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Comparing narrow and broad-band vegetation indices to estimate leaf chlorophyll content in planophile crop canopies

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Abstract A comparison of the sensitivity of several broad- and narrow-band vegetation indices (VIs) to leaf chlorophyll content in planophile crop canopies is addressed by the analysis of a large synthetic dataset. Broad-band indices included classical slope-based VIs (i.e. NDVI—normalized difference VI and SR—simple ratio) and some indices incorporating green reflectance (i.e. Green NDVI, NIR/green ratio and the newly proposed CVI—chlorophyll vegetation index), whereas narrow-band indices included those specifically proposed to estimate leaf chlorophyll at the canopy scale (i.e. MCARI—modified chlorophyll absorption reflectance index, TCARI—transformed CARI, TCARI/OSAVI ratio—TCARI/optimized soil adjusted VI and REIP—red edge inflection position). Synthetic data were obtained from the coupled PROSPECT + SAILH leaf and canopy reflectance models in the direct mode. In addition to traditional regression-based statistics (coefficient of determination and root mean square error, RMSE), changes in sensitivity of a VI over the range of chlorophyll content were analyzed using a sensitivity function. The broad-band chlorophyll vegetation index outperformed the other VIs considered as a leaf chlorophyll estimator at the canopy scale, with the exception of the TCARI/OSAVI ratio for some soil conditions.

Keywords Remote sensing · Variable-rate fertilizer application · Vegetation indices

Introduction

Leaf area index (LAI) and chlorophyll content per unit mass or per unit leaf area are widely used by agronomists and ecologists to detect and quantify crop stress (Baret et al. 2007). The overall photosynthetic capacity of a canopy, as expressed by canopy chlorophyll content (i.e. pigment content per unit crop area), can be estimated effectively with both narrow- and broad-band vegetation indices (VIs) because of their sensitivity to leaf area

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index (LAI) and to leaf chlorophyll content (Baret and Guyot 1991; Broge and Leblanc 2000; Elvidge and Chen 1995). However, to use a VI to prescribe variable-rate fertilizer applications, its specific sensitivity to leaf chlorophyll content, an effective indicator of nutritional stress, is more useful (Daughtry et al. 2000; Haboudane et al. 2002; Zarco-Tejada et al. 2005; Baret et al. 2007). Portable leaf chlorophyll meters (e.g. Minolta SPAD-502) have been used widely for many crops to obtain optimum N recommendations (Bullock and Anderson 1998).

Only narrow-band VIs that require reflectance data of high-spectral resolution have been reported to be specifically sensitive to leaf chlorophyll content at the canopy scale (Baret et al. 1992; Blackburn 1998; Daughtry et al. 2000; Haboudane et al. 2002; Horler et al. 1983). At present, however, the use of airborne hyperspectral sensors is expensive and the availability of high spatial resolution space-borne hyperspectral sensors is limited. Broad-band VIs from space-borne or air-borne multi-spectral sensors are being used to obtain the information for variable fertilizer application.

We developed the chlorophyll vegetation index (CVI), a broad-band VI that is sensitive to leaf chlorophyll content at the canopy scale from a field spectrometric experiment conducted on sugar beet canopies (Vincini et al. 2007). Recently, we proposed an optimized version of the CVI (OCVI) using a large synthetic dataset (Vincini et al. 2008). The OCVI can take into account differences in spectral behaviour related to different types of crop and soil, sensor spectral resolution and scene sun zenith angle. In the same study, the results from the synthetic dataset indicated that the broad-band CVI index could be used to estimate leaf chlorophyll for planophile crops (i.e. with low average leaf angle) in most soil conditions (Vincini et al. 2008). This paper compares the sensitivity of broad-band indices, including the CVI, and of different narrow-band VIs, proposed specifically to estimate leaf chlorophyll content, in planophile crops canopies. The sensitivity analysis was conducted on a large synthetic dataset obtained with the coupled PROSPECT + SAILH leaf and canopy reflectance model in the direct mode.

