Anais da

Academia Brasileira de Ciências

MCMXVI

Vol. 69, Nº 4, 1997

Wheat Development Evaluated by Remote Sensing Using Two Vegetation Indices

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Manuscript received on April 9, 1996; accepted for publication on April 9, 1997
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ABSTRACT

Remote sensing techniques, such as vegetation indices, can be used to study crop development. Here, two of such vegetation indices (NDVI – normalized difference vegetation index and SAVI – soil adjusted vegetation index) were evaluated for deriving biophysical variables of wheat through its development. Two viewing zenithal angles are tested as additional influencing factors. Implications of reflectance derived from field radiometric measurements in the intervals of two Thematic Mapper (TM) bands (red and near infrared) on the vegetation indices are discussed. It is shown that the TM4 (near infrared band) reflectance has much more influence on the SAVI than on the NDVI. When the viewing angle changed from 0 to 30 degrees the correlations between VIs and biophysical parameters decreased for TM3 and NDVI; and the changes of those correlations for TM4 and SAVI were not conclusive. The correlations between agronomic variables and the SAVI or NDVI were better than those correlations obtained with single TM3 but not with single TM4 band.

Key words: remote sensing, vegetation indices, wheat, NDVI, SAVI, reflectance.

INTRODUCTION

Vegetation is an important component in the Earth environment. It is in between the soil and the atmosphere and many physical processes take place in the vegetation environment. Except for water, ice and desert environments, vegetation is the most widespread natural cover of the Earth. Thus, it is an important component in remote sensing studies. In addition to the monitoring process, there is a great deal of interest in the evaluation of some biophysical vegetation variables through the use of individual bands, vegetation indices (VIs), or by applying other models or transformations, such as mixture models. Employment of vegetation indices (VIs) is a simplified process, as their making from the original radiometric data or from satellite images is, in general, a non complex procedure.

The most extensively used VI is the NDVI (normalized difference vegetation index, eq. 1) (Jackson *et al.*, 1983). It is largely used for building global databases based on data from the AVHRR (Advanced Very High Resolution Radiometer) sensor on board of the NOAA (National Oceanic and Atmospheric Administration) satellites (Huete *et al.*, 1994). This device has channels in the visible and near infrared, from which the NDVI can be built.

$$NDVI = (NIR - Red) / (NIR + Red) \qquad (1)$$

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where,
NIR = near infrared reflectance
Red = red reflectance

However, NDVI relationship to biophysical variables has presented some constraints, such as calibration, saturation at relatively low vegetation biomass values, and influences of soil, atmosphere, and viewing and illumination conditions. In order to overcome some of the NDVI weakness other VIs have been developed seeking basically to reduce one or more of those problems (Wiegand *et al.*, 1991). One of these VIs is the SAVI (soil adjusted vegetation index, eq. 2; Huete, 1988), which was basically designed by introducing two constants in the original NDVI equation (eq. 1), leading to the following SAVI equation:

$$SAVI = 1.5\,(NIR - Red) / (NIR + Red + 0.5) \quad (2)$$

With these changes, SAVI was expected to be less sensitive to soil background effects.

Another parameter to be taken into account in the analyses related to the evaluation of biophysical variables through remote sensing is the viewing angle influence on these relationships. This issue is important in function of the availability of sensor systems with off-nadir imaging capability, such as the French satellite SPOT or even some systems with large or very large field of view, e.g., AVHRR/NOAA and the WFI/CEBERS (Wide Field Imager/China-Brazil Earth Resources Satellite). The influences of such viewing conditions on the VIs need further evaluation.

It is well known that generally NIR has higher penetration within the canopies than red wavelengths. Both VIs studied here are composed by these two wavebands. The basic premise of this paper is that when relating spectral and biophysical variables, the performance of each individual band will be reflected in those relationships. The objectives of this paper are twofold. It is sought a better understanding of the spectral behavior of wheat along its development cycle, and an evaluation of two vegetation indices and their behavior as a function of some biophysical variables and of viewing angle variations.

MATERIAL AND METHODS

An experiment with irrigated wheat (*Triticum aestivum* L.) was set up in an experimental station at Campinas, SP, Brazil (47°5′W, 22°5′S), during the 140-261 Julian days, in 1991. The soil was an oxisol (Latossolo Roxo) (Oliveira & Menk, 1984), derived from basic eruptive rocks, with low albedo (around 0.12). The IAC-24 wheat cultivar was sowed mechanically in a row spacing of 17 cm. The rows were oriented NE-SW (48°E), and a border of 10 rows was left in the front and in the back of the experimental field. In each field campaign for data collection, 20 of the 257 rows left were chosen to be the center of the sampling points (Almeida Jr., 1993).

