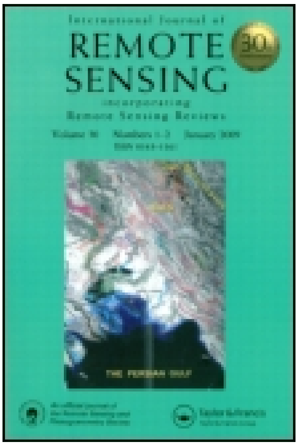

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Estimating maize ground cover using spectral data from Aqua-MODIS in Córdoba, Argentina

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Ground cover by foliage is a biophysical property of vegetation linked both to the interception of photosynthetically active radiation and to the crop transpiration rate. The spectral information provided by the Moderate Resolution Imaging Spectroradiometer on board the Aqua (Aqua-MODIS) satellite, which has a spatial resolution of 250 m, is an observation and monitoring resource that may be appropriate for estimating the ground cover of maize when plots exceed 40 ha. In this research, 10 maize plots were monitored in the central region of the province of Córdoba, Argentina, during the 2005–2006 growing season, obtaining photographic records of ground cover and soil moisture data. The normalized difference vegetation index (NDVI) of the Aqua-MODIS images showed a significant linear relationship with maize ground cover which, when the complete cycle is taken into account, is sufficient to explain 87% of the variability of ground cover, with an RMSE of 9%, a level of accuracy that increases when the crop is in the vegetative stage and the moisture conditions of the soil are less limiting. Other vegetation indices and linear mixed models were assessed. In addition to using data from the red and near-infrared channels, they incorporate information about soil conditions, but they showed no predictive advantages compared to the NDVI, resulting in simple models that explained between 77% and 87% of the variability of ground cover, with RMSE values of between 9% and 14%.

1. Introduction

The structural aspects of canopy can be evaluated through leaf area index (LAI), the fraction of absorbed photosynthetically active radiation (fAPAR), and the fraction of ground cover (%C) (North 2002; Gitelson 2004; Jiang et al. 2006). The remote estimation of these parameters has been performed using vegetation indices developed from multispectral satellite information or with field radiometers; the normalized difference vegetation index (NDVI) is the one which has been in more widespread use (Tarpley, Schneider, and Money 1984; Anderson et al. 2004; Jiang et al. 2006).

Most vegetation indices combine spectral reflectance of two or more spectral bands, usually the red (r) and near-infrared (nir). The basis of this relationship is the strong absorption of red light by chlorophyll and the low absorption of nir in green leaves (Shanahan et al. 2001). With respect to canopy, reflectance changes are higher in nir wavelengths as the crop cycle advances, due to the increase in biomass (Hatfield et al. 2008).

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NDVI presents an approximately linear increase with the increase of LAI at the start of the cycle; then, with higher values of LAI, the ratio grows asymptotically, NDVI increasing slowly with increase in LAI. Huete, Jackson, and Post (1985) observed in cotton that NDVI reaches its maximum values with ground cover of between 80% and 90%. This limited sensitivity of NDVI to LAI values >3 was demonstrated by Myneni, Nemani, and Running (1997) for six structural types of ground cover, including pastures and cereal. Particularly for maize, Gitelson et al. (2003) found that NDVI, calculated with a handheld spectrometer in the bands corresponding to the Moderate Resolution Imaging Spectroradiometer (MODIS), remained virtually unchanged with LAI values greater than 2. Rundquist et al. (2001) also observed that NDVI remained unchanged with %C over 50%, due to the fact that above this ground cover value, the red and nir bands did not show appreciable changes.

The estimation of foliage ground cover has been used for both crop monitoring and establishing crop yields. Gitelson, Kaufman, et al. (2002) indicated three basic methods for estimating %C using spectral data: spectral mixture models (Adams, Smith, and Johnson 1986; Ustin et al. 1996; Maas 2000), neural networks (Baret, Clevers, and Steven 1995), and vegetation indices. Spectral vegetation indices are indicators of temporal and spatial variations of the structure and the biophysical parameters of vegetation. Their importance has also been widely demonstrated for the monitoring and evaluation of changes experienced by different biophysical variables: %C, LAI, fAPAR, and biomass (Gitelson 2004; Liu et al. 2004). Expressions of vegetation indices assessed in this study are presented in Table 1.

Vegetation indices have limitations associated with the spectral resolution used, as the relationship between nir reflectance and ground cover percentage varies according to the phenological state of the crop (Gitelson, Stark, et al. 2002). This restricts the ability of the

Table 1. Vegetation indices (VI) and methods used to assess the status of maize ground cover under different soil moisture conditions. Córdoba, Argentina, 2005/2006 crop year.