Methods

The PROSPECT + SAILH leaf and canopy coupled reflectance model (Jacquemoud 1993; Jacquemoud et al. 1995, 2000) was used in the direct mode to obtain a large synthetic dataset. These data were then used to compare the sensitivity of the different VIs to leaf chlorophyll content in planophile crop canopies for different soil conditions and two sun zenith angles. The soil reflectance database (Daughtry et al. 1997) used as an input to the model included the spectral signatures of six different soil types (Fig. 1; Table 1) that represent the spectral variability of many mid-latitude cropland topsoils. For each soil type with considerable variation in reflectance between wet and dry conditions (Othello, Cecil, Portneuf and Cordorus soil types in Fig. 1) two spectral signatures were used, representing wet and dry soil conditions (i.e. wetted and allowed to drain and air-dried, Daughtry et al. 1997). For the soil types with little difference in soil reflectance related to soil moisture (Barnes and Houston Black Clay soil types in Fig. 1) a single spectral signature, representing intermediate soil moisture conditions, was used.

An average leaf angle (ALA) value of 30° and a ‘hot-spot’ size parameter value of 0.5 (unitless) were used as model inputs to represent planophile canopies. The size of the ‘hot-spot’ parameter depends on the mean size and shape of leaves and on canopy height. It has been introduced into the SAILH model to reproduce the canopy spectral behaviour of the ‘hot-spot’, i.e. the cone where the solar and viewing directions are close together. The

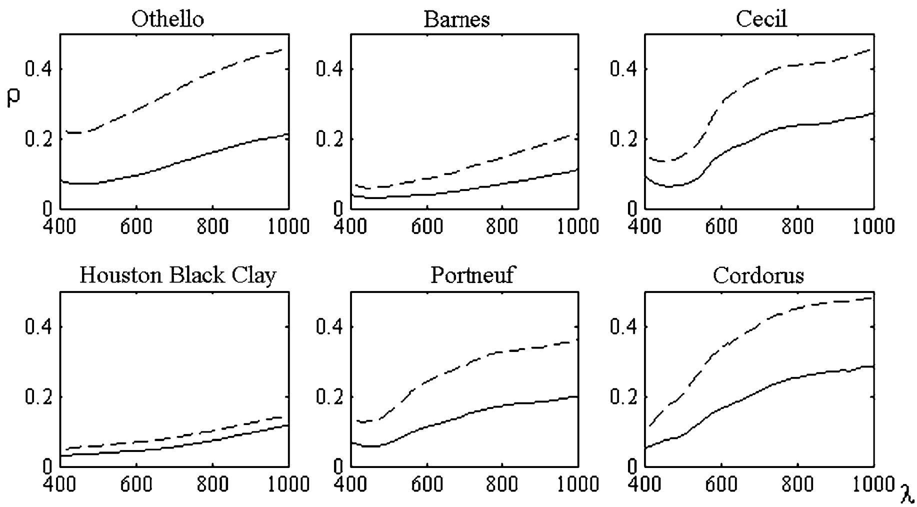

Fig. 1 Spectral signatures (reflectance ρ) of six different wet (wetted and allowed to drain, *solid line*) and air-dried (*dashed line*) cropland topsoils in the 400–1000 nm, λ, spectral range

Table 1 Soil taxonomy classification (Soil Survey Staff 1975) of the six soil types (Daughtry et al. 1997) used for the soil reflectance database

Soil series	Classification
Othello	Fine-silty, mixed mesic Typic Ochraquult
Barnes	Coarse-loamy, mixed Udic Haploboroll
Cecil	Clayey, kaolinitic, thermic Typic Hapludult
Houston Black Clay	Fine, montmorillonitic, thermic Udic Pellustert
Portneuf	Coarse-silty, mixed, mesic Durixerollic Calciorthid
Cordorus	Fine-loamy, mixed, mesic Fluvaquentic Dystrochrept