TABLE I
Field campaigns for data collection.

Radiometric campaign	Date (Julian day)	Feeks and Large
1	6/12/91 (164)	4.
2	6/26/91 (178)	7.
3	7/2/91 (184)	9.
4	7/17/91 (199)	10.
5	7/25/91 (207)	10.4.
6	7/30/91 (212)	10.5.1.
7	8/15/91 (228)	10.5.4.
8	8/20/91 (233)	11.2.
9	9/4/91 (248)	11.3.
10	9/17/91 (261)	11.4.

There were 10 field compaigns for collecting biophysical and radiometric data (Table I). Thus it was possible to characterize the four main wheat phenological stages. These phenological stages could be well characterized following the Feeks and Large scale (Large, 1954; Scheeren, 1986). According to this scale, values from 1 to 5 correspond to the tillering stage (from one shoot to leaf sheaths strongly erected), values from 6 to 10 correspond to stem extension, values from 10.1 to 10.5 correspond to heading (ear production/flowering), and the stage 11 corresponds to the ripening.

The radiometric measurements were done using the spectroradiometer Spectron SE-590[1] over 20 sampling points randomly selected for each radiometric campaign. Because the angular field of view (FOV – are defined by the view angle of the spectroradiometer, and equal to 15°) was fixed, as long as the crop grew along the cycle the height of the instrument had to be adjusted in order to keep the viewing area (corresponding to the top of the canopy) nearly constant. This adjustment was done four times along the entire cycle. However, since the wheat height was measured in each field campaign it was possible to evaluate the effective FOV at each specific date.

Radiometric measurements were done at zenith angles of 0° (nadir) and 30° off nadir (forward scattering). In the forward scattering, the radiometer is positioned in the opposite direction to the incidence of the sun beam. All radiometric measurements were done before noon (10-12H). In each sampling point two measurements on the target were done in order to minimize errors, and one on a barium sulfate reference plate. From these measurements it was derived the bidirectional reflectance factor (BRF) for each sampling point and for each viewing angle. BRF can be defined as the ratio between the spectral radiant flux of a studied sample and the spectral radiant flux of a reference material, both measured in the same viewing and illumination conditions (Nicodemus *et al.*, 1977). Later, these BRFs obtained in narrow bands (almost continuous wavelengths) were weighted for the equivalent Thematic Mapper (TM) bands 3 (red, TM3) and 4 (near infrared, TM4) in order to generate the vegetation indices.

The main biophysical parameters measured during the field campaigns were the Percent Soil Cover, Leaf Area Index (LAI), Leaves Dry Matter Weight (LDW), Leaves Dry Matter Weight Adjusted for the FOV (LDWA)[2], and Plant Height.

[1]Neither INPE nor the authors suggest or recommend any equipment. The explicit indication in this case is only for the better understanding of the reader.

[2]LDWA is the leaves dry weight corrected for the radiometer effective changing FOV area at the top of the canopy ($g.m^{-2}$).

These measurements were done for the plants included into the field of view (FOV). The percentage of vegetation cover was evaluated using 35 mm photographic pictures. Determination of leaf area inside the FOV was based on the existing relation between leaf area and dry weight (Daughtry, 1990). For each field campaign, three from the 20 sampling points were randomly chosen and for these points a sub-sample of 30 plants was collected and defoliated. These detached leaves had their area measured in the leaf integrator Li-cor 3100[1]. The leaves of these sub-samples had their dry weight determined after at least 24 hours in forced draught oven. The remaining leaves of these three samples as well as of the remaining 17 sampling points were oven dried also. From the relationship between the leaf area of the three points and their respective weights it was possible to estimate the area of the remaining samples. The leaf area index (LAI) was determined by dividing the total one-side leaf area of each point by the FOV area at 0°. The leaves dry matter weight adjusted for the FOV (LDWA) was calculated by dividing the leaves dry matter weight by the FOV area at that respective date.

RESULTS AND DISCUSSION

Crop development was normal, as we can see in Figure 1. In general, the wheat development begins with a fast production of phytomass and leaf area. There is a close graphic relationship between LAI and leaves dry matter weight (LDW).

