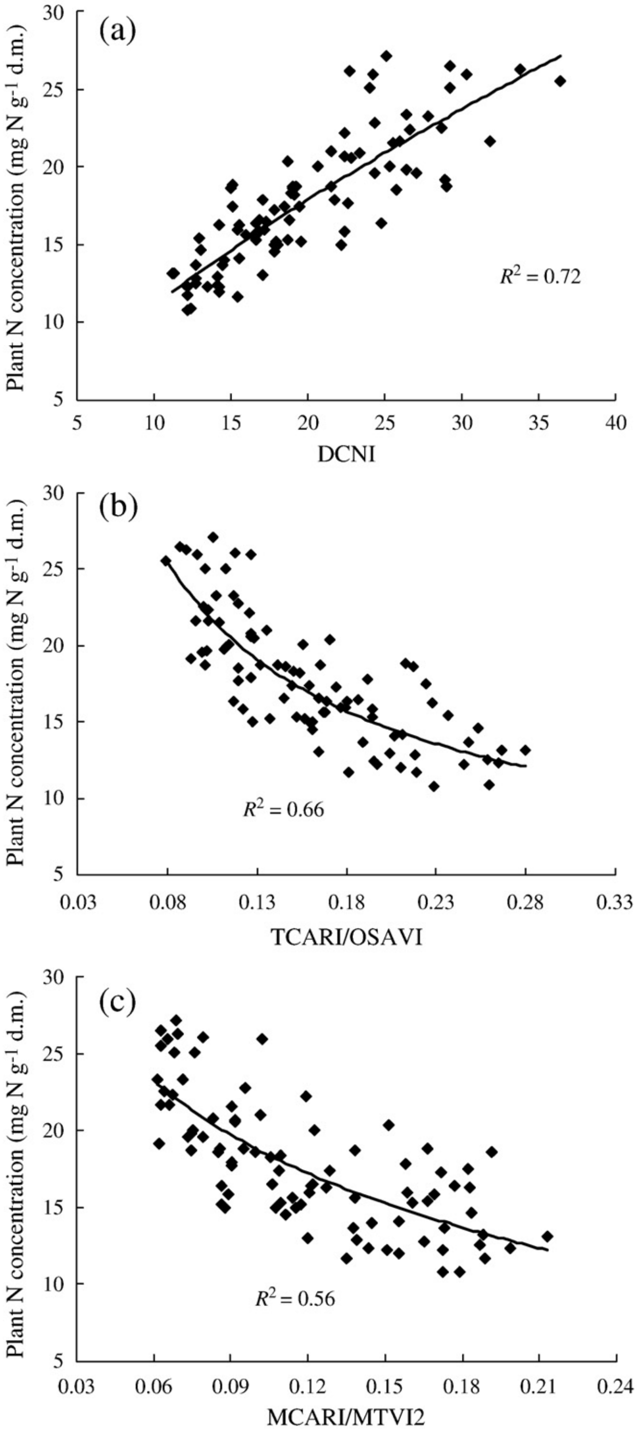

Fig. 5. Regression analysis results between plant N concentration (mg N g^{-1} d.m.) and spectral indices obtained from corn data of years 2006–2008: DCNI (*a*), TCARI/OSAVI (*b*) and MCARI/MTVI2 (*c*).