VI or methods	Equation	Authors
NDVI	$\mathrm{NDVI} = (\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})/(\rho_{\mathrm{nir}} + \rho_{\mathrm{r}})$	Rouse et al. (1974)
EVI	$\mathrm{EVI} = 2.5[(\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})/(\rho_{\mathrm{nir}} + 6\rho_{\mathrm{r}} - 7.5\rho_{\mathrm{b}} + 1)]$	Xiao et al. (2006)
SAVI	$\mathrm{SAVI} = (1 - L)(\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})/(\rho_{\mathrm{nir}} + \rho_{\mathrm{r}} + L)$	Huete (1988)
TSAVI	$\mathrm{TSAVI} = \dfrac{\mathrm{pen}[(\rho_{\mathrm{nir}} - (\mathrm{pen}\rho_{\mathrm{r}}) - \mathrm{ord})]}{[\rho_{\mathrm{r}} + \mathrm{pen}(\rho_{\mathrm{nir}} - \mathrm{ord}) + 0.08(1 + \mathrm{pen}^2)]}$	Rondeaux, Steven, and Baret (1996)
WDRVI	$\mathrm{WDRNVI} = (a\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})/(a\rho_{\mathrm{nir}} + \rho_{\mathrm{r}})$	Gitelson (2004)
Baret	$\%C = 1 - [(\mathrm{NDVI}_{\infty} - \mathrm{NDVI})/(\mathrm{NDVI}_{\infty} + \mathrm{NDVI}_{\mathrm{s}})]^{0.6175}$	Baret, Clevers, and Steven (1995)
Maas	$\%C = (\mathrm{Rsc} - \mathrm{Rs})/(\mathrm{Rc} - \mathrm{Rs})$	Maas (2000)
Jiang	$\%C = \mathrm{SDVI} = (\mathrm{DVI} - \mathrm{DVI}_{\mathrm{s}})/(\mathrm{DVI}_{\mathrm{v}} - \mathrm{DVI}_{\mathrm{s}})$	Jiang et al. (2006)

Note references: ρ_{r}, ρ_{nir}, and ρ_{b} denote the reflectance of the red, near-infrared, and blue bands, respectively; NDVI_{∞} and $\mathrm{NDVI}_{\mathrm{s}}$ are the NDVI values for vegetation with infinite LAI and for bare ground, respectively; pen and ord are the slope and intercept of the linear relationship between ρ_{r} and ρ_{nir} for bare soil conditions (without vegetation, in this case) and under different states: wet, dry, smooth, rough; $L = 0.1$; a is a an adjustment coefficient that aims to eventually make the relation between the VI and %C a linear one; Rsc is the reflectance of the scene for a particular spectral band; Rc is the reflectance of the upper surface of the plant canopy; Rs is the reflectance of the bare ground surface; DVI is $(\rho_{\mathrm{nir}} - \rho_{\mathrm{r}})$ for bare ground ($\mathrm{DVI}_{\mathrm{s}}$) and for ground with dense vegetation ($\mathrm{DVI}_{\mathrm{v}}$), respectively.

indices to estimate %C under conditions of moderate to high ground cover. Gitelson (2004) proposed using the wide dynamic range vegetation index (WDRVI), where the weighting coefficient has a value between 0.1 and 0.2, in order to establish a linear relationship with %C. Thus, it is possible to increase the correlation between NDVI and the canopy of wheat, soybean, and maize. The sensitivity of WDRVI with moderate to high LAI values (2–6) was found to be at least three times greater than that shown by NDVI.

Many authors have proposed the use of indices that consider the effect of the soil; among others, the soil-adjusted vegetation index (SAVI) (Huete 1988), the transformed soil-adjusted vegetation index (TSAVI) (Baret, Guyot, and Major 1989), and the optimized-soil adjusted vegetation index (OSAVI) (Rondeaux, Steven, and Baret 1996). Shanahan et al. (2001) use TSAVI to analyse yield variations of maize associated with different rates of nitrogen fertilization.

Baret, Clevers, and Steven (1995) and Campbell and Norman (1998) proposed a method to derive the fraction of ground covered by vegetation from an NDVI scaled between the minimum and maximum values of the time series.

Maas (1998) developed a technique for estimating the %C of a cotton crop by minimizing the effects of shading. This technique uses a linear mixed-model from which a simple equation for obtaining %C is developed. Jiang et al. (2006) developed the scaled difference vegetation index (SDVI), in consideration of the fact that NDVI may be inadequate for inferring %C due to its non-linearity and scale effects. It is a scale-invariant index, also based on the concept of linear spectral mixing of red and nir reflectances.