acquisition geometries considered in the synthetic database included only nadir observations (i.e. with zero view zenith angle) and two solar zenith angles of 30° and 60°. Leaf chlorophyll (a + b) content was varied from 20 (i.e. leaf chlorosis) to 50 μg cm^{-2} in increments of 2.5 μg cm^{-2}, whereas 35 LAI values, from 0.2 to 7.0 in increments of 0.2, were used. Suggested typical values used for the other model input parameters were water content, 0.012 g cm^{-2}; dry matter content, 0.005 g cm^{-2}; brown pigment content, 0; leaf surface roughness angle, 59° and mesophyll structure index value, 1.5. These parameters are in general less relevant for spectral behaviour of the canopy in the visible-NIR (near infra-red) range. The resulting database included simulated soil-canopy spectral reflectance data for 9100 different soil-canopy-acquisition conditions, i.e. 10 soil spectral signatures of different soil types and soil wetness, 35 LAI values, 13 leaf chlorophyll contents and 2 sun zenith angles.

Vegetation indices, described below, that were considered in this study in addition to the broad-band CVI included several narrow-band VIs proposed specifically to estimate leaf chlorophyll at the canopy scale (i.e. VIs obtained from canopy reflectance) and some broad-band indices reported to be sensitive to chlorophyll content at the leaf level (i.e. VI obtained from leaf reflectance). The broad-band indices were obtained from the synthetic spectra using the average reflectance in the 500–590 nm (green), 610–680 nm (red) and 780–890 nm (NIR) spectral ranges, corresponding to the SPOT sensor's multi-spectral bands, whereas narrow-band VIs were obtained using the model's spectral resolution of 1 nm.

Blackmer et al. (1994) found that the green band was very sensitive to photosynthetic pigment content. Gitelson et al. (1996) proposed 'green NDVI' using a green rather than a red band, as in the classic NDVI, to estimate leaf chlorophyll content:

$$\text{Green NDVI} = \frac{\rho_{\text{NIR}} - \rho_{\text{green}}}{\rho_{\text{NIR}} + \rho_{\text{green}}}. \tag{1}$$

Schepers et al. (1996) reported strong correlations between the narrow band 550/850 nm reflectance ratio and chlorophyll content for leaves of corn grown under different nitrogen regimes. Gitelson and Merzlyac (1996) found similar results for the 750/550 nm reflectance ratio of maple and chestnut leaves. Close relationships were found between the model $[(\rho_{\text{NIR}}/\rho_{\text{green}}) - 1]$ and chlorophyll content in maize and soybean canopies (Gitelson et al. 2005). To obtain a broad-band VI incorporating the spectral information of the green band with enhanced sensitivity to leaf chlorophyll content and insensitive to the variation in LAI, we developed the chlorophyll vegetation index (CVI). The CVI is probably the only broad-band vegetation index reported to be specifically sensitive to leaf chlorophyll content at the canopy scale (Vincini et al. 2008):

$$\text{CVI} = \frac{\rho_{\text{NIR}}}{\rho_{\text{green}}} \cdot \frac{\rho_{\text{red}}}{\rho_{\text{green}}}. \tag{2}$$

The CVI index is obtained from the NIR/green reflectance ratio by introducing the red/green ratio to minimize the sensitivity to differences in the canopy LAI before canopy closure.

The chlorophyll absorption reflectance index (CARI) has been proposed as a measure of the depth of chlorophyll absorption at 670 nm relative to the green reflectance peak at 550 nm (Kim et al. 1994). The modified CARI (MCARI), developed to be responsive to chlorophyll variation, is also sensitive to variation in LAI even though no NIR band is considered (Daughtry et al. 2000):

$$\text{MCARI} = [(\rho_{700} - \rho_{670}) - 0.2\,(\rho_{700} - \rho_{550})]\frac{\rho_{700}}{\rho_{670}}. \tag{3}$$

The 700 nm wavelength matches the boundary between the region where vegetation reflectance is dominated by pigments and the beginning of the red edge where the structural characteristics of vegetation dominate. The ratio ρ_{700}/ρ_{670} was introduced to minimize the effect of the underlying soil reflectance. Another modification, the transformed CARI (TCARI) was proposed by Haboudane et al. (2002) to estimate chlorophyll:

$$\text{TCARI} = 3\left[(\rho_{700} - \rho_{670}) - 0.2\,(\rho_{700} - \rho_{550})\frac{\rho_{700}}{\rho_{670}}\right]. \tag{4}$$

