ORBITAL SPECTRAL VARIABLES, GROWTH ANALYSIS AND SUGARCANE YIELD

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ABSTRACT: Temporal analysis of crop development in commercial fields requires tools for large area monitoring, such as remote sensing. This paper describes the temporal evolution of sugar cane biophysical parameters such as total biomass (*BMT*), yield (*TSS*), leaf area index (*LAI*), and number of plants per linear meter (*NPM*) correlated to Landsat data. During the 2000 and 2001 cropping seasons, a commercial sugarcane field in Araras, São Paulo state, Brazil, planted with the SP80-1842 sugarcane variety in the 4th and 5th cuts, was monitored using nine Landsat images. Spectral data were correlated with agronomic data, obtained simultaneously to the imagery acquisition. Two methodologies were used to collect spectral data from the images: four pixels (2 × 2) window and average of total pixels in the field. Linear and multiple regression analysis was used to study the spectral behavior of the plants and to correlate with agronomic variables (days after harvest-*DAC*, *LAI*, *NPM*, *BMT* and *TSS*). No difference was observed between the methodologies to collect spectral data. The best models to describe the spectral crop development in relation to *DAC* were the quadratic and cubic models. Ratio vegetation index and normalized difference vegetation index demonstrated correlation with *DAC*, band 3 (*B3*) was correlated with *LAI*, and *NDVI* was well correlated with *TSS* and *BMT*. The best fit curves to estimate *TSS* and *BMT* presented r^2 between 0.68 and 0.97, suggesting good potential in using orbital spectral data to monitor sugarcane fields.
Key words: biomass, leaf area index, crop development analysis, spectral behavior

VARIÁVEIS ESPECTRAIS ORBITAIS, INDICADORAS DE DESENVOLVIMENTO E PRODUTIVIDADE DA CANA-DE-AÇÚCAR

RESUMO: Dados de satélites são tradicionalmente utilizados em monitoramento de culturas. O presente trabalho busca contribuir no entendimento da evolução temporal de indicadores de crescimento da cana-de-açúcar como a biomassa total (*BMT*), produtividade (*TSS*), índice de área foliar (*LAI*) e número de plantas por metro (*NPM*) por meio de dados orbitais dos satélites Landsat 5 e 7, e verificar o seu potencial para o monitoramento desta. Durante as safras 2000 e 2001, uma área comercial em Araras, SP, cultivada com a variedade SP80-1842 no 4º e 5º cortes, foi acompanhada por imagens, buscando-se correlacionar dados espectrais com dados agronômicos. Os dados espectrais foram coletados de duas formas: uma com janelas de quatro pixels e outra com dados médios do talhão (*DMt*). Regressão linear e múltipla foram usadas para a análise temporal das bandas 3 e 4 e de índices de vegetação. As correlações e ajuste de modelos entre os dados espectrais orbitais e as variáveis agronômicas não apresentaram diferenças estatísticas. Os modelos quadráticos e cúbicos melhor descreveram o desenvolvimento temporal das variáveis espectrais, em função dos dias após o corte e apresentaram significância com os índices de vegetação da razão e por diferença normalizada (*NDVI*). As correlações entre os dados espectrais médios do talhão e as variáveis agronômicas foram significativas para banda*3* e *LAI*, e entre *NDVI* e *TSS/BMT*. Os dados médios do talhão (*DMt*), para primeira safra (*1ªS*), para a segunda safra (*2ªS*) e ambas juntas geraram regressões múltiplas, com coeficientes determinação (r^2) variando de 0,68 a 0,97 para a *TSS* e a *BMT*, mostrando que os dados espectrais orbitais estudados podem ser empregados no monitoramento da cultura da cana-de-açúcar.
Palavras-chave: biomassa, índice de área foliar, evolução temporal da cultura

INTRODUCTION

The importance in predicting sugarcane yield is unquestionable and has an impact on commodities such as sugar and alcohol. Large areas occupied by the crop create the need for alternative methodologies to help forecasting the production. The synoptic view provided by orbital remote sensing permits the monitoring of the crop cycle for yield estimates (Ippoliti-Ramilo et al., 1999).

The use of satellite images for yield estimates has been studied by several authors, such as Batista et al. (1976), Batista et al. (1978), Rudorff (1985), Rudorff & Batista (1990), Pellegrino (2001), Machado (2003) and Fortes (2003), but studies on the relations between agronomic variables and spectral data are still lacking, either with spectral bands, separately, or with vegetation indexes.

The hypothesis of this study is that there is a relation between agronomic variables of the sugarcane crop and orbital spectral data and that orbital remote sensing can be used to map crop yield. Thus, the objective of this study is to relate agronomic variables linked to sugarcane yield such as leaf area, number of plants per linear meter and the total biomass area with its spectral response, using different vegetation indexes.