Remote-sensing systems such as Terra-and Aqua-MODIS (Huete et al. 2002; Myneni et al. 2002) produce vegetation indices in an operational mode, which are used to monitor photosynthetic activity and phenological development, and to deduce structural and radiometric biophysical parameters from the vegetation of terrestrial ecosystems. These indices are an integral part of many regional biospheric models and biogeochemical cycles (Myneni et al. 2002). Two indices are generated from specific algorithms: NDVI, designated as a ‘continuity index’ because it is a continuation of the series started by the National Oceanographic and Atmospheric Administration’s Advanced Very High Resolution Ratiometer (NOAA-AVHRR), which, when Terra-MODIS was launched (in 1999), had already been running for almost 20 years (1981–1999), and the ‘enhanced’ vegetation index (EVI), with higher sensitivity for detecting differences in vegetation in conditions ranging from sparse to very dense vegetation.

As is clear from the background, there are several alternatives for determining %C from radiometric information. Some of the methods and vegetation indices were developed with spectral records obtained in the field, so that their use for determining %C from satellite data requires a particular assessment (Gitelson 2004; Jiang et al. 2006). In addition, other issues requiring an answer are: the potential to make direct use of the indices produced by the Aqua-MODIS system in a monitoring programme of maize crops; determination of which indices may be more appropriate and convenient for temporarily assessing %C; understanding the nature of the relationship between %C and the indices; how a drought scenario may affect estimates of %C produced from satellite radiometric data; and finally, to what extent the dynamics of ontogenetic development of the crop could alter the relationship between %C and the index.

The objectives of this research are: (i) generation of different vegetation indices from the spectral data of Aqua-MODIS in order to evaluate the canopy cover of maize crops in the central region of Córdoba (Argentina); (ii) comparison of the behaviour of these indices in the estimation of maize %C at the plot level, focusing on the performance of the NDVI-MODIS and EVI-MODIS indices in comparison to other vegetation indices; and (iii) evaluating the changes in the relationship between the indices and %C during the agricultural cycle and under different soil moisture conditions.

2. Materials and methods

2.1. Study region

The study was conducted in the central region of the province of Córdoba, during the 2005/2006 agricultural cycle. Ten maize plots were selected, with surfaces ranging between 40 and 100 ha (Figure 1). In all plots, cultivation was done by direct seeding, with a distance between plant rows of 50 cm and a density of 8 plants m^{-2}. The soils of the region correspond to the orders Mollisol, Alfisol, and Entisol (Jarsún et al. 2006).

2.2. Canopy cover data (%C)

Periodic photographic records of crop ground cover were obtained (records of up to eight dates per plot), covering the entire evolution of the crop, from planting to harvest. On each date, five photographs were obtained in different sectors of the plot. Estimates of %C were made from digital photographs taken perpendicularly to the ground, between two adjacent rows of plants, from a height of 2.5 m, approximately, with a Sony Cybershot camera. The photographic images were analysed with a supervised classification algorithm of maximum likelihood to identify areas with and without vegetation cover (Ovando et al. 1999; Rodriguez et al. 2000). Resulting %C values from the five photographs were averaged and the standard deviation values were obtained.

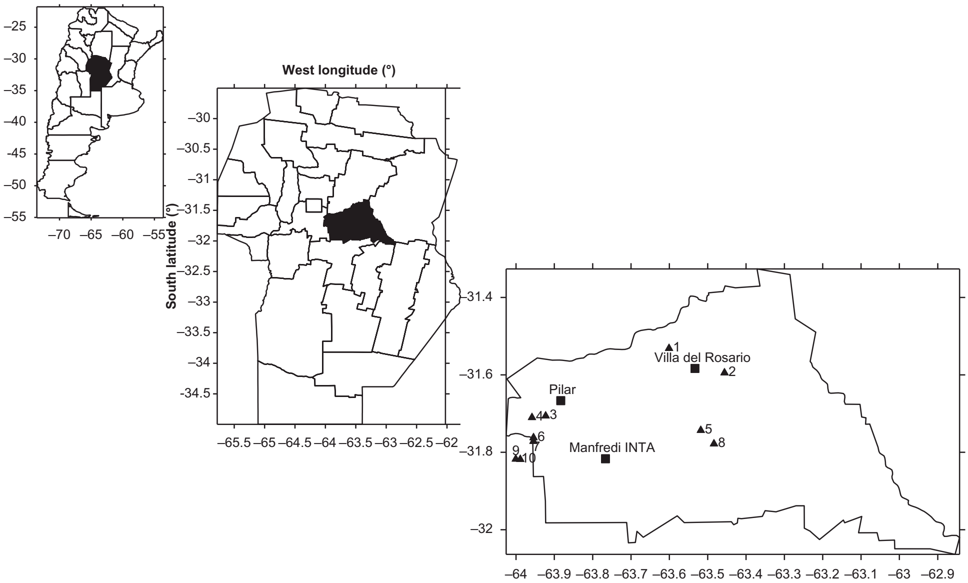

Figure 1. Study region with the geographic location of the 10 monitored plots in the centre and west of the Rio Segundo Department, Córdoba, Argentina, 2005/2006.

