NARROW-BAND VEGETATION INDEXES FROM HYPERION AND DIRECTIONAL CHRIS/PROBA DATA FOR CANOPY CHLOROPHYLL DENSITY ESTIMATION IN MAIZE

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ABSTRACT

In the context of the CITIMAP (Centre for the application of Remote Sensing in Precision Agriculture Mechanization) precision farming research program at the Vittorio Tadini experimental farm the values of several narrow-band vegetation indices (VIs) were determined for maize 2005/2006 crops from hyperspectral CHRIS/Proba and Hyperion observations. The sensitivity of the different VIs to Biophysical crop parameters relevant to nutritional status and nitrogen variable rate fertilization (LAI and leaf chlorophyll concentration measured directly in the field) is addressed. The Spectral Polygon Vegetation Index (SPVI) is proposed for LAI and canopy chlorophyll estimation.

1. INTRODUCTION

Many studies [1, 2] have indicated that narrow-band and broad-band vegetation indices (VIs) can be effectively used, due to their sensitivity to leaf area index (LAI) and, secondarily, to leaf chlorophyll concentration, to evaluate the overall photosynthetic capacity of a canopy as expressed by canopy chlorophyll density (CCD), a measure of photosynthetic potential at the canopy level calculated as the product of LAI and leaf chlorophyll concentration. Canopy chlorophyll density is sensitive to soil N availability [3] and can be used as an indicator of N deficiency for variable rate fertilization prescriptions.

A major problem in the use of classical ratio-based indices for the assessment of CCD and N deficiency for field crops arises from the fact that they tend to exhibit asymptotic saturated signals over medium-high biomass and LAI conditions. Medium-high biomass conditions, however, characterize many crops during important N treatments such as fertigation (i.e. the application of fertilizer dissolved in irrigation water) or liquid manure applications.

Several optical indices with improved sensitivity to LAI and CCD, in general obtained by improving the linearity of the relationship with these biophysical parameters, have been proposed in the literature [4, 5, 6]. However, there is currently little agreement on which VI has the strongest relationships with LAI or CCD over medium-high biomass and LAI conditions.

The present work addresses the comparison of different narrow-band VIs obtained from the space-borne Hyperion and CHRIS sensors for the estimation of canopy chlorophyll density (CCD) in maize. Vegetation indices that were considered included traditional and more recent slope-based VI and indices incorporating green reflectance specifically proposed for LAI or CCD estimation.

2. METHODS

Field data were collected at the Vittorio Tadini experimental farm, located in the Po plain in Italy on a silt loam soil. The soil type is classified as Eutric Cambisol by FAO and it is characterized as a silt loam. Maize biophysical parameters were measured for experimental crops with different seeding dates (2005) and for ordinary maize crops (2006) grown in an area of about 10 ha characterized by local poor organic matter contents (approximately 1.5% in the topsoil). Due to these site-specific conditions an appreciable spatial variability of crops structural (LAI) and biochemical (chlorophyll) properties is regularly obtained in the considered fields. Biophysical crop parameters relevant to nutritional status and nitrogen variable rate fertilization (LAI and leaf chlorophyll concentration) have been determined by multi-temporal measures collected directly in the field assisted by DGPS positioning with sub-metric accuracy (LICOR LAI-2000 and Minolta SPAD 502) and leaf samples collection for laboratory analysis. A calibration function (r^2 = 0.83) obtained from multi-temporal analytical determination of chlorophyll a+b concentration per leaf area on leaf samples, allowed the calibration of the SPAD instrument readings.

CHRIS/Proba multi-angular data were collected over the site on June 28th 2005, using acquisition mode 5 (37 bands from 440 to 1024 nm with 17 m spatial resolution) whereas Hyperion data (220 bands from 400 to 2400 nm with 30 m spatial resolution) were acquired on June 26th 2006. Atmospheric correction has been applied to the data using the ENVI FLAASH tool (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) based on

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the MODTRAN4 algorithm. A minimum of seven pixels was considered for the determination of VIs plot average values for each 2005 CHRIS/Proba observation geometry, whereas 29 pixels with LAI and leaf chlorophyll concentration measures were selected in the Hyperion 2006 data. LAI and leaf chlorophyll concentration values were obtained by interpolation of measures collected one week before and after the 2005 multi-angular CHRIS/Proba acquisition. Measures collected the day after the Hyperion acquisition were available in 2006.