MATERIAL AND METHODS

The experiment was carried out on a 27 ha commercial sugarcane field located in Araras, São Paulo state, Brazil (47°19'01"W to 47°19'30"W and 22°21'45"S to 22°22'17"S) with three predominant classes of soils: Rhodic Eutrudox, Rhodic Hapludox, Typic Hapludox, presenting a moderate slope (less than 12%) which allows mechanized harvest without the need to burn the trash for harvest, using the raw cane harvesting system. The studied area has a CWa type climate (Köppen) (Oliveira et al., (1982). The rain distribution follows the typical regime of low altitude tropical zones, i.e. rainy summer and dry winter. The SP 80-1842 variety was in its fourth and fifth cut (ratoon) in the 2000/2001 (07/11/2001) and 2001/2002 (07/22/2002) harvest seasons, respectively. The variety is characterized by its decumbent habit and regular bedding, average sprouting and plants that show vigorous growth. The leaves are long, average in width, and have bent tops (Copersucar, 1993).

The leaf area index (*LAI*), number of plants per linear meter (*NPM*), yield (*TSS* – tons of industrially usable stalks), total biomass (*BMT*), and the radiometric data were gathered simultaneously with the image acquisition by the Landsat 5/TM and Landsat 7/ETM+, representing the three characteristic phases of crop development (stablishment, vegetative development, stabilization/senescence). Using a regular sampling grid with 50 meters spacing and 25 meters buffer at the borders with surrounding roads, field data were collected in order to represent a four pixel window area within the satellite images. *BMT* and NPM at the eighteen sampling points were obtained by harvesting two linear meters of sugarcane from three adjacent sugarcane rows at the establishment and development stages of the crop. Phytomass was divided into aerial (leaves), stalk, and straw, in order to obtain stalk productivity per hectare (*TSS*). Figure 1 illustrates the location of the eighteen sampling points (4 pixel window, 2 × 2 pixels) within the study area and the type of sampling that was carried out. For LAI measurements a LAI2000 (LI-Cor, 2007) was used to collect data in five lines chosen around the sample central point (7.5 m × 7.5 m) diagonally with three replicates, and a visual count was used for NPM. During the 2000-2001 and 2001-2002 cropping seasons, the sugarcane vegetative cycle was monitored by nine field campaigns: five in the first year and four in the second year. Further description of the data gathered on agronomic variables and the radiometric data are detailed in Simões et al. (2003). Finally the number of the sample points varied around 18 due to operational problems, such as rain or equipment failure.

Analyses of the orbital spectral data were conducted using two sampling methods. The first methodology included the average data from 18 (4 pixel) windows placed close by the sample points (Figure 1), called sampling point analysis (*PtA*). These points represent the quantities of total area need to represent the biomass variability. The second methodology consisted of collecting data from the entire field using a single sample. This methodology was called average field data (*DMt*), as portrayed in Figure 1. Four sampling points

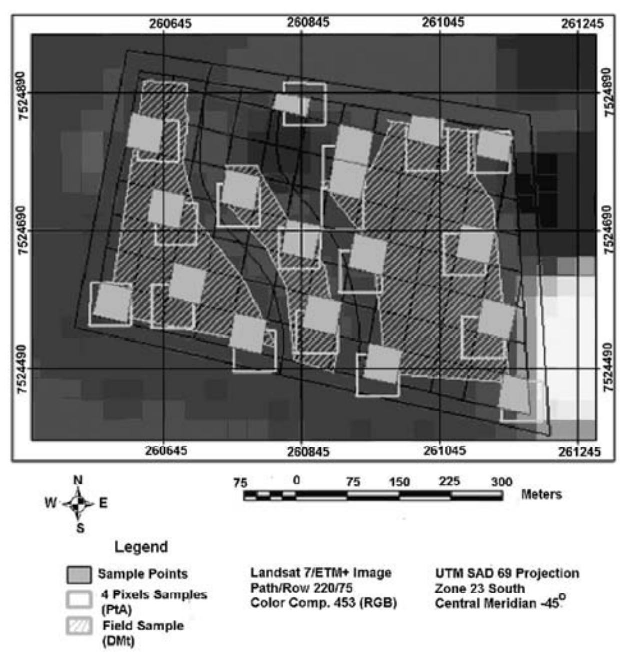

Figure 1 - Landsat 7 image with the location of the sample pixels to obtain reflectance and the two spectral data collecting methodologies. (Sampling points with 4 pixel windows - PtA - and sampling with average field data-DMt).

had to be disregarded from the punctual analyses and from the average field data on 3/23/2001 and on 7/5/2001, due to an accidental fire that destroyed parts of the biomass in the field. The same occurred with six points in the analyses of data collected on the 06/17/2002.

A Cimel CE313A radiometer was used to measure within field spectral reflectance. Once the spectral bands of the Cimel CE 313a radiometer coincide with the bands of the TM and ETM+ sensors, their data can be extrapolated (Formaggio, 1983; Demattê & Nanni, 2003 and Pellegrino, 2001). The dates of the orbital images from the 220/76C WRS path/row and the sensors used in the study are shown in Table 1. All nine scenes underwent radiometric correction and atmospheric correction according to the procedures described by Zullo Jr. & Bezerra (1993), using the 5S Model (Simulation du Signal Satellitaire dans le Spectre Solaire) developed by Tanré et al. (1990) to remove the effects caused by absorption phenomena and atmospheric spreading. For that, the model requires the optical thickness value, the kind of aerosol and the amount of water vapor in the atmosphere as input parameters.