To separate LAI and chlorophyll sensitivity, Haboudane et al. (2002) proposed the combined TCARI/OSAVI ratio, where the optimized soil adjusted vegetation index (OSAVI) is introduced to minimize the sensitivity to differences in canopy LAI:

$$\frac{\text{TCARI}}{\text{OSAVI}} = \frac{3\left[(\rho_{700} - \rho_{670}) - 0.2\,(\rho_{700} - \rho_{550})\frac{\rho_{700}}{\rho_{670}}\right]}{\frac{\rho_{800} - \rho_{670}}{\rho_{700} - \rho_{670} + 0.16}}. \tag{5}$$

The spectral position of the inflection point in the red edge (REIP) is sensitive to leaf chlorophyll at the canopy scale (Baret et al. 1992; Horler et al. 1983) and different methods have been proposed for its calculation. In the present study two simplified methods were used, both based on a linear interpolation procedure between NIR and red reflectances (Clevers 1994; Guyot and Baret 1988):

$$\lambda_{\mathrm{REIP1}} = 710 + 50 \cdot \left(\frac{\frac{1}{2}(\rho_{810} + \rho_{660}) - \rho_{710}}{\rho_{760} - \rho_{710}} \right) \tag{6}$$

and

$$\lambda_{\mathrm{REIP2}} = 700 + 40 \cdot \left(\frac{\frac{1}{2}(\rho_{780} + \rho_{670}) - \rho_{700}}{\rho_{740} - \rho_{700}} \right). \tag{7}$$

A power regression function with three unknown coefficients (a, b, c), Eq. 8, was used in this study to describe the relationship between the VI and leaf chlorophyll ($a + b$) content (*Chl*) values obtained from the synthetic dataset for different soil types, soil water content and sun zenith angles:

$$\mathrm{VI} = a \cdot \mathrm{Chl}^b + c. \tag{8}$$

The power model was selected from the commonly used regression functions based on its large significance levels for both linear and non-linear relationships between chlorophyll content and the different VIs tested.

In addition to traditional regression-based statistics (R^2, coefficient of determination, and root mean square error, RMSE), changes in sensitivity of a VI over the range of leaf chlorophyll content were analyzed with a sensitivity function obtained by the method proposed by Ji and Peters (2007).

The sensitivity function (Eq. 9) is calculated as the ratio of the first derivative of the regression function (Eq. 8) using leaf chlorophyll content as the independent variable (x), the VI values as the dependent variable (y) and the standard error $\sigma_{\hat{y}}$ of the predicted value ($\hat{y}$):

$$s = \frac{\mathrm{d}\hat{y}/\mathrm{d}x}{\sigma_{\hat{y}}}. \tag{9}$$

The sensitivity function, rather than providing a single goodness-of-fit value, can describe the changes in VI sensitivity over the range of biophysical variables, and, being independent of the unit or magnitude of the VI, can be used for a direct comparison of the performance of various VIs. The absolute value of s was considered in the present study to compare VIs characterized by direct (e.g. CVI) and inverse (e.g. TCARI/OSAVI) relationships with leaf chlorophyll content.

Results and discussion

Table 2 gives the results of the power function regression (Eq. 8) between the VI values and leaf chlorophyll content from the synthetic dataset for different soil types, soil wetness conditions and two sun zenith angles.