Vegetation indices, described below, that were considered in the present work included traditional and more recent slope-based indices (SR, NDVI, MSR, RDVI) and VIs incorporating green reflectance specifically proposed for LAI or canopy (CCD) chlorophyll estimation (Green NDVI, Green SR, TVI, MTVI1, MTVI2 and the newly proposed SPVI).

Slope based VIs [7] are typically ratios that focus on the contrast between the NIR and red spectral response of vegetation.

The ratio VI or simple ratio (SR) is calculated as the ratio of the reflectances in the NIR (800 nm) and red (670 nm) parts of the spectrum. The SR has been reported as the best estimator of both LAI and CCD for low LAI values [2]. The normalized difference vegetation index (NDVI), probably the most widely used VI, saturates in case of dense canopies:

$$NDVI = \frac{\rho_{800} - \rho_{670}}{\rho_{800} + \rho_{670}} \tag{1}$$

The renormalized difference vegetation index (RDVI) [8]:

$$RDVI = \frac{\rho_{NIR} - \rho_{RED}}{\sqrt{\rho_{NIR} + \rho_{RED}}} \tag{2}$$

and the modified simple ratio (MSR) [9]:

$$MSR = \left(\frac{\rho_{800}}{\rho_{670}} - 1\right) \Big/ \sqrt{\left(\frac{\rho_{800}}{\rho_{670}} + 1\right)} \tag{3}$$

have been developed in order to linearize the relationships with vegetation biophysical variables.

Indices incorporating bands in the green have proved to be effective LAI and CCD estimators. The, triangular vegetation index (TVI) [2], is calculated as the area of the triangle defined in the spectral space by the green peak, the chlorophyll absorption maximum in the red and the NIR shoulder:

$$TVI = 0.5\left[120(\rho_{750} - \rho_{550}) - 200(\rho_{670} - \rho_{550})\right] \tag{4}$$

Haboudane et al. [6] developed, for LAI estimation, the modified TVI1 by introducing a scale factor and replacing the 750-nm wavelength, sensitive to leaf chlorophyll content, by the 800-nm wavelength and the modified TVI2 by introducing a soil adjustment factor:

$$MTVI1 = 1.2\left[1.2(\rho_{800} - \rho_{550}) - 2.5(\rho_{670} - \rho_{550})\right] \tag{5}$$

$$MTVI2 = \frac{1.5\left[1.2(\rho_{800} - \rho_{550}) - 2.5(\rho_{670} - \rho_{550})\right]}{\sqrt{(2\rho_{800} + 1)^2 - (6\rho_{800} - 5\sqrt{\rho_{670}}) - 0.5}} \tag{6}$$

The MTVI1 index share the same algorithm of the MCARI1 [6] vegetation index, obtained in the same work as a modification of the modified chlorophyll absorption ratio index [4].

Haboudane et al. [6] noticed that the increase of chlorophyll concentration results in the decrease of the green reflectance, leading, therefore, to a relative decrease of the spectral triangle area. On the basis of this observation we have developed in the framework of CHRIS/Proba experimental activities the spectral polygon vegetation index (SPVI) [10]. The SPVI index is based on the general idea of the TVI but measures the area of the polygon defined in the spectral space by the green peak, the minimum reflectance in the red region, the NIR shoulder and the point of co-ordinates given by the green peak wavelength (550 nm) and the reflectance of the NIR shoulder. The SPVI index, proposed for LAI and CCD estimation, increases for decreasing green peak reflectance values:

$$SPVI = 0.4\left[3.7(\rho_{800} - \rho_{670}) - 1.2\left|\rho_{550} - \rho_{670}\right|\right] \tag{7}$$