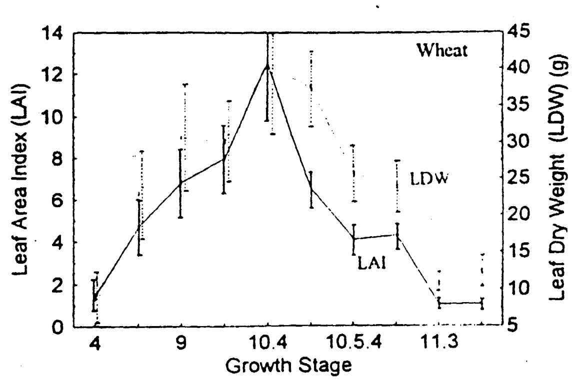

Fig. 1 — Leaf area index (LAI) and leaf dry weight (LDW) along the wheat development as a function of phenological stages.

TABLE II

Correlation coefficients (r) between biophysical and spectral variables for wheat. ND and SA are NDVI and SAVI, respectively; and the suffix 0 and 30 means viewing angles of 0° and 30°, respectively. r values greater than 0.60 are significant at the significance level of 0.05.

	LDW	LDWA	TM3_0	TM3_30	TM4_0	TM4_30	ND_0	ND_30	SA_0	SA_30
LAI	0,92	0,97	–0,55	–0,46	0,90	0,90	0,70	0,67	0,86	0.86
LDW		0,90	–0,60	–0,51	0,98	0,92	0,79	0,75	0,95	0.92
LDWA			–0,50	–0,39	0,91	0,96	0,68	0,64	0,85	0.88
TM3_0				0,98	–0,61	–0,55	–0,96	–0,97	–0.80	–0.80
TM3_30					–0,52	–0,42	–0,91	–0,93	–0.72	–0.70
TM4_0						0,94	0,79	0,75	0,96	0.94
TM4_30							0,73	0,68	0,90	0.94
ND_0								1,00	0,93	0.92
ND_30									0,90	0.98
SA_0										0.89

From these basic relationships for the biophysical parameters it is possible to derive some relationships with radiometric spectral variables. In order to facilitate the Table II shows the correlation between biophysical and spectral data. Field reflectance in TM4 band is more correlated to the biophysical parameters LDW, LAI and LDWA than the TM3 band. This occurs because TM3 (red) reaches the asymptote faster than TM4 (near infrared), mainly due to the high absorption of the TM3 electromagnetic radiation which occurs in the first leaf layers. The TM4 band, in function of its higher penetration capability into the lower leaf layers, and because it has more reflection and transmission within the canopy, carries additional information from the lower layers as well.

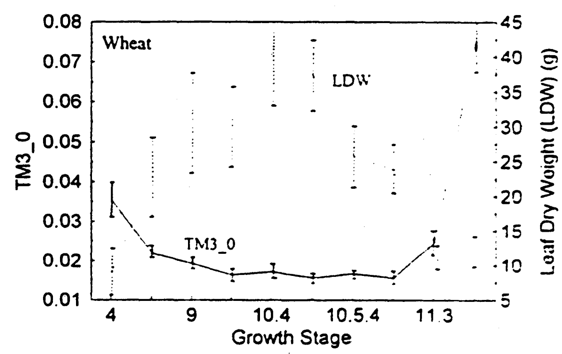

Fig. 2 — Simulated TM3 band (nadir) reflectance (red) and leaves dry matter weight (LDW) along the wheat development.

Figure 2 depicts the wheat reflectance in TM3 band along its development stages. TM3 reflectance levels are low, and remain this way during most of the crop cycle, with a steep increasing at the end of the cycle, mainly due to the decay of foliar pigments responsible for energy absorption. Although there was some variation in LDW, one cannot observe a good fitness of TM3 band to this biophysical variable. This is stressed by a correlation coefficient of –0.60.