For all soil and sun zenith conditions considered the strongest correlations (R^2 values in bold in Table 2) between VIs and leaf chlorophyll content were obtained by the broad-band CVI ($0.60 < R^2 < 0.95$, Table 2) or the narrow-band TCARI/OSAVI ratio ($0.71 < R^2 < 0.98$). The R^2 values confirm that leaf chlorophyll content in planophile crops can be estimated effectively using the broad-band CVI. The results also seem to indicate that a narrow-band VI, i.e. the TCARI/OSAVI ratio, which requires high spectral

Table 2 Regression statistics (R^2 and RMSE) of VIs versus leaf chlorophyll content for different soil types, soil wetness conditions (dry, wet, intermediate) and two sun zenith angles (maximum R^2 values in *bold*)

			Othello		Barnes	Cecil		Houston Black Clay	Portneuf		Cordorus	
			Dry	Wet	Intermediate	Dry	Wet	Intermediate	Dry	Wet	Dry	Wet
Sun Zenith 30°	CVI	R^2	0.872	**0.935**	**0.878**	0.679	0.604	**0.747**	**0.954**	**0.938**	0.915	**0.874**
		RMSE	0.167	0.113	0.157	0.342	0.394	0.238	0.098	0.114	0.142	0.175
	NDVI	R^2	0.087	0.182	0.244	0.076	0.118	0.232	0.089	0.148	0.075	0.121
		RMSE	0.136	0.097	0.084	0.145	0.122	0.087	0.137	0.109	0.145	0.119
	SR	R^2	0.273	0.383	0.435	0.258	0.317	0.429	0.278	0.353	0.255	0.319
		RMSE	2.73	2.29	2.11	2.81	2.54	2.13	2.71	2.40	2.83	2.53
	Green NDVI	R^2	0.271	0.484	0.523	0.416	0.572	0.430	0.319	0.470	0.298	0.473
		RMSE	0.089	0.061	0.058	0.065	0.050	0.070	0.081	0.062	0.083	0.060
	NIR/green ratio	R^2	0.412	0.554	0.578	0.517	0.612	0.521	0.446	0.545	0.433	0.548
		RMSE	1.01	0.786	0.756	0.842	0.707	0.837	0.948	0.799	0.976	0.793
	MCARI	R^2	0.301	0.297	0.302	0.280	0.284	0.298	0.323	0.291	0.301	0.292
		RMSE	0.078	0.078	0.008	0.082	0.081	0.077	0.071	0.079	0.079	0.079
	TCARI	R^2	0.439	0.358	0.345	0.359	0.337	0.346	0.391	0.352	0.433	0.367
		RMSE	0.068	0.078	0.080	0.080	0.082	0.080	0.075	0.079	0.698	0.077
	TCARI/OSAVI	R^2	**0.971**	0.756	0.710	**0.795**	**0.725**	0.723	0.905	0.764	**0.962**	0.812
		RMSE	0.019	0.060	0.084	0.056	0.066	0.065	0.036	0.059	0.022	0.052
	REIP1	R^2	0.712	0.642	0.629	0.503	0.508	0.627	0.606	0.575	0.583	0.588
		RMSE	2.02	2.58	2.71	3.25	3.39	2.75	2.66	3.00	2.70	2.82
	REIP2	R^2	0.699	0.660	0.621	0.575	0.575	0.633	0.657	0.615	0.611	0.633
		RMSE	1.32	1.47	1.62	1.75	1.76	1.57	1.47	1.63	1.61	1.55