There is no proven method for obtaining the true values of %C over a plot in the field with certainty. Nevertheless, there are several ways to assess the accuracy of ground cover estimation methods, for example, testing against artificial plots with known %C or intercomparison between procedures (Chen et al. 2010). In this sense, the maximum likelihood method is among the best for estimation of ground vegetation cover with the use of broadband digital cameras, having been used to estimate the physiological age of sugarcane (Mobasheri et al. 2008).

The method used was developed by Rodriguez et al. (2000), who found that the leaf area estimated was equivalent to that measured by an integrative instrument, with a linear regression among them ($R^2 = 0.99$; $p < 0.001$) and mean percentage error regarding the observed values of –3.62%, with a standard deviation of 5.14%. The photographs had a pixel resolution of 1280 × 960 = 1.2 megapixels (ultra VGA, UVGA), with an average spatial resolution of 13.5 px cm^{-1}.

The use of photographic images in the field to determine maize ground cover, covering an area of about 3 or 4 m^2, is clearly problematic with respect to the MODIS pixel scale of 250 m. However, the correlation and regression analysis is supported both methodologically by the marked uniformity of corn crops and by the experimental results of Guindín-García et al. (2012), who estimated green LAI (GLAI) in corn using MODIS 8- and 16-day composite periods with 250 and 500 m resolution. In this case, the correlation with GLAI values in three sites with areas ranging between 48.7 to 65.4 ha, from destructive samples collected from a 1 m linear row section in six plots for each site, obtained R^2 equal to or higher than 0.7 and RMSE between 0.50 and 1.07 $\text{m}^2\ \text{m}^{-2}$. Also, Yi et al. (2008) estimated wheat LAI from daily and 8-day composite MODIS reflectance values with 500 m in a large region of several kilometres where the cropland was almost homogeneously covered by the same wheat crop. LAI was measured in three 1 m^2 blocks selected randomly. For daily and 8-day composite Collection 5 data from Aqua, similar to those used in this study, all vegetation indices showed significant correlation with LAI. Sakamoto, Gitelson, and Arkebauer (2013) used an 8-day time series of 250 m and 500 m MODIS surface reflectance data obtained by the Terra and Aqua satellites. With these reflectances, these authors calculated WDRVI (the same as used in this work) that correlated with corn GLAI. They showed that the slope of the lineal best function of the relationship between MODIS WDRVI and GLAI in a rainfed field was lower than that in an irrigated field. Both functions yielded R^2 values greater than 0.9.

2.3. Soil moisture data

Soil moisture was measured gravimetrically at depths of 0.05, 0.20, 0.40, and 0.80 m. Drill extractions were performed at two sites in each plot, between plant rows, totalling up to eight sampling dates per plot during the cycle. Two groups were identified: Group 1 (five plots), with soil moisture values above the set average, and Group 2 (five plots), with values below average.

2.4. Satellite data

We used the MYD13Q1 product derived from the satellite/sensor system Aqua-MODIS, which is provided by the EROS Data Center (EOS 2005). This product consist of blue (b), r, and nir reflectances, centred at 469, 645, and 858 nm, respectively. These images have a spatial resolution of 250 m for r and nir, and 500 m for the b channel, and correspond to the composition of a 16-day period.

Also, this product has two vegetation indexes (VI): the standard NDVI and an EVI with improved sensitivity for high-biomass regions and improved vegetation monitoring, through a de-coupling of the canopy background signal and a reduction in atmospheric influence. This VI uses MODIS surface reflectances, corrected for molecular scattering, ozone absorption, and aerosols, and adjusted to nadir with use of a BRDF model, as input to the VI equations (Huete et al. 2002).

We considered the full set of images from September 2005 to May 2006. Accurate identification of the plots in the Aqua-MODIS images was performed using a Landsat 7 TM image (Scene 229–82) from 28 November 2005.

2.5. *Vegetation indices*

The variability of maize ground cover was estimated from the vegetation indexes and methods given in Table 1.

In computing TSAVI and SDVI, corrective functions were incorporated in relation to regional soil conditions. The ground line was obtained from the information of the r and nir bands, using the three lowest values of NDVI from each plot throughout the entire period with available data (between October 2004 and May 2006). Figure 2 shows the