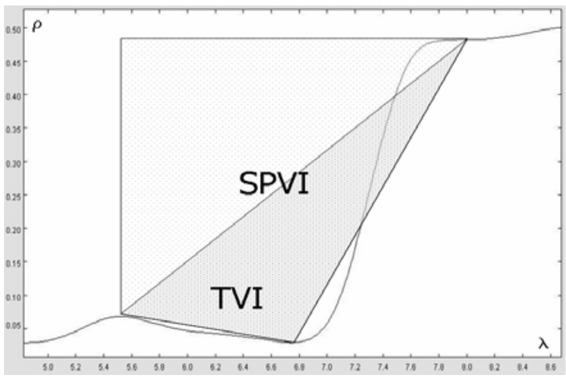

Figure 1. Graphical illustration in the spectral space of the TVI, triangular vegetation index (with 800 nm NIR wavelength) and of the spectral polygon vegetation index, SPVI

Gitelson and Merzlyac [11] found that "Green NDVI" employing a green band rather than a red band, as in the classic NDVI, was sensitive to leaf chlorophyll content. Similarly the "Green simple ratio", the ratio of the reflectances in the NIR (800 nm) and green (550 nm) parts of the spectrum, has been considered in the present work.

A sensitivity function obtained according to the method proposed by Ji and Peters [12] was used in order to compare the sensitivity to LAI and CCD of the different VIs obtained from Hyperion data. The sensitivity function is calculated as the ratio of the first derivative of the regression function – using LAI or CCD as the independent variable (x) and the VI values as the dependent variable (y) – and the standard error $\sigma_{\hat{y}}$ of the predicted value ($\hat{y}$):

$$s = \frac{d\hat{y}/dx}{\sigma_{\hat{y}}} \qquad (8)$$

3. RESULTS

3.1 VIs from 2005 directional CHRIS/Proba data

A comparison [10] among SR, TVI, MTVI1, MTVI2 and the newly proposed SPVI, addressing the relative angular dependence of VI obtained from a single multi-angular CHRIS/Proba acquisition for 2005 maize experimental parcels with different seeding dates, seem to indicate a lower sensitivity of MTVI2 and SPVI to the observation angle. In Fig. 2 the average spectra for three Chris/Proba nominal observation angles of two maize experimental plots along with the average CCD levels are reported.

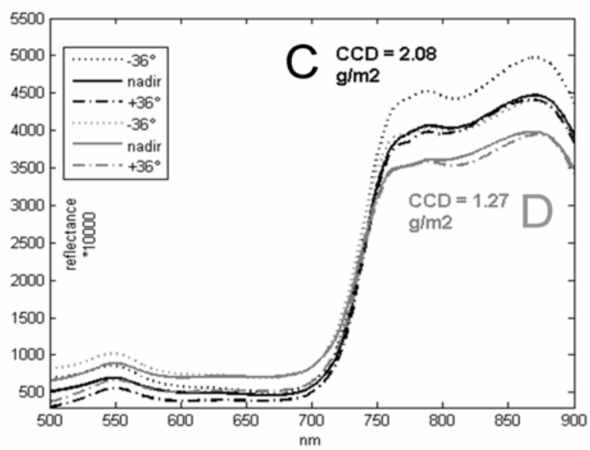

Figure 2. Average spectra for three Chris/Proba nominal observation angles and average canopy chlorophyll density (CCD) of two maize experimental plots

Maize plots B and C, planted 14 day before plots A and D, were characterized by a higher CCD mainly due to the higher LAI. The plot average VIs and standard deviation values reported in Fig. 3 reflect in general the higher vegetation biomass of maize early planting plots (B, C).