Table 2 continued

			Othello		Barnes	Cecil		Houston Black Clay	Portneuf		Cordorus	
			Dry	Wet	Intermediate	Dry	Wet	Intermediate	Dry	Wet	Dry	Wet
Sun Zenith 60°	CVI	R^2	0.866	**0.905**	**0.837**	0.747	0.673	0.714	**0.950**	**0.927**	0.937	**0.910**
		RMSE	0.182	0.145	0.197	0.300	0.349	0.275	0.108	0.130	0.126	0.151
	NDVI	R^2	0.096	0.193	0.253	0.084	0.127	0.242	0.098	0.158	0.083	0.131
		RMSE	0.130	0.093	0.081	0.139	0.116	0.084	0.131	0.105	0.139	0.114
	SR	R^2	0.324	0.421	0.466	0.309	0.363	0.460	0.327	0.394	0.307	0.365
		RMSE	2.88	2.41	2.24	2.96	2.67	2.26	2.85	2.53	2.99	2.66
	Green NDVI	R^2	0.286	0.483	0.515	0.425	0.566	0.430	0.332	0.470	0.312	0.476
		RMSE	0.088	0.061	0.059	0.064	0.051	0.070	0.080	0.063	0.082	0.061
	NIR/green ratio	R^2	0.449	0.567	0.583	0.545	0.621	0.533	0.479	0.559	0.470	0.567
		RMSE	1.06	0.846	0.820	0.897	0.767	0.897	0.999	0.857	1.03	0.849
	MCARI	R^2	0.338	0.328	0.332	0.317	0.317	0.328	0.323	0.322	0.340	0.325
		RMSE	0.069	0.070	0.069	0.073	0.072	0.069	0.071	0.071	0.070	0.071
	TCARI	R^2	0.493	0.399	0.385	0.407	0.378	0.385	0.440	0.393	0.489	0.411
		RMSE	0.057	0.067	0.069	0.068	0.070	0.069	0.063	0.068	0.585	0.066
	TCARI/OSAVI	R^2	**0.983**	0.807	0.765	**0.849**	**0.777**	**0.778**	0.938	0.814	**0.976**	0.857
		RMSE	0.014	0.048	0.054	0.043	0.053	0.052	0.026	0.047	0.016	0.041
	REIP1	R^2	0.700	0.609	0.596	0.481	0.488	0.593	0.573	0.547	0.553	0.559
		RMSE	2.20	2.71	2.84	3.33	3.45	2.89	2.79	3.10	2.82	2.93
	REIP2	R^2	0.668	0.633	0.597	0.557	0.558	0.607	0.629	0.592	0.589	0.610
		RMSE	1.42	1.55	1.69	1.81	1.81	1.66	1.56	1.70	1.68	1.62

resolution data, can achieve an appreciably higher sensitivity for a limited number of soil conditions (e.g. Cecil soil characterized by the largest red/green reflectance ratio among the soil types considered, Fig. 1). The other narrow-band VIs were outperformed by the broad-band CVI.

The broad-band NIR/green ratio, from which the CVI is obtained by minimizing the sensitivity to LAI with the red/green reflectance ratio, was the second best broad-band estimator of leaf chlorophyll content with values of R^2 from 0.41 to 0.62 (Table 2). In most cases the NIR/green ratio has stronger correlations than the narrow-band TCARI and MCARI indices, and in one case (Cecil soil wet) it has a slightly greater correlation than the CVI. Green NDVI ($0.27 < R^2 < 0.57$, Table 2) has a few moderate correlations, whereas classical broad-band indices that do not incorporate green reflectance had small (SR $0.27 < R^2 < 0.47$, Table 2) or negligible (NDVI $0.08 < R^2 < 0.25$, Table 2) correlations. Among the narrow-band VIs, REIP is sensitive to leaf pigment, especially when calculated according to Eq. 6 ($0.50 < R^2 < 0.71$), whereas TCARI ($0.34 < R^2 < 0.49$) and MCARI ($0.28 < R^2 < 0.34$) have weak correlations (Table 2).

Figure 2 shows the scatter plots of the broad-band CVI and narrow-band TCARI/OSAVI (i.e. the best estimators of leaf chlorophyll) against leaf chlorophyll content for Othello soil in dry and wet conditions. Figure 2 also shows the regression lines fitted to the