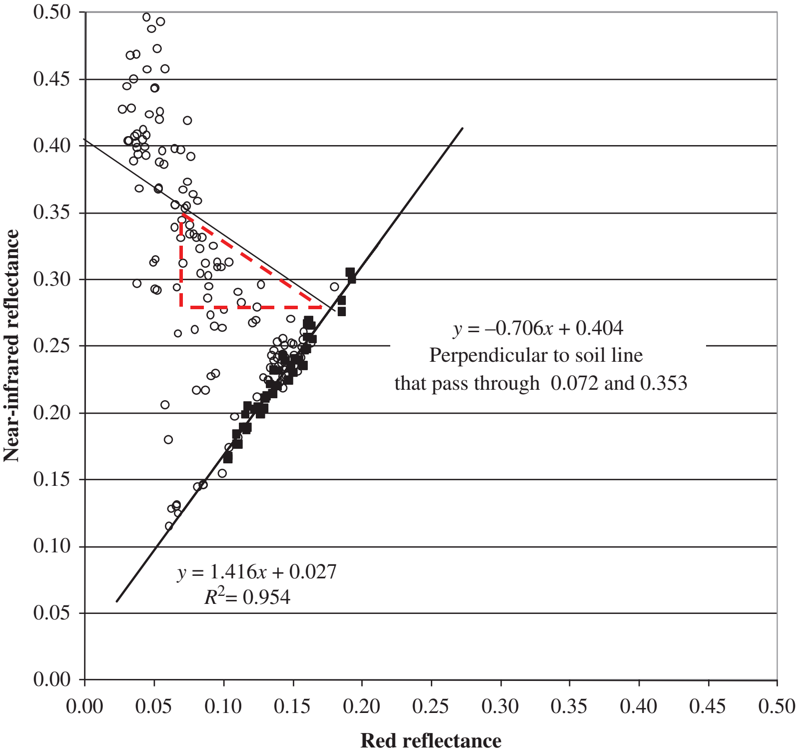

Figure 2. Scatter plot of the reflectance values for red and near-infrared channels (o) during the 2005/2006 maize cycle, and of the reflectance values of ground without vegetation (▪) used to calculate the ground line, in Córdoba, Argentina. The hypotenuse of the triangle is the distance (DVI) representing the presence and abundance of vegetation.

dispersion of r and nir values corresponding to the observed condition of %C, for the purpose of illustrating Jiang's method. It includes the linear fit corresponding to the ground line and the one perpendicular to it that passes through the point (0.072–0.353). The hypotenuse of the triangle below the perpendicular line corresponds to the distance that determines the presence and abundance of vegetation, in order to obtain the fraction of the vegetation according to SDVI.

2.6. Statistical comparison of vegetation indices

The accuracy of the indices was evaluated by the coefficient of determination (R^2) and the coefficient of concordance (d) (Willmott 1981). The statistical significance of the adjustment functions was evaluated with an error probability of less than 1% ($p < 0.01$). The root mean square error (RMSE), mean absolute error (MAE), and mean deviation error (MBE) were also calculated (Anderson et al. 2004).

3. Results and discussion

Figure 3 presents the evolution of maize crop ground cover over the 2005–2006 cycle in four selected plots. The curves of the temporal variation of %C show differences in the maximum and amplitude values in each plot. In plots 1 and 2 there was higher growth than in the others, with values of %C that remained above 80% for about 40 days; the more pronounced differences occurred in the second half of the cycle, 100 days after planting. Plots 3 and 6 are those in which planting occurred earlier, and both were affected by water stress by about 100 days after sowing; %C declined rapidly and then stabilized when stress disappeared.

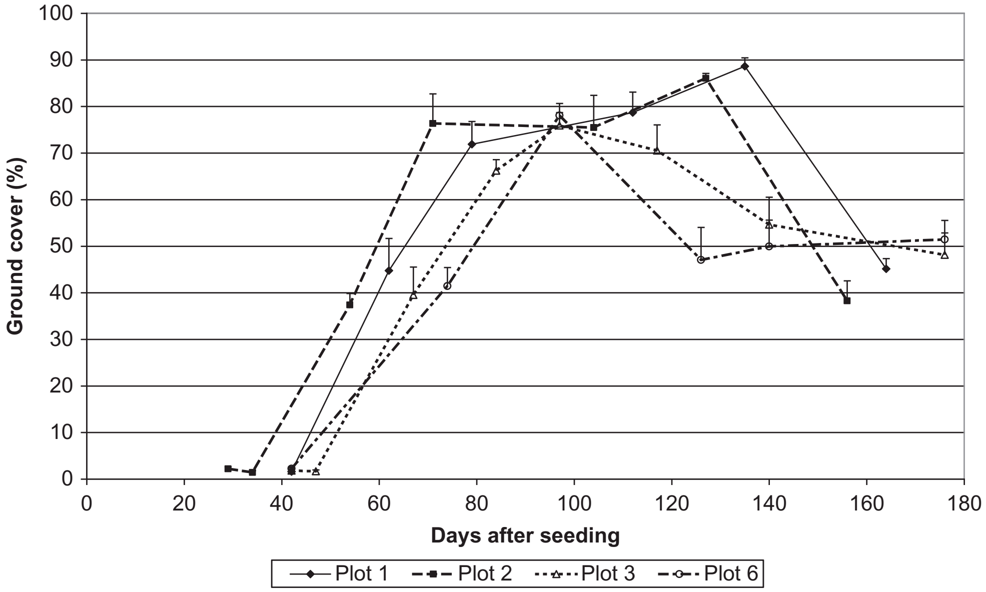

Figure 3. Ground cover (%C) variation in four maize plots during the 2005/2006 crop year in Córdoba, Argentina. The vertical bars above the mean value indicate the standard deviation.