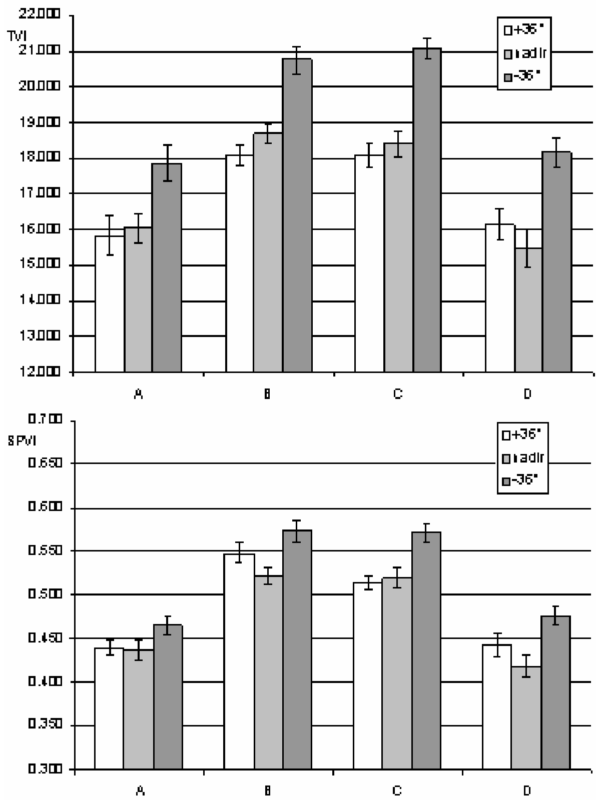

Figure 3. TVI (top) and SPVI(bottom) average and standard deviation values of maize experimental plots for +36°, 0° and -36° CHRIS/Proba along track zenith angles

However, the SR, TVI and MTVI1 indices showed a marked angular dependence with levels of variability caused for each plot by the observation geometry noticeably higher than the internal dispersion of each observation geometry and comparable to those caused by large variations of the CCD level. As shown in Fig. 3, similar TVI (and MTVI1) values have been obtained for -36° (close to the hot-spot zone) A-D plots (average LAI 3.2) and 0°, +36° B-C maize plots (average LAI 5.0). In contrast the newly proposed SPVI and the MTVI2, a ratio obtained dividing MTVI1 by a soil adjustment factor, seem to be less affected by the observation angle, with variations caused by the observation geometry for each plot in general comparable to the internal variability for each observation angle (Fig. 3).

3.2 **VIs from 2006 Hyperion data**

In Fig. 4 are reported the scatter-plots and linear fittings vs. maize canopy chlorophyll density (CCD), LAI and chlorophyll concentration per leaf area of NDVI, Green NDVI, MTVI1 and SPVI, all varying nominally in the 0-1 range. In Table 1 the values of the r^2 determination coefficient vs. maize biophysical parameters are reported for all indices considered. As shown in Fig. 4, NDVI exhibited the expected saturation over the medium-high biomass experimental conditions with low r^2 values mainly due to the flatness of the fitting line.