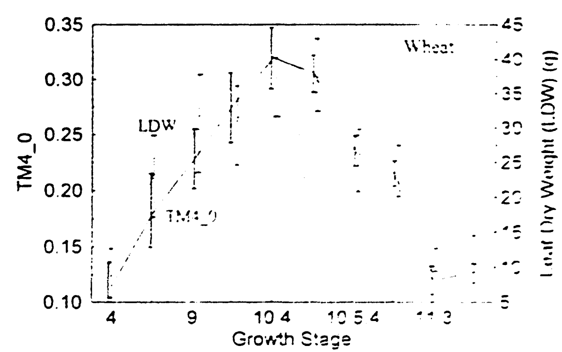

Fig. 3 — Simulated TM4 band (nadir) reflectance (near infrared) and leaves dry matter weight (LDW) along the wheat development.

On the other hand, TM4 spectral band had a strong fitness to LDW (Fig. 3), with a correlation coefficient of 0.98. This means that in this experiment the TM4 band was a good estimator of this important biophysical parameter. This can be attributed mainly to the high interaction of the near infrared radiation within thicker portions of the canopy. It can be observed in Table II that the correlation between TM4 and LAI (0.90) is lower than with LDW (0.98), for nadir viewing. This can be explained by the fact that during the crop growth there is a correspondence between leaf area and leaf weight changes. However, due to the LAI formulation, in which the denominator is the plant projection and the numerator is the leaf area, there is not always a so close correlation between leaf area and LAI growth as between leaf area and weight changes.

The design of vegetation indices is intended to improve the remote sensing relationship to biophysical variables or even to decrease the remote sensing sensitivity to some external factors such as soil and viewing and illumination geometries. Besides, the fact that VIs have more than one spectral band in their formula could be a positive factor, since more spectral information would be embedded into just one remote sensing spectral parameter (Epiphanio & Formaggio, 1991).

However, Table II shows that both the NDVI and the SAVI (see the nadir viewing first) present greater correlation coefficients with biophysical variables when compared to TM3 single band, and lower correlation coefficients when compared to TM4. That is, when one couples information from two single bands into the VIs it could not always be taken for granted an improvement in their relationships with biophysical variables. Actually, in relation to the TM4 single band, both VIs showed lower correlation coefficients for those relationships. This means that, in some situations in which the effects of atmosphere and soil are reduced, as in this experiment, the use of single bands could be preferred instead of vegetation indices. However, when soils and atmospheric effects should be taken into account, it has been demonstrated that VIs are more effective than single bands (Cihlar *et al.*, 1994; Gutman *et al.*, 1994; Gutman & Ignatov, 1995).

Another aspect to be observed is that the correlations between biophysical variables and the VIs are higher for SAVI than for NDVI (Table II). As showed by Epiphanio & Huete (1995), for alfalfa, SAVI is more sensitive to near infrared (TM4) than for red (TM3) radiation, and the inverse is true for NDVI. For wheat, this relationship seems to be confirmed, since the correlation between TM4 (nadir) and SAVI is higher than for NDVI (0.96 and 0.79, respectively). For the TM3 band the correlation coefficients with NDVI and SAVI are –0.96 and –0.80, respectively. Since the near infrared band carries more density of information from the lower layers of the canopy, it is better correlated to biophysical parameters which are indicators of such density (e.g. LAI, LDW). Thus, it is expected that a VI which is more sensitive to NIR, be more indicative of those biophysical parameters.

The above points can be better visualized when analyzing Figures 3 and 4 together. As the crop develops, the NDVI increases and eventually reaches a semi saturation plateau, remaining at this level from stage 9. to 11.2 (for practically 6 field campaigns in this research). SAVI, on the other hand, remains on this plateau for only two field campaigns (stages 10.4. and 10.5.1.) (Fig. 4). Figures 3 and 4 show that LDW and TM4 band have a behavior more similar to SAVI than to NDVI.

Another approach to the analysis involves the estimation of biophysical variables from remote sensing spectral data. This investigation describes the VIs behavior in relation to the LAI values during the wheat phenological cycle, a fundamental biophysical variable in vegetation and crop analysis. Figure 5 depicts the "track phenomenon" already described by Tucker *et al.* (1979), Holben *et al.* (1980) and Formaggio & Epiphanio (1989). This phenomenon is characterized by two "paths" of the spectral variables: one when the crop is in the growing phase, and the second when the crop is advancing towards the senescence phases. In order to improve the estimation of LAI from VIs it seems that the track phenomenon should be taken into account.