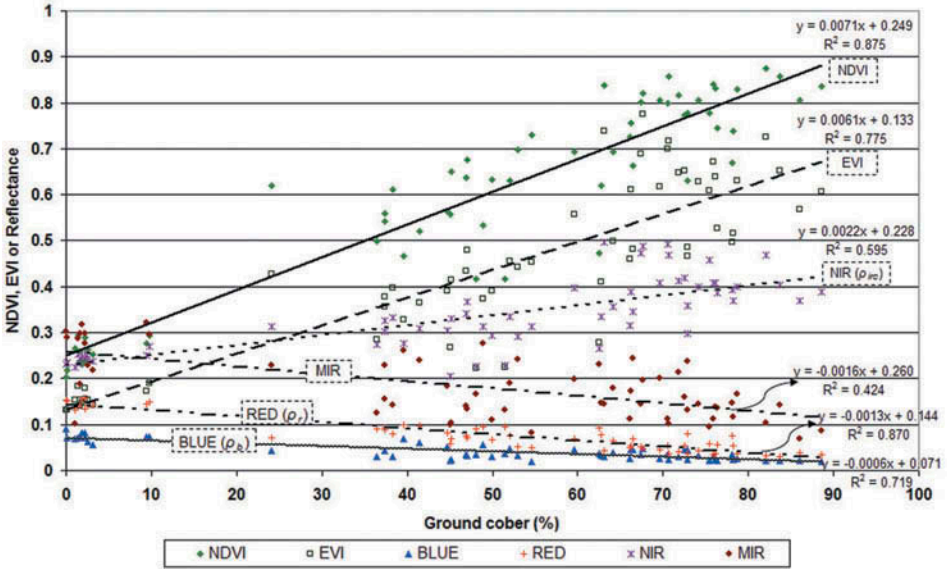

Figure 4. Relation between the vegetation indices of the Aqua-MODIS satellite (NDVI and EVI) and the reflectance of the blue (BLUE), red (RED), near-infrared (NIR), and mid-infrared (MIR) bands, with respect to ground cover (%C) in 10 maize plots during the 2005/2006 crop year in Córdoba, Argentina.

Figure 4 shows the ground cover recorded on the field for the entire set of maize plots and the different vegetation indices and Aqua-MODIS channels. NDVI describes the observed variation in %C more precisely than EVI, and has the highest coefficient of determination (0.87; $p < 0.01$). EVI has a tendency toward saturation for higher values of %C. This less satisfactory behaviour could be explained by the lower spatial resolution (500 m) of EVI compared with that of NDVI (250 m), as a result of using blue channel reflectance.

The red band exhibited an inverse relationship with respect to %C, denoting the increased absorption of solar energy for that wavelength as the leaf area of the crop increased. Also, this optical channel alone explains 87% of the variability of %C, although its dynamic range is small and is between 2.7% and 18.0%. The nir band showed the opposite behaviour, since reflectance increases as the crop soil ground cover increases, due to the greater dispersion of solar energy that causes a more developed vegetative structure and larger leaves. Its dynamic range was broader, between 11.5% and 49.6%, similar to the behaviour reported by Hatfield et al. (2008). For both bands the relationships are linear up to a maximum of 90% ground cover, in contrast to what was observed in maize by Rundquist et al. (2001), who showed unchanging behaviour for these bands above 50% ground cover, probably due to using reflectance data obtained from a manual radiometer.

Figure 5 shows that the relationship between NDVI and %C changes its slope when considering increasing or decreasing values of maize ground cover during the cycle. The relationship is similar to that shown in Figure 3, but using NDVI as the independent variable and discriminating cases into two groups: before and after maximum canopy cover. The linear relationship achieves greater accuracy when the