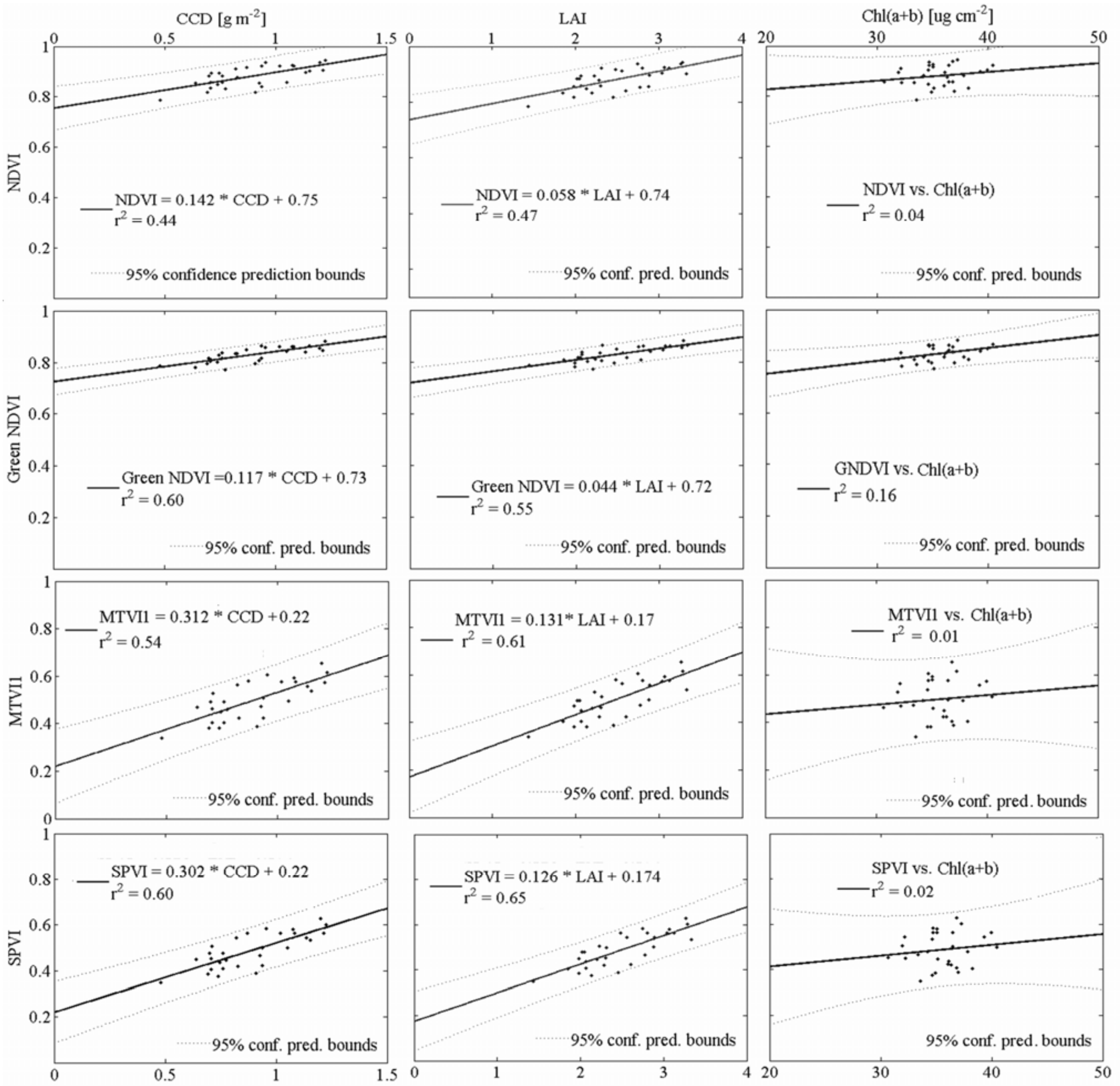

Figure 4. Scatter-plots and linear fittings of the NDVI, Green NDVI, MTVI1 and SPVI indices vs. canopy chlorophyll density (CCD - left), LAI (center) and chlorophyll concentration per leaf area (right)

Table 1. VIs r^2 determination coefficient values vs. canopy chlorophyll density, LAI and chlorophyll (a+b) concentration per leaf area (maximum values in bold characters).

VI	CCD g m^{-2}	LAI	Chl.(a+b) μg cm^{-2}
NDVI	0.44	0.47	0.04
RDVI	0.56	0.62	0.02
SR	0.45	0.46	0.04
MSR	0.45	0.47	0.04
Green NDVI	0.60	0.55	**0.16**
Green SR	**0.61**	0.56	0.15
TVI	0.47	0.55	0.00
MTVI1	0.54	0.61	0.01
MTVI2	0.51	0.56	0.02
SPVI	0.60	**0.65**	0.02

With respect to the quantitative values of the r^2 determination coefficient reported in Table 1 it should be noticed that the statistic has been obtained over the limited green biomass range of the experimental condition with data (29 selected pixels) referring to a total area of approximately 10 ha for a single date and a single acquisition. This is typically the case of the use of a timely single multi-spectral acquisition for variable-rate N prescription.

In comparison with NDVI and SR only the RDVI among slope based VIs (NDVI, RDVI, SR, MSR) showed a substantial improvement of the correlation, mainly with LAI (Table 1), and, as a consequence, with CCD. The "Green" slope-based indices (Green NDVI, Green SR) were characterized, together with the proposed SPVI, by the highest correlation levels with CCD (Table 1).