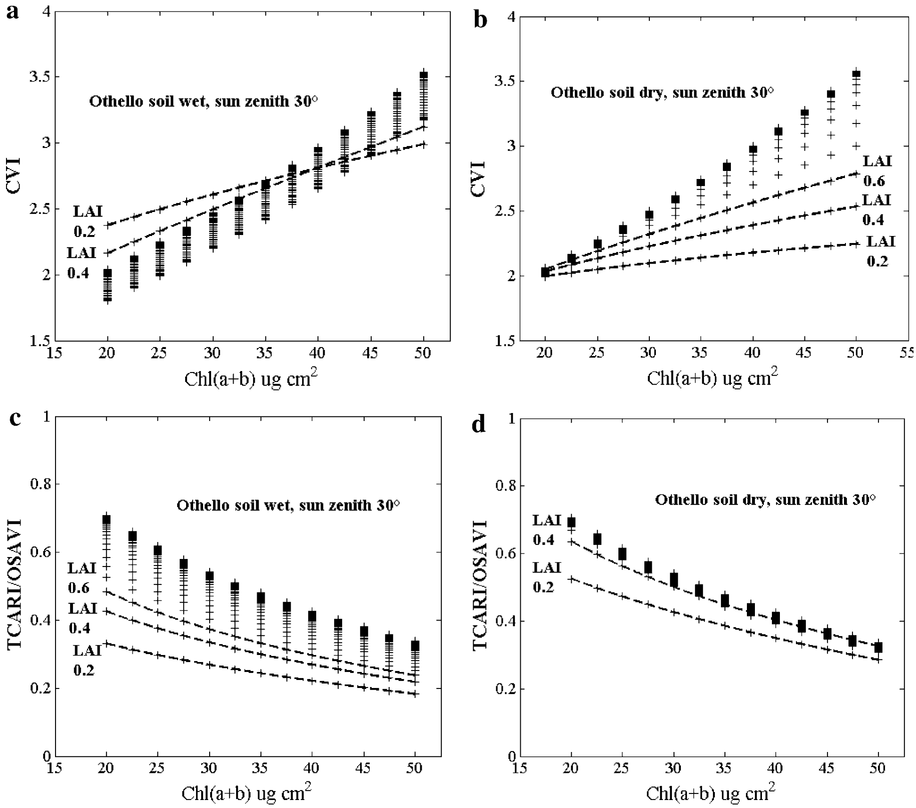

Fig. 2 Scatter plots and regression lines for small values of LAI for Othello soil: **a**, **b** the broad-band CVI and **c**, **d** the narrow-band TCARI/OSAVI, plotted against leaf chlorophyll content for 30° sun zenith angle; **a** and **c** are for wet soil, and **b** and **d** are for dry soil

scatter of points of the two indices versus leaf chlorophyll content for some small values of LAI.

Both the CVI and the TCARI/OSAVI ratio are indices that minimize the sensitivity to LAI, the former by using the red/green reflectance ratio and the latter by taking the ratio of chlorophyll (TCARI) and LAI estimators (OSAVI). As shown in Fig. 2, depending on differences in soil spectral behaviour and on the variability in soil reflectance because of soil water content (Fig. 1), the LAI normalization of both indices can be ineffective with low vegetation cover (i.e. small LAI values). The difference in significance of the correlations between the two LAI-normalized indices and leaf chlorophyll content for different soil conditions are mainly due to differences in residual sensitivity to LAI before canopy closure. In Fig. 3, the CVI and TCARI/OSAVI sensitivity functions plotted against leaf chlorophyll content are shown for some soil and sun zenith conditions. The broad-band CVI tends to be more sensitive for larger ranges of leaf chlorophyll content, which is more realistic for a crop's nutritional status, than the narrow-band TCARI/OSAVI. These two VIs have similar R^2 values for dry Portneuf soil and a sun zenith angle of 60° (Table 2), but the sensitivity functions (Fig. 3c) indicate that for such conditions TCARI/OSAVI is a more effective estimator of leaf chlorophyll in the 20–30 μg cm^{-2} range (i.e. severe chlorotic conditions), whereas CVI becomes progressively more sensitive in the 30–50 μg cm^{-2} range.