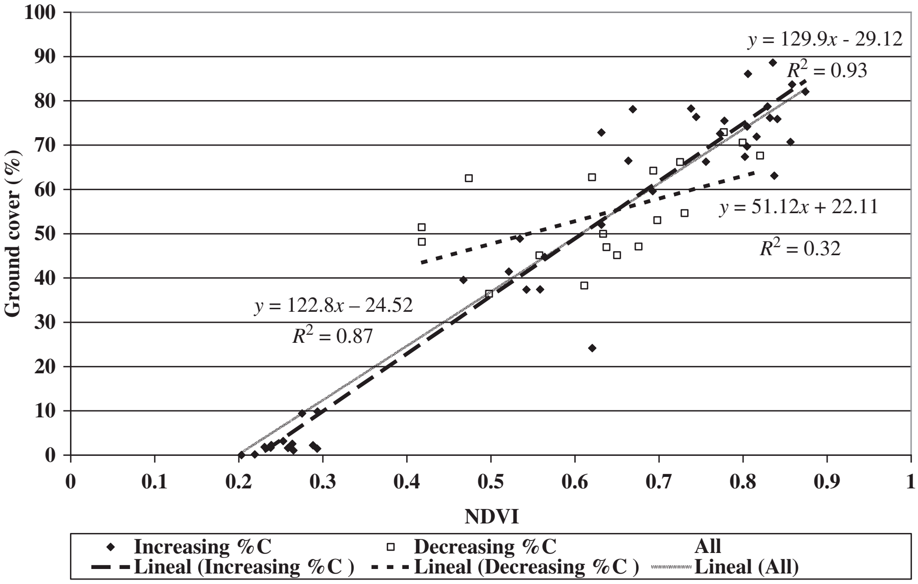

Figure 5. Relation between maize ground cover (%C) and NVDI, discriminating the values before and after the maximum ground cover for the 2005/2006 crop year in Córdoba, Argentina.

crop is in the increasing stage of its growth and development cycle (R^2 = 0.93, $p <$ 0.01). Once maize exceeds the maximum values of %C and enters the senescence period, towards the end of the cycle, the adjustment becomes less (R^2 = 0.32, $p <$ 0.01). The decreased sensitivity of the NDVI signal to detection of changes in ground cover when corn is approaching the end of the cycle highlights its limitation in regard to the use of this vegetation index to estimate biological properties associated with the chlorophyll content of vegetation, in concordance with research papers such as Viña and Gitelson (2005).

3.1. Influence of soil moisture in the estimation of %C

Water deficiency is a very common situation in rainfed maize production (Sadrás and Calviño 2001), which is why it is important to establish how this contingency can modify the relationship between NDVI and %C. In Figure 6, plot discrimination by soil moisture allowed the definition of a coefficient of determination (R^2) of 0.94 ($p <$ 0.01) for those with higher moisture during the cycle, and a lower R^2 of 0.83 ($p <$ 0.01) for the plot group that experienced water stress. The negative influence of water deficiency on foliar growth and the canopy structure of maize alters the radiometric signal in the visible and infrared spectrum bands and explains the variation experienced by the index (Grant et al. 1989; Earl and Davis 2003).

3.2. Comparison of vegetation indices

Statistical evaluation of the behaviour of the indices is presented in Table 2. These results confirm that none of the methods used for estimating %C in maize was better than NDVI.

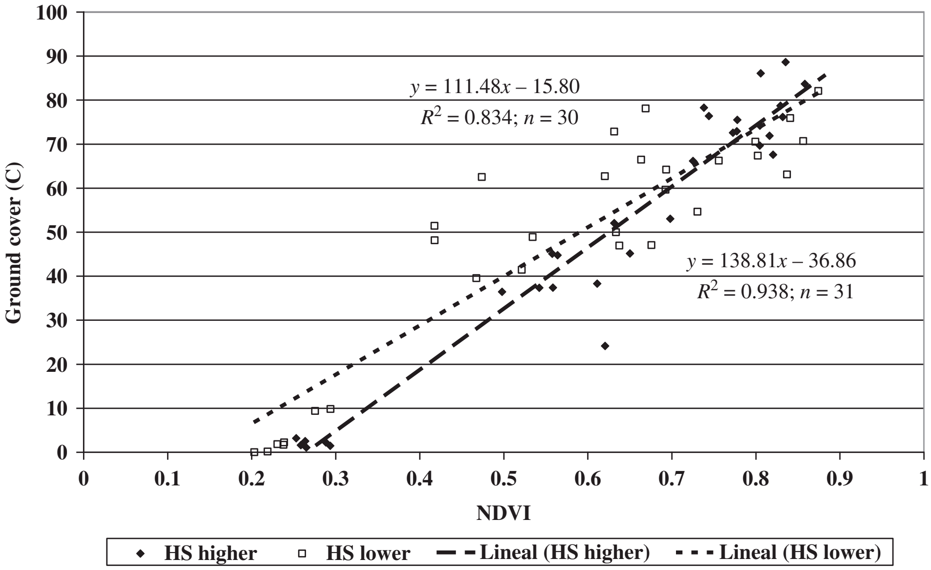

Figure 6. Relation between NDVI and maize ground cover in Córdoba, Argentina, during the 2005/2006 crop year for different soil moisture (HS) conditions. Average soil moisture of each plot is above (HS higher) or below (HS lower) the overall average.

Table 2. Evaluation of estimation models for maize ground cover from Aqua-MODIS data under different soil moisture conditions during the 2005/2006 crop year in Córdoba, Argentina.