Optical thickness and ozone in the atmosphere were calculated using direct radiation (DR) measures conducted on the days the images went through the Cimel 317c photometer. This photometer measures the DR in five bands of the spectrum, permitting the adjustment of a regression curve of the atmospheric optical thickness and the ozone to be entered into the model. The measurements were made at constant intervals every five minutes from 9h00 am to 12h00 pm on the days the satellites passed by (Tanré et al., 1990). These data were used for radiometric correction by the Satellite Image Radiometric Correction System (SCORADIS) developed by Zullo Jr. (1994).

The Simple Ratio - *SR (*Pearson & Miller, 1972), Ratio Vegetation Index - *RVI* (Jordan, 1969), Normalized Difference Vegetation Index - *NDVI* (Rouse et al., 1973) and Soil Adjusted Vegetation Index - *SAVI* (Huete, 1988) were generated from real reflectances of the Cimel 313A sensor and orbital sensor spectral bands according to the equations described below:

$$SR = \frac{V}{IVP} \quad (1)$$

$$RVI = \frac{IVP}{V} \quad (2)$$

$$NDVI = \frac{(IVP - V)}{(IVP + V)} \quad (3)$$

$$SAVI = \frac{(IVP - V)}{(IVP + V + L)} * (1 + L) \quad (4)$$

Table 1 - Agronomic data and spectral data for the SP80-1842 variety during the 2000 and 2001 harvests.

Sensor	Image Date	Cutting Date	*DAC*	*LAI*		*NPM*		*TSS*		*BMT*		*B3* (reflectance)			*B4* (reflectance)		
												Rad	PtA	DMt	Rad	PtA	DMT
			Days	Mean/SD	# of field meas.	Mean/SD	# of field meas.	Mg ha^{-1} Mean/SD	# of field meas.	Mg ha^{-1} Mean/SD	# of field meas.	---------- % ----------					
TM	09/20/2000	06/14/2000	10	0.00	18	0.00	18	0.00	18	0.00	18	18.74 a	12.18 b	12.53 b	29.13 a	23.21 b	23.93 a
TM	10/25/2001	07/11/2001	99	1.02/0.20	18	21.79/7.7	18	13.11/6.22	18	13.11/6.22	18	7.87 a	10.54 b	10.93 b	23.51 a	28.34 b	28.93 b
TM	10/22/2000	06/14/2000	127	0.92/0.25	18	24.96/6.98	18	33.78/11.30	18	33.45/11.19	18	9.83 a	11.41 ab	11.35 b	37.24 a	29.76 b	29.07 b
ETM+	03/10/2002	07/11/2001	235	---	---	---	---	25.13/10.31	18	25.13/10.31	18	5.12 a	1.56 b	4.00 c	45.30 a	8.33 b	21.41 c
ETM+	02/19/2001	06/14/2000	249	3.34/0.45	16	16.80/2.55	10	57.36/13.26	13	78.28/18.00	13	6.58 a	2.52 b	2.48 b	61.24 a	22.36 b	22.53 b
ETM+	04/11/2002	07/11/2001	267	3.72/0.92	14	14.80/3.11	10	---	---	---	---	6.84 a	3.83 b	3.64 b	60.01 a	19.82 b	20.33 c
TM	03/23/2001	06/14/2000	281	3.38/1.05	14	14.45/2.59	14	67.40/8.12	14	86.11/32.70	14	4.46 a	4.39 a	4.28 a	33.28 a	20.42 b	20.63 b
ETM+	06/17/2002	07/11/2001	363	1.01/0.16	12	10.23/3.66	12	61.41/8.99	12	111.63/20.98	12	5.84 a	6.88 b	6.60 b	34.52 a	26.23 b	27.04 c
TM	07/5/2001	06/14/2000	384	1.04/0.2	14	10.79/1.46	14	89.57/15.45	14	108.28/21.45	14	6.57 a	6.93 a	6.74 a	36.68 a	32.80 ab	33.52 b

DAC = days after cutting, LAI = leaf area index, NPM = number of plants per meter, TSS = yield, BMT = total biomass for the crop.

where *IVP* and *V* are the reflectances that correspond to the TM and ETM+ sensors' near-infrared (band 4) and red (band 3) wavelengths, respectively.

To evaluate the feasibility of monitoring sugarcane with orbital data, a temporal analysis was performed for the *B3*, *B4* reflectances and the *SR*, *RVI*, *NDVI* and *SAVI* indexes in relation to the days after cutting (*DAC*), using sample point data, average field data and field radiometry data (Table 1). In fact DAC refers to the apparent condition of the plant after cutt because sometimes during dry periods, the rate of plant growth is smaller and thus there are no significant changes in its apparent conditions.

The difference between orbital reflectance sampling and the field radiometry methods was tested using the Test of Averages (Single Factor ANOVA), thus obtaining the significant differences between the two methods. At the same time, the temporal development curves for the spectral variables were analyzed for the 4-pixels window (*PtA*) in relation to *DAC* (Figure 2), and a simple regression analysis was performed using the AJUSTE program (Zullo Jr. & Arruda, 1986), to ascertain the best models to explain the development of spectral variables for sugarcane during the two cycles being studied. Curves were examined in light of the evolution of agronomic variables to verify agreement with crop evolution and statistical significance (Determination Coefficient (r^2) and $p < 0.01$).