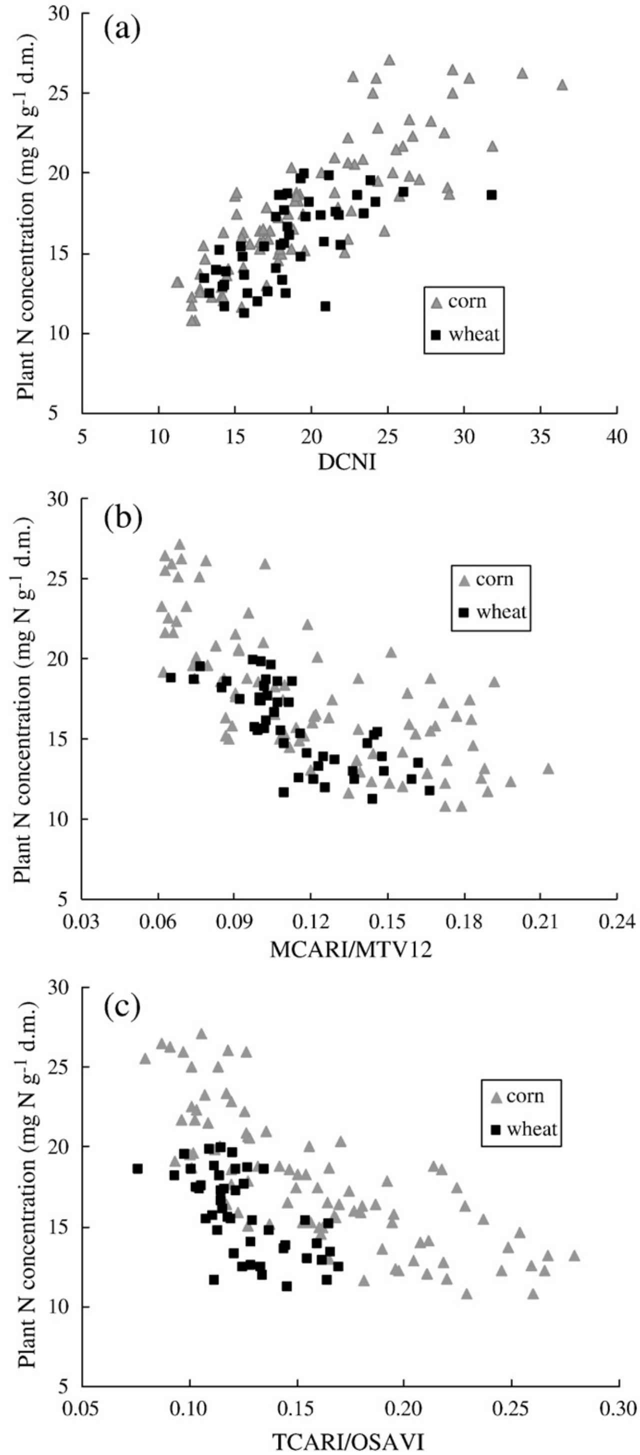

Fig. 6. Crop type effects on the correlation between spectral indices and plant nitrogen concentration (mg N g^{-1} d.m.), from corn data of years 2006–2008 and wheat data of year 2005: DCNI (*a*), MCARI/MTVI2 (*b*) and TCARI/OSAVI (*c*).

4.2. Evaluation of spectral indices on their ability to estimate plant N concentration

It is critical to minimize the influence of LAI on the detection of crop N concentration. Daughtry et al. (2000) and Haboudane et al. (2002) reported that the ratio of indices sensitive to chlorophyll variations to traditional vegetation indices may minimize the effects of LAI and soil background while maximizing the sensitivity to canopy chlorophyll concentration. Indices based on ratio may show a better ability to predict N concentration based on the relationship between chlorophyll concentration and N concentration. Eitel et al. (2007) reported that a combined index (MCARI/MTVI2) was the best indicator for flag leaf N concentration of winter wheat, a conclusion confirmed by our results. Among the existing spectral indices, the combined indices (TCARI/OSAVI and MCARI/MTVI2) performed best in predicting N concentration. In addition, DCNI, taking LAI influence