In this investigation the evaluation of this aspect was done by making three linear regression fitness: the first one considering all data points altogether; the second, using only the first stages of the wheat cycle (ascending phase); and finally using the data of senescence phase only. As can be

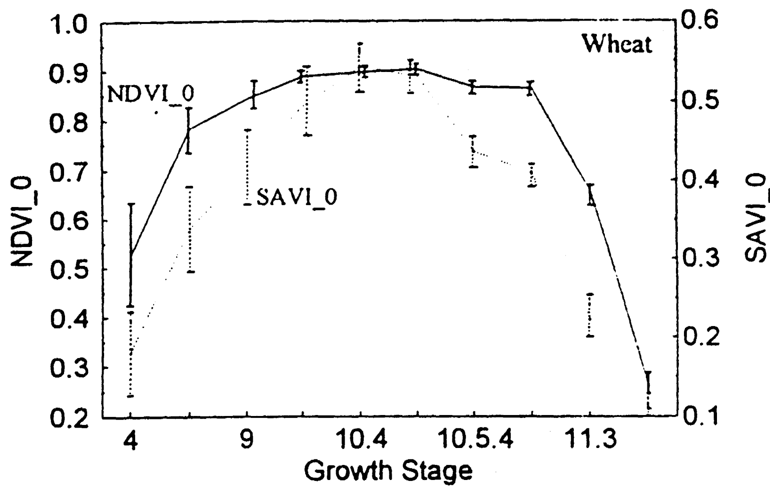

Fig. 4 — NDVI and SAVI (nadir) along the wheat development.

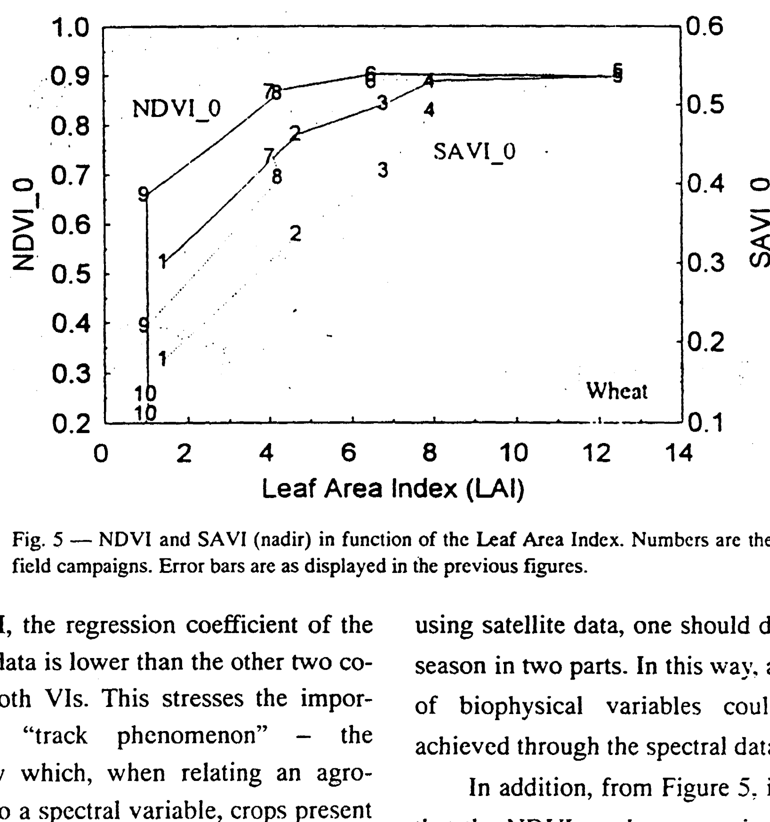

Fig. 5 — NDVI and SAVI (nadir) in function of the Leaf Area Index. Numbers are the field campaigns. Error bars are as displayed in the previous figures.

seen in Table III, the regression coefficient of the group using all data is lower than the other two coefficients, for both VIs. This stresses the importance of the "track phenomenon" – the characteristic by which, when relating an agronomic variable to a spectral variable, crops present different relationships in the growing and in the senescing phases (Tucker *et al.*, 1979). As a consequence, two regressions are better than only one when one evaluates biophysical variables through the spectral data. One practical benefit of these analyses is that in the evaluation of a specific crop using satellite data, one should divide the growing season in two parts. In this way, a better estimation of biophysical variables could be eventually achieved through the spectral data.

In addition, from Figure 5, it can be observed that the NDVI reaches saturation for LAIs greater than around 4. As this saturation point is in the begining of the crop cycle (field campaign 2), the predictive capability of NDVI beyond that LAI value is ambiguous. For SAVI, mainly for the ascending phase, the saturation almost does not exist.