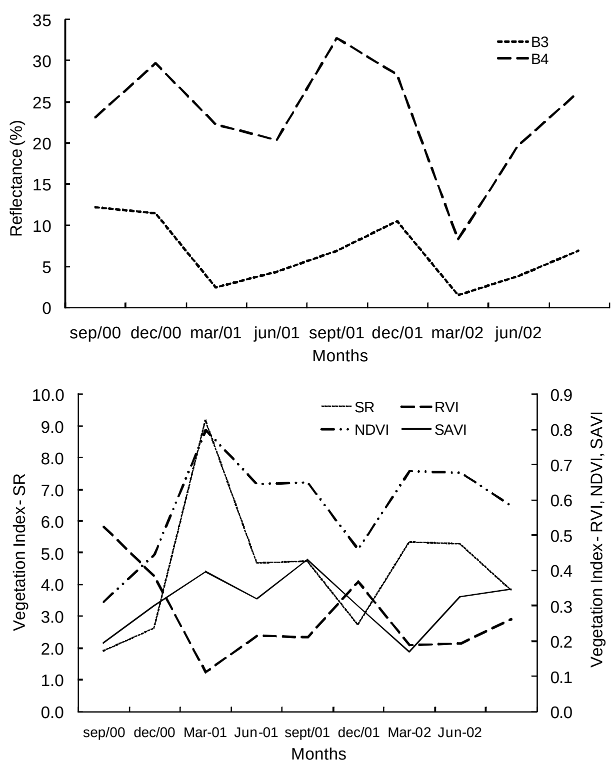

Figure 2 - Temporal evolution of the orbital spectral variables over the two harvests.

The Pearson Correlation Index for crop agronomic variables with the spectral variables from the *PtA* sampling method was tested using data from the establishment, vegetative development, maturation and complete plant cycle phases. Statistical significance was evaluated by the F Test represented by *p (at 5% and 1%)* value according to the results presented by Xavier (2003) and Pellegrino (2001). The Correlation matrix between the agronomic variables and the spectral data was obtained with the average data from eighteen points per date (image) for the two harvests. It was possible to determine which data offer the best explanation for the variation in the *TSS*, *BMT*, *LAI* and *NPM* agronomic variables during plant cycle.

The Stepwise technique was used to obtain multiple linear regressions to evaluate the relation of the spectral variables of *PtA and DMt* samples with yield (*TSS*) and the total biomass (*BMT*). MiniTab 13 for Windows was the program used. In the case of *DMt* samples, seven images out of nine were used because for two of them the *NPM*, *DMT* and *LAI* data were not available. An *F* value (F > 0.04) was used as threshold for removing or including variables of the model. The coefficient of determination (r^2), significance and model adjustment using ANOVA were employed to test model effectiveness. To generate the multiple regression to evaluate the relation of the spectral variables of PtA with *TSS/BMT* from the 162 variables (18 points ´ 9 images) only those having all variables for all dates were used, thus 51 for the 1st harvest, 28 for the 2nd harvest and 79 for both harvests together. On the other hand, for the multiple regression to evaluate the relation of the spectral variables of *DMt* with *TSS/BMT* the mean data per date were used.

The best vegetation index and which harvest best explained the variation in the orbital spectral data in comparison to *TSS/BMT* was found by evaluating the results of statistical significance regressions and the r^2 values. The regression analysis was used to correlate the *TSS* and the *IVs*, thus obtaining the degree of correlation for each remote sensing product for yield explanation.

RESULTS AND DISCUSSION

Table 1 shows the average data for the analyzed field parameters during the nine field campaigns that were carried out and their correlation with *DAC*. The evaluation of the orbital spectral data for temporal monitoring of the sugarcane crop revealed reflectance values different from those revealed by the spectral data at ground level (Simões et al., 2003). However, the orbital data for both *PtA* and *DMt* sampling types had similar values in seven of the nine images. The dates with statistical differences were 3/10/02 for both bands (B3 and B4) and on 4/11/02 and 6/17/02 for band B4. These differences could result from variations in the crop canopy structure after the crop was knocked over during two storms in February 2002. These differences in the two spectral bands were transmitted by the *IV* values (Table 2), showing that the indexes could not reduce these effects even when using the information from more than one spectral band (Leeuwen & Huete, 1996). Therefore, the averages of field data (*DMt*) were adopted.

The intensity of the spectral response of the radiometry data and the orbital data was different, with greater values for data obtained in field radiometry. The date 03/10/2002 presented the greatest variation, followed by 02/19/2001 and by 04/11/2002 (Table 1). On the first date, the variation reached approximately 328% in B3 and 543% in B4. On the other dates, the variations were smaller, but still significant, showing the great influence of canopy spatial variations on the spectral response. The difference in spatial resolution between the sensors imposes changes in the spectral response level of the sensors was also observed (Pinter Jr. et al., 1990).