	NDVI	EVI	SAVI	TSAVI	WDRVI	Baret	Maas	Jiang
R^2	0.875	0.775	0.864	0.862	0.869	0.841	0.808	0.789
d	0.964	0.929	0.961	0.960	0.963	0.952	0.941	0.934
RMSE (%)	9.8	13.1	10.2	10.3	10.0	11.6	13.4	14.1
MAE (%)	7.1	10.6	7.7	7.7	7.4	8.3	9.9	10.3
MBE (%)	−0.0007	0.0003	0.0001	−0.0015	0.0001	3.14	0.126	1.017

Note: R^2, coefficient of determination between the observed and estimated values; d, Willmott concordance index (1981); RMSE, root mean square error; MAE, mean absolute error; MBE, mean deviation error.

Given that the processed radiometric data generally involve the use of contrast between the red and infrared bands, the high coefficients of determination obtained, between 0.77 and 0.87 in all cases, support the theory behind the use of this spectral information for representing the existence, status, and vigour of vegetation.

The coefficient d reveals that in all indices there is a high concordance between measurements of %C and their corresponding estimates, with very high values between 0.93 and 0.96. Also, in all cases non-systematic or random errors predominate, indicating that the contribution of the index to the total error is rather low. These results support the suitability of directly using NDVI provided by the Aqua-MODIS satellite in order to monitor the ground cover of maize crop. This simplifies the methods related to data processing and avoids the need to use any other type of complementary information.

The analysis of RMSE values shows that NDVI also presents the best performance in the estimation of %C, followed by WDRVI. In general, the set of evaluated indices and methods presents an RMSE ranging between 9.8% and 14.1%.

There is a general trend in all methods to underestimate %C for ground cover values between moderate and high. The scaling methods (Baret, Maas, and Jiang models) produce an underestimation of %C because they present the highest MBE values. The indices that take into account the soil factor (SAVI and TSAVI) did not show better results than NDVI, probably due to the uniformity of the soil type and the stubble ground cover shown on the plots, all planted by direct seeding and under very similar handling conditions.

The R^2 value obtained for maize in this work (0.81) using the method of Maas (2000) is similar to that obtained for cotton by this author (0.83) with LANDSAT data. This method has an important theoretical basis and is a robust estimation alternative that takes into account changes in soil conditions, lighting, time of scene, etc. Furthermore, the appropriate degree of accuracy and consistency achieved makes the method of Maas (2000) a particularly attractive alternative.

Jiang et al. (2006) present a comparative analysis of the performance of different methods for deducing the vegetation fraction from surface reflectance data. The index developed by these authors achieved the lower RMSE (7.11%), followed by the method of Baret, Clevers, and Steven (1995), with 8.28%. The results of these studies, albeit with slightly higher RMSE (14.1%) for Jiang and 11.6% for Baret, support the use of radiometric information from Aqua-MODIS for estimating %C.

Gitelson (2004) developed the wide dynamic range vegetation index, WDRVI (see Table 1), to estimate %C in maize and other crops. Using hyperspectral data from a portable narrowband radiometer, he proposed a value of 0.1–0.2 for the weighting coefficient '*a*', because it increases the correlation with vegetation fraction by linearizing the relationship for typical wheat, soybean, and maize canopies. By using MODIS data, the '*a*' coefficient that produced the best fit was 0.65, but the correlation with ground cover here is slightly inferior to the field data of Gitelson (R^2 = 0.87, similar to NDVI).

4. Conclusions

Both NDVI and EVI from MODIS, with a spatial resolution of 250 m, are reliable and appropriate for the operational satellite monitoring of maize canopy cover evolution at the plot scale. However, the performance of NDVI in estimating this property was more accurate than EVI, probably because of the original lower resolution of the blue channel (500 m) used in calculating EVI.

The best behaviour of NDVI could be explained because the reflected red energy decreases with plant development due to chlorophyll absorption within actively photosynthetic leaves and, the reflected nir energy, on the other hand, will increase with plant development in healthy and turgid leaves; and also, due to its 'ratioing' properties, which cancel out a large proportion of signal variations attributed to calibration, noise, and changing irradiance conditions from changing sun angles, topography, clouds/shadow, and atmospheric conditions.

EVI behaviour is related to the spatial resolution of the spectral data it uses (particularly from the blue channel) and the size of the plots analysed. The methods using linear mixing did not show better ground cover estimates, but they are still general alternatives to be considered, as they have a better physical basis and their performance was acceptable.

The ability to estimate %C from satellite NDVI can be improved to the extent that one has available complementary information on the phenological development of the crop and on the moisture conditions of the soil during the cycle. The highest coefficients of determination for the relationship were obtained when the crop was in the vegetative growth period (discarding the %C values later than the maximum), and under conditions of greater water availability in the soil. In this scenario, none of the vegetation indices used for estimating %C in maize produced better results than NDVI.

The canopy cover estimation from digital photographs is a simple field method and it was shown here that this biophysical signal can be reproduced accurately by MODIS data at plot level. However, further tests across a broader range of biome types will be needed to quantitatively confirm this finding.

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