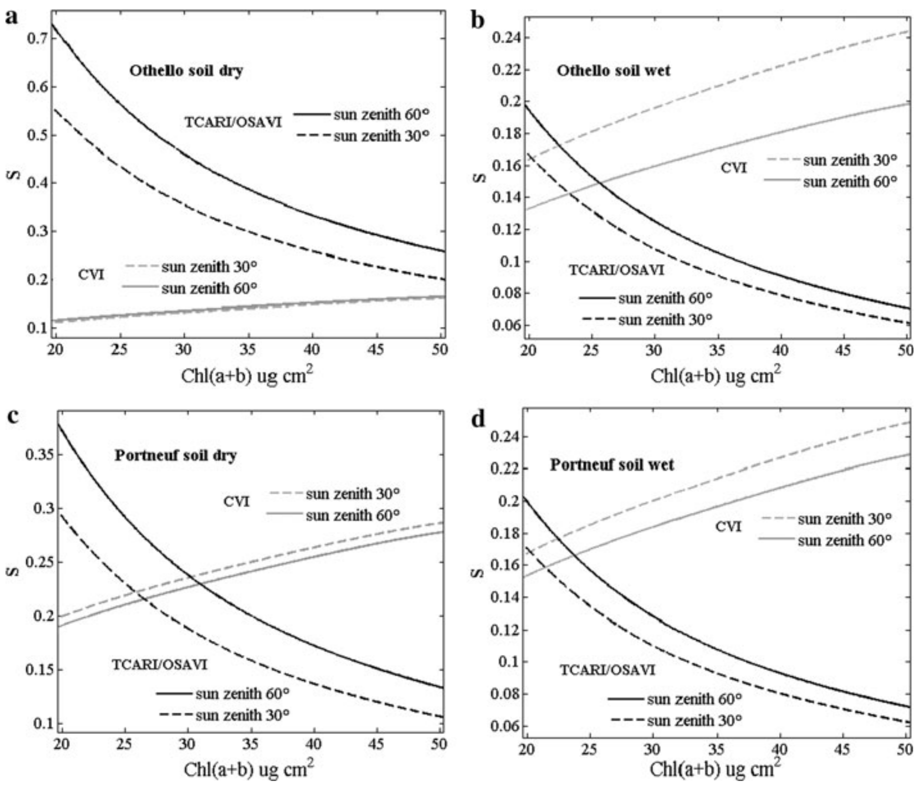

Fig. 3 The CVI and TCARI/OSAVI sensitivity functions, *S*, plotted against leaf chlorophyll (a + b) content (μg cm^{-2}) for some soil and sun zenith conditions

Sensitivity patterns similar to those represented in Fig. 3 over the range of leaf chlorophyll content considered were obtained for the two VIs (CVI and TCARI/OSAVI) for all soil and sun zenith combinations. These results confirm previous indications of the existence of a linear relationship, not saturated for high pigment contents, per leaf area as well as per crop area, between CVI and leaf chlorophyll contents (Vincini et al. 2008). In contrast, the relationship between the TCARI/OSAVI and leaf chlorophyll contents is not linear (Fig. 2c, d) and tends to saturate for large pigment contents.

Conclusions

The results of a comparison of the sensitivity of several broad-band and narrow-band vegetation indices to leaf chlorophyll content from the analysis of a large synthetic dataset, confirm that the broad-band CVI can be used to estimate leaf chlorophyll at the canopy scale for planophile crop canopies. The results suggest that, compared with the broad-band CVI, the empirical use (i.e. the use of relationships between VIs and biophysical vegetation variables) of high spectral resolution reflectance data can only marginally improve estimates of leaf chlorophyll content at the canopy level. For planophile canopies TCARI/OSAVI, the most effective among narrow-band VIs considered, seems to be more sensitive than CVI for limited soil conditions only. In comparison with the narrow-band TCARI/OSAVI ratio, the CVI seems to be more sensitive for larger leaf chlorophyll contents, which is more realistic for a crop's nutritional status. The other broad-band and narrow-band VIs were outperformed by the CVI and the TCARI/OSAVI ratio.

The wide LAI and chlorophyll content ranges where CVI is sensitive to leaf chlorophyll content suggest a possible use of the index not only before canopy closure for side-dressing variable-rate fertilizer application, but also for later N treatments such as fertigation (i.e. the application of fertilizer dissolved in irrigation water).

The broad-band CVI, which is specifically sensitive to leaf chlorophyll content in planophile crops canopies, could be used effectively for variable prescription of N fertilizer based on reflectance data from space-borne high-spatial resolution multi-spectral sensors.

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