Going from a ground level to an orbital level scale introduces countless factors that interfere in the spectral behavior of the targets detected by the sensors, such as atmospheric interference, even with the carrying out of corrections to minimize these effects, aspects of spatial variability of the target due to the larger image area and the geometry of orbital data acquisition (Pinter Jr. et al., 1990).

The standard deviation among the data, for each spectral variable, is shown in Table 3. The difference between the reflectance intensities of the TM and ETM+ sensors in relation to the reflectance data from the Cimel 313A sensor can be explained by the size of the area detected by each of the sensors, 0.0060 m^2 in the case of the Cimel and 900 m^2 for the TM and ETM+ sensors. Since the area detected by the orbital sensors is larger, the integration of the spectral response within the same pixel also encompasses a broader spectral composition, which in the case of agricultural crops can vary between healthy vegetation, vegetation in senescence, shade, soil and straw (Davidson & Csillag, 2001). The signal values received by the land sensors tend to be larger than the satellite values due to atmospheric interference in the response signals from the targets received by the orbital sen-

Table 3 - Standard Deviation for spectral data.

		SD min	SD max
B3	PtA	0.0008	0.021
	DMt	0.0032	0.023
B4	PtA	0.0053	0.004
	DMt	0.0069	0.020
SR	PtA	0.14	1.545
	DMt	0.10	1.488
RVI	PtA	0.013	0.050
	DMt	0.013	0.054
NDVI	PtA	0.018	0.053
	DMt	0.020	0.053
SAVI	PtA	0.013	0.038
	DMt	0.011	0.041

Table 2 - Spectral vegetation indexes for the SP80-1842 variety during the 2000 and 2001 harvests.

ImageDate	Cutting Date	*DAC*	*SR*			*RVI*			*NDVI*			*SAVI*		
			Rad	PtA	DMt	Rad	PtA	DMt	Rad	PtA	DMt	Rad	PtA	DMt
			%											
09/20/2000	06/14/2000	10	1.55 a	1.91 b	1.91 b	0.64 a	0.53 b	0.52 b	0.22 a	0.31 b	0.31 b	0.16 a	0.19 b	0.20 b
10/25/2001	07/11/2001	99	3.11 a	2.71 a	2.68 a	0.36 a	0.37 a	0.38 a	0.49 a	0.46 a	0.45 a	0.28 a	0.30 a	0.30 a
10/22/2000	06/14/2000	127	3.96 a	2.61 b	2.56 b	0.26 a	0.38 b	0.39 b	0.58 a	0.45 b	0.44 b	0.42 a	0.30 b	0.29 b
03/10/2002	07/11/2001	235	9.15 a	5.37 b	5.40 b	0.12 a	0.19 b	0.19 b	0.79 a	0.68 b	0.69 b	0.59 a	0.17 b	0.35 c
02/19/2001	06/14/2000	249	9.78 a	9.08 a	9.26 a	0.10 a	0.11 a	0.11 a	0.81 a	0.80 a	0.80 a	0.67 a	0.40 b	0.40 b
04/11/2002	07/11/2001	267	9.45 a	5.24 b	5.61 c	0.11 a	0.19 b	0.18 c	0.80 a	0.68 b	0.70 c	0.68 a	0.32 b	0.34 c
03/23/2001	06/14/2000	281	7.69 a	4.68 b	4.82 b	0.13 a	0.22 b	0.21 b	0.77 a	0.65 b	0.66 b	0.49 a	0.32 b	0.32 b
06/17/2002	07/11/2001	363	6.02 a	3.82 b	4.14 b	0.17 a	0.26 b	0.25 b	0.71 a	0.58 b	0.60 b	0.47 a	0.35 b	0.37 c
07/5/2001	06/14/2000	384	6.21 a	4.74 ab	4.99 b	0.18 a	0.21 a	0.20 a	0.70 a	0.65 a	0.67 a	0.48 a	0.43 ab	0.45 b

DAC = days after cutting, LAI = leaf area index, SR: simple ratio, RVI = ratio vegetation index, NDVI = normalized difference vegetation index, SAVI = soil adjusted vegetation index.

sors. Although atmospheric correction of the images was carried out, it does not completely eliminate these effects and the approximations employed in the correction process can introduce other errors in the signal received by the orbital sensors, excessively correcting the reflectance values and altering the spectral response of the crop (Moran et al., 1991).

The temporal evolution for *B3*, *B4*, and for the *SR*, *RVI*, *NDVI* and *SAVI* spectral indexes, is shown in Figure 2. The orbital data curves were different from the radiometry data curves found by Simões et al. (2003). The *B3* and *B4* spectral band curves did not have a determined temporal standard to accompany the evolution of agronomic variables.

B3 had two reflection peaks and two absorption peaks (Figure 2). The high reflections are related to the high reflection of the sugarcane straw left on the ground after the mechanized harvest without burning, and represent the spectral behavior of the beginning of the cycle in the two harvests (Biard & Baret, 1997). On the other hand, the strong absorption is the result of crop canopy development that completely covered the straw and expresses the spectral behavior in the crop development phase (Gitelson et al., 2002).