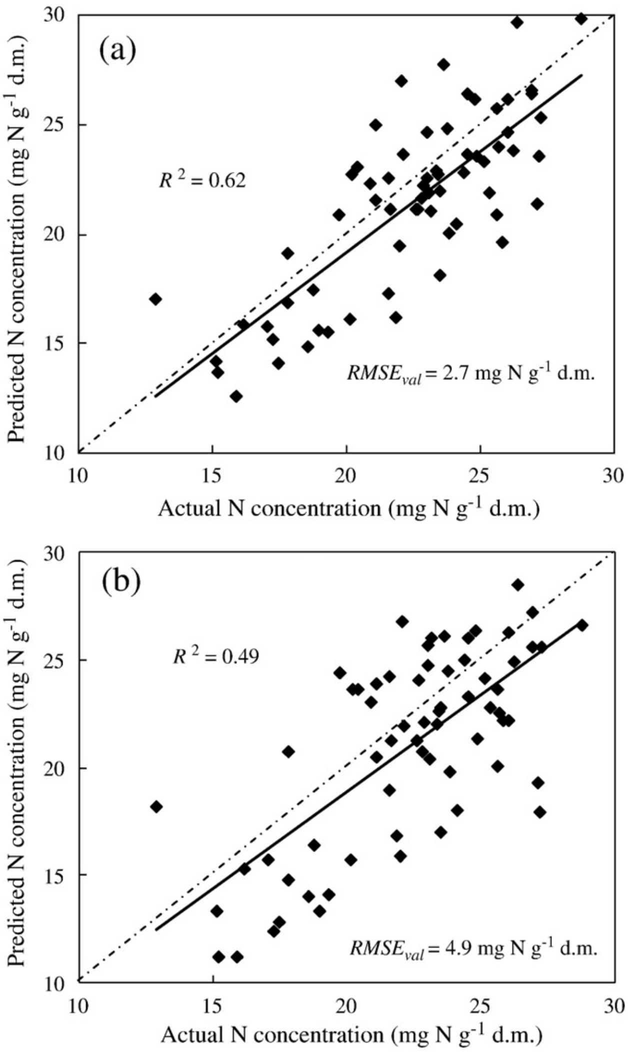

Fig. 7. Plant N concentration estimated by the regression equation of DCNI compared to actual plant N concentration, using ASD spectra in 2005. (*a*) Plant N concentration estimated by the regression equation of MCARI/MTVI2 compared to actual plant N concentration, using ASD spectra in 2005. (*b*) Dashed lines represent a zero error of prediction ($RMSE_{val} = 0$).

into consideration, performed best for N concentration estimation, whereas the other indices showed a high correlation with LAI but was poor in predicting plant N concentration.

4.3. Application of the new N concentration index

In this study, corn and wheat data were used to design a new N concentration index (DCNI) based on the strong relationship between N and chlorophyll concentrations. When compared to some existing indices, DCNI was the best indicator for N concentration. Combined with other indices used for dry biomass forecasting, NNI may well be predicted accurately by remote sensing. This will be a great helpful for site-specific N management. Since close relationships have been established between NNI during vegetative period and the yield of several grain crops (Lemaire et al., 2008; Ziadi et al., 2008), remotely sensed NNI should also have great potential to be used for grain yield forecast.

5. Conclusions

Based on the use of a wide range of corn data [4 years, different growth stages (V5–VT)], two crop species (corn and wheat), ground-based reflectance spectra, airborne imagery and the comparison of many spectral indices, DCNI was designed and determined as the best index for estimating corn and wheat plant N concentration in this study. It was the most sensitive to N concentration changes during the critical N management stage (V5–VT) of corn and can be used both for corn and wheat N concentration estimation. In conjunction with some indices designed for biomass estimation, DCNI may be instrumental in the evaluation of NNI by remote sensing.

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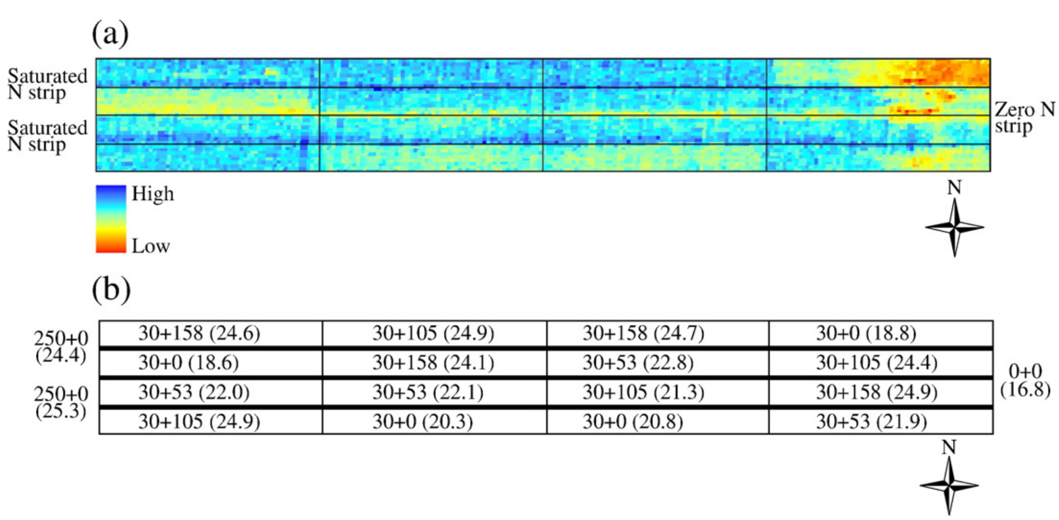

Fig. 8. Map of plant N concentration from a CASI hyperspectral image of summer 2005 for corn field. Predicted plant N concentration was calculated using predictive equation of DCNI. Plant N concentration ranges from 9.2 (reddish tones) to 31.9 mg N g^{-1} d.m. (bluish tones) (*a*). Map of N treatment and corresponding mean plant N concentration in corn V9 growth stage in each plot. Numbers (0, 250, 30) before plus symbol represent amount of applied sowing N and numbers (0, 53, 105, 158) after represent amount of applied topdressing N, they all expressed in kilograms per hectare. Numbers in the bracket represent the mean plant N concentration of GPS points in each plot (*b*).

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