The high correlation of Green NDVI and Green SR with CCD seems to be due to an improved sensitivity to leaf chlorophyll concentration (Table 1, Fig, 4) obtained by employing a green band rather than a red band as in the classic slope-based VIs. This specific sensitivity of "Green" slope-based indices to leaf chlorophyll concentration has often been reported in the literature [11, 13]. As shown in Fig. 4, in comparison with NDVI the regression line vs. CCD of the Green NDVI is characterized by a similar asymptotic, "saturated", behaviour but also by a substantially lower error of the estimate, possibly due to an enhanced sensitivity to leaf chlorophyll.

On the contrary, the improved linearity (Table 1) of more recent VIs describing the visible-NIR spectral shape (TVI, MTVI1, MTVI2, SPVI) arise mainly from an enhanced sensitivity to LAI not affected by signal saturation over the medium biomass experimental conditions (Fig. 4 for MTVI1 and SPVI).

The newly proposed SPVI showed the highest correlation with LAI, and, as a consequence, a correlation level with CCD similar to those of Green NDVI and Green SR.

A more detailed quantification of relationship between VIs and biophysical parameters can be obtained using a sensitivity function [13] calculated as the first derivative of the regression function divided by the standard error of the dependent variable prediction (Eq. 8). In Fig. 5 the sensitivity functions vs LAI and CCD are reported for some of the VIs considered. Despite the common nonlinearity of the relationships of VIs with biophysical parameters, only linear regressions were used in the present work due to the limited biomass range of the experimental conditions. The bell shape of the sensitivity functions reported in Fig. 5 is a consequence of the use of linear regressions for all VIs considered: a constant, the slope of the regression line, is divided by the standard error of the prediction which increases moving away from the average value of the independent variable (LAI or CCD). As shown in Fig. 5 the sensitivity functions confirmed the indications of the r^2 statistic of Green NDVI, Green SR and SPVI as the best CCD estimators and SPVI as the best LAI estimator among VIs considered.

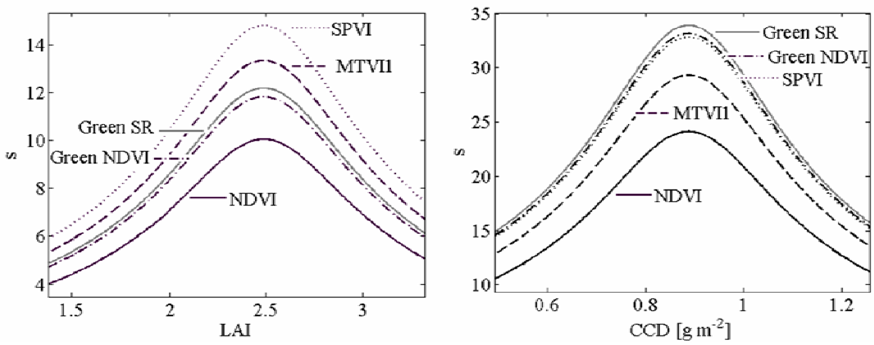

Figure 5. Sensitivity functions vs. LAI and CCD for Green NDVI, Green SR, SPVI, MTVI1 and NDVI

4. CONCLUSIONS

"Green" slope-based indices (Green NDVI, Green SR) and the newly proposed SPVI showed to be the best canopy chlorophyll density (CCD) estimators in a comparison of the sensitivity to CCD and LAI of several VIs obtained from a single Hyperion acquisition on maize crops with medium biomass conditions (LAI range 1.4 - 3.3). The improved sensitivity of Green NDVI and Green SR to CCD seems to be due to an improved sensitivity to leaf chlorophyll concentration in comparison with classic slope-based VIs.

Among classic and more recent VIs based on the NIR/red slope (NDVI, RDVI, SR, MSR), only the RDVI index showed a comparable correlation with maize biophysical parameters (mainly with LAI, and, secondarily, with CCD).

Recent indices describing the visible-NIR spectral shape (TVI, MTVI1, MTVI2, SPVI), were not affected, over the medium biomass experimental conditions, by saturation, evident for slope based VIs.

The newly proposed SPVI showed the highest sensitivity to LAI, and, as a consequence, a sensitivity to CCD comparable to those of Green NDVI and Green SR. Further work is required to test the SPVI index as a LAI and CCD estimator in different crops and soil conditions.

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