In the case of *B4,* the temporal behavior did not correspond to an elevation in reflectance values in this band due to the increase in crop biomass during the initial development phases of the crop (Price & Bausch, 1995). A saturation of the sensor to the increase in crop biomass may have occurred. Also, the inability of this band to detect the increase in LAI, biomass and canopy coverage percentage has to be considered (Gitelson et al., 2002). This reduction in reflectance values could have been caused by the crop being knocked down, which exposes the straw and the crop stalks, altering the characteristic spectral behavior (Leuwen & Huete, 1996). This reduction behavior in infrared radiation reflection from January to April was also observed by Rudorff & Batista (1990) and was explained by the authors as a typical behavior for the traditional behavior of the vegetation in the near-infrared band. On the other hand, this behavior corresponded to what was observed by Kanemasu (1974) for sorghum, characterized by an elevation in reflectance values until the middle of the cycle, followed by an increase in crop biomass. After this phase, *B4* presented a reduction in its values even with the increase in biomass and coverage percentage. In the case of sugarcane, the reflectance values increased in the months prior to the two crop harvests, during a phase when the crop increases the translocation of photosynthesized elements to the stalks and reduces the photosynthetically active area, resulting in an expected reduction in reflectance in the infrared band (Wiegand et al., 1991).

The *RVI* and *NDVI* indexes were the ones that revealed a correlated behaviour with the temporal evolution of agriculture crops such as sugarcane, characterized by the accompanying temporal evolution of agronomic variables, such as soil coverage percentage, *LAI*, *NPM* and *BMT* (Moran et al., 1995). However, the curves did not show continuous trends (Figure 2). The *SR* and *SAVI* indexes did not show high correlations with the infrared band (*B4*) (Table 4), as expected, and the behavior accompanied *TSS* and *BMT* evolutions (Epiphânio et al., 1996). On the other hand, the *RVI*, which has a greater correlation with the red band (*B3*), demonstrated an inverse behavior when related to the other indexes (Table 4), with a reduction in reflectance values during the months of great sugarcane biomass development and a slight increase in reflectance values at the end of the cycle (Price & Bausch, 1995).

The results of the linear regressions of the orbital reflectance data with *DAC* (Figure 3) also demonstrated a lack of defined behavior for the spectral bands in relation to crop development and temporal evolution of *LAI*, *NPM*, *TSS* and *BMT*. No regression model demonstrated significance at 1% (T Test) and $r^2 > 0.90$ for these bands. However, the cubic and senoidal curves, which do not biologically represent the temporal phenomenon of crop development, had the highest r^2 values, 0.87 and 0.74 respectively for *B3* and 0.64 and 0.54 for *B4*. *B3* and *B4* should have their temporal behaviors explained by exponential curves, whose asymptotic phase would represent a stabilization of the reflectance increase due to saturation of the *B3* and *B4* bands and the stabilization of the increase in biomass (Kanemasu, 1974; Carlson & Ripley, 1997). The lack of adjustment of a curve that would describe the temporal behavior of the bands can be explained: i) by the effects of the variations in the atmosphere at the measurement dates, even after conducting atmospheric corrections (Moran et al., 1991); ii) by the differences in the solar elevation angle between images, an effect not completely eliminated by the radiometric corrections (Epiphânio & Huete, 1995) and; iii) by the variations in the optical properties of the vegetal coverage and canopy (Epiphânio et al., 1997). The use of spectral mixture models can contribute by separating the effects of shade, soil, straw and vegetation from the sugarcane canopy response, making the spectral analyses easier (Xavier, 2003) and radiometric normalization of the images also tends to eliminate variations in the geometry of spectral data acquisition.

Among the vegetation indexes, *SR* and *SAVI* did not show significance in the adjustment models with *DAC*. *SR's* temporal behavior was adjusted by a cubic exponential model with $r^2 = 0.77$ and *SAVI's* was adjusted

Table 4 - Correlation indexes for the sampling point (PtA) reflectance data of nine Landsat images, the days after cutting and the agronomic data using the average field data with the SP80-1842 varieties for the 2001 and 2002 harvests.

	DAC	LAI	NPM	TSS	BMT	B3	B4	SR	RVI	NDVI
LAI	0.61	Correl								
	0.22	p Value								
NPM	-0.05	0.25								
	0.99	0.38								
TSS	**0.99**	0.63	0.06							
	0.00	0.26	0.99							
BMT	**0.99**	0.65	-0.02	**0.99**						
	0.00	0.22	0.93	**0.00**						
B3	**-0.68**	**-0.94**	-0.10	**-0.66**	**-0.72**					
	0.02	**0.02**	0.97	**0.04**	**0.02**					
B4	-0.05	-0.62	0.04	0.04	-0.04	0.66				
	0.98	0.30	0.70	0.69	0.80	0.14				
SR	0.53	**0.77**	0.13	**0.78**	**0.84**	-0.83	-0.33			
	0.10	**0.05**	0.96	**0.03**	**0.01**	**0.00**	0.31			
RVI	**-0.81**	**-0.87**	-0.29	**-0.87**	**-0.90**	0.92	0.33	-0.88		
	0.005	**0.04**	0.68	**0.01**	**0.00**	**0.00**	0.45	0.00		
NDVI	**0.78**	**0.87**	0.24	**0.86**	**0.89**	**-0.93**	-0.35	0.91	-0.99	
	0.01	**0.04**	0.77	**0.01**	**0.00**	**0.00**	0.40	0.00	0.00	
SAVI	**0.60**	**0.49**	0.12	**0.65**	0.59	-0.15	0.63	0.45	-0.50	0.49
	0.01	**0.04**	0.77	**0.01**	0.09	0.60	0.40	0.78	0.43	0.77