TABLE III

Relationships between LAI and vegetation indices when one uses all data and when one splites the phenological cycle in two phases. Coefficient of determination (r^2) values greater than 0.399 and 0.658 are significant at the significance level of 0.05 for n=9 and n=5, respectively.

	$n^{(1)}$	Regression	r^2
NDVI_0 (all data)	9	y = 0.599 + 0.322log(LAI)	0.740
NDVI_0 (ascending phase)	5	y = 0.474 + 0.427log(LAI)	0.959
NDVI_0 (senescence phase)	5	y = 0.689 + 0.237log(LAI)	0.855
SAVI_0 (all data)	9	y = 0.179 + 0.341log(LAI)	0.850
SAVI_0 (ascending phase)	5	y = 0.102 + 0.398log(LAI)	0.969
SAVI_0 (senescence phase)	5	y = 0.227 + 0.316log(LAI)	0.944

(1) For "all data" and "descending data" the data of the last field campaign were omitted because in that phenological phase the crop was so dry that there was no good physical reason for using them in any relation with spectral data.

and even for high LAI values (around 8), it shows some sensitivity.

Regarding to the viewing angles, Table II allows the evaluation of the impact of changing in viewing angle from nadir to 30° (in the forward scattering direction) on the VIs and on the correlations with biophysical variables. In general, the correlations between NDVI_0 (nadir viewing) and LDW, LDWA, and LAI were higher than those obtained with NDVI_30 (30° off nadir viewing). This can be attributed to the contrasting behavior of TM4 and TM3 when the viewing angle changes. As the viewing angle changes from nadir to 30° there is a decrease in the correlation between TM3 and the biophysical parameters, while the TM4 shows a non-uniform behavior. As a result, Table II indicates a decrease in the correlation of NDVI_0 in relation to NDVI_30. This effect stresses the weight of the red band on the NDVI.

The tendencies of changes of the values of correlation coefficients from SAVI_0 to SAVI_30 are not as clear as for NDVI. The changes in correlations between SAVI and the biophysical variables when SAVI changed from nadir to 30° followed a behavior similar to TM4, irrespective of the behavior of the TM3 (red). This can be explained by the fact that when the radiometer is pointed off-nadir, the vegetation thickness viewed is greater than when it is at nadir pointing. Thus, when at off-nadir pointing, there is a higher interaction of the radiation within the canopy. These results strengthen the hypothesis of Epiphanio & Huete (1995) on the contrasting sensitivity of VIs with respect to their forming bands, and consequently on the potential of each VI for assessing multiple environmental variables.

CONCLUDING REMARKS

The crop development of wheat was better explained by near infrared reflectance band (TM4) than by the red band (TM3), mainly because the higher interaction of the TM4 with deeper internal layers of the canopy.

When analyzing the relationship between spectral and biophysical variables, both vegetation indices studied here (NDVI and SAVI) did improve the correlation coefficients obtained with the single TM3 band, but did not improve the correlation coefficients for TM4. For correlation purposes, the inclusion of band TM3 causes some "noise" in the vegetation indices. This could be explained by its fast absorption in the first canopy layers, thus decreasing the correlation coefficient of the vegetation indices when compared to the TM4 band alone, which has deep interactions within the canopy. Actually, as the vegetation indices are composed by TM4 and TM3, the correlation coefficients for vegetation indices are somewhere between the TM4 and TM3 coefficients. However, the VIs contribution was not evaluated on the normalization for spurious effects, such as soil and atmosphere. Nevertheless, in general, the correlation coefficients between VIs and biophysical variables were high.

When relating vegetation indices to LAI, the NDVI presented fast saturation in relatively low LAI values. SAVI, on the other hand, was more responsive to variations of LAIs, even on relatively high LAI values.

The change of the viewing angle from 0° to 30° had a negative impact on the correlations between biophysical variables and TM3 and NDVI and a non conclusive impact on the correlations of TM4 and SAVI.

As new sensors become available to users and larger databases are obtained, there is a growing need for deeper studies in this field. Besides, there is a demand for quantitative relationships between remote sensing data and environmental variables like those studied here.

ACKNOWLEDGEMENTS

The authors wish to thank UNICAMP for the experimental area, and Fundação Banco do Brasil for supporting the Estima Project.

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