DAC = days after cut, LAI = leaf area index, NPM = number of plants per meter, TSS = yield, BMT = total biomass for the crop.

by a cubic model with $r^2 = 0.51$. The other *RVI* and *NDVI* indexes had significant adjustments with cubic and cubic exponential models, respectively, demonstrating that these indexes eliminated part of the atmospheric and geometric effects and improved the correlations with the biophysical variables of the crop (Jackson & Huete, 1991) to which the spectral bands are subjected when used separately (Table 4).

These data suggest that the spectral bands used separately did not satisfactorily represent the temporal evolution of the crop and should therefore be used with reservation for the temporal monitoring of sugarcane. The coefficients of determination (r^2) for the indexes were 0.89 for *RVI* and 0.91 for *NDVI*, with the latter being the one that best explained the temporal behavior of the sugarcane, probably because *NDVI* is more sensitive to variations in the red than *SAVI* and due to the fact that *RVI* is more sensitive than *NDVI* to variations in soil coverage and the presence of straw in the sugarcane canopy spectral response (Epiphânio & Huete, 1995; Huete, 1988). The maximum values for the spectral indexes were observed in the images from 2/19/01 and 3/10/02, as was mentioned previously, the dates when the crop had been knocked over, which interfered in the spectral data for the *B3* and *B4* spectral bands.

The correlation data shown in Table 4 confirm the results obtained by the regression models and the temporal analysis of the spectral variables. Band *B4* showed no correlation with the measured agronomic variables, using the average data of the two harvests. These same results help to explain the absence of a model that significantly adjusts to *DAC* and the lack of a defined behavior for the temporal development of the band. Band *B3*, on the other hand, demonstrated a correlation with *DAC*, *LAI*, *TSS* and *BMT* between the agronomic variables and presented correlations above 83% with the spectral indexes, except for *SAVI*, with values greater than those obtained for *B*4 with the same indexes. This result could be attributed to the behavior of *B3*, which seemed to be less influenced by the variations in the sugarcane canopy structure throughout the cycle and the changes in the solar elevation angle (Pinter Jr. et al., 1990).

The spectral indexes had very similar correlation coefficients, especially *LAI's* 87% correlation with *RVI* and with *NDVI*, which demonstrates the potential for using Landsat orbital data for the *LAI* estimate for sugarcane (Price & Bausch, 1995; Xavier, 2003). *TSS* and *BMT* had greater correlation indexes with *RVI* and *NDVI* respectively, making it possible to state that these

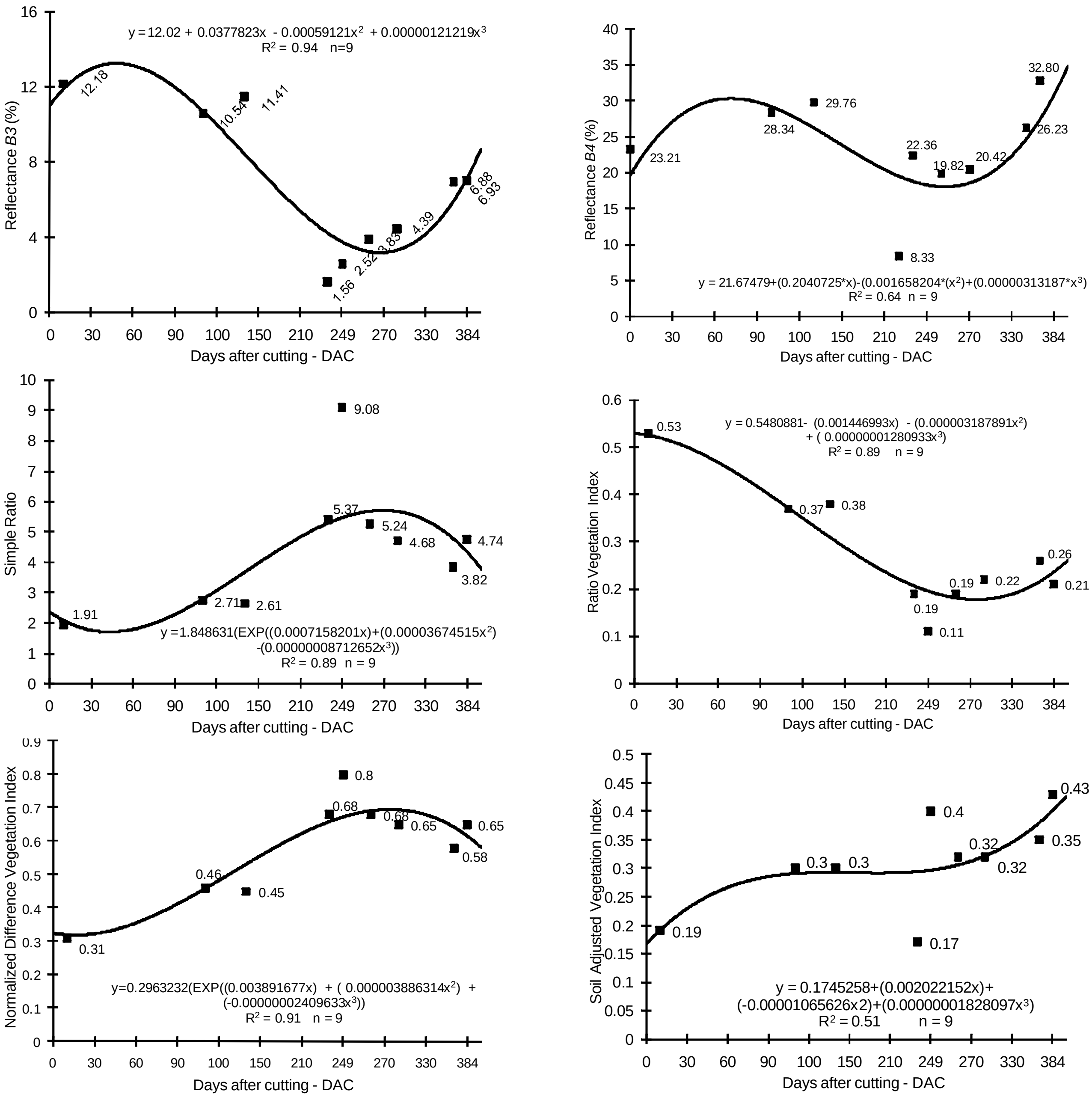

Figure 3 - Cubic Models adjusted for B3, B4, RVI and SAVI, Cubic Exponential Models adjusted for SR and NDVI, obtained for 2000/2001 and 2001/2002 harvests.* significance at 1% (F Test). SR = simple ratio, RVI = ratio vegetation index, NDVI = normalized difference vegetation index, SAVI = soil adjusted vegetation index.

indexes are adequate for the estimation of models for sugarcane crop yield (Pellegrino, 2001; Machado, 2003).

The multiple regressions shown in Table 5 demonstrate the models used to estimate sugarcane yield (*TSS*) and sugarcane total biomass (*BMT*) in the field, for different sets of data. The average data in the nine field campaigns (*DMt*) revealed significant levels for the models *TSS* and *BM* at 95%, with the exception of a *BMT* model that reached a 99% significance level. The r^2 values were greater for the models with *BMT* than with *TSS*, even though Stepwise selected the same input variables for composing the models (*B3*, *B4* and *NDVI*), which suggests that the Landsat spectral data had better adjustments for *BMT* than for *TSS*. The second model generated for *BMT* with the average data (*DMt*) includes both the *B3*, and the *LAI* variable, indicating that data that refer to leaf canopy would complement the spectral information in the sugarcane aerial biomass estimate models (Pellegrino, 2001).

The models obtained only using first harvest data

Table 5 - Multiple regression models for agronomic variables of the SP80-1842 sugarcane variety and orbital spectral variables from the TM and ETM+ sensors and Landsat for the 2000/2001 and 2001/2002 harvests.

Data	Model	# of data	r^2	*P*
DMt	*TSS* = 44.79-1129.51**B3*+391.20**B4*	7	0.84*	0.02
DMt	*TSS* = -118.25+1.58**B4*+245.17**NDVI*	7	0.79*	0.02
DMt	*TSS* = -63.19+213.90**NDVI*	7	0.68*	0.01
1stS (PtA)	*TSS* = 30.21+3.27**LAI*+10.15**B3*-92.37**RVI*	51	0.59**	0.00
2ndS (PtA)	*TSS* = 47.86**B3*-1183.27**RVI*+2390.69**NDVI* 3800.70**SAVI*	28	0.97**	0.00
2S(PtA)	*TSS* = 152.79-2.80**NPM*-4.88**B3*-3.69*SR	79	0.44**	0.00
DMt	*BMT* = 64.09-14.62**B3*+4.63**B4*	7	0.88**	0.00
DMt	*BMT* = 91.06-7.08**LAI*-16.47**B3*+4.63**B4*	7	0.86*	0.03
DMt	*BMT* = -146.32+1.60**B4*+316.41**NDVI*	7	0.82*	0.02
1stS (PtA)	*BMT* = 65.16-4.65**B3*	51	0.37**	0.00
2ndS (PtA)	*BMT* = -1322.84+66.68**B4*-6524.43**NDVI*-11755.9**SAVI*	28	0.89**	0.00
2S (PtA)	*BMT* = 202.17-3.20**NPM*-8.02**B3*-5.37**SR*	79	0.50**	0.00

DMt = Average field data, 1st S = first harvest data, 2nd S = second harvest data and 2S = data from both harvests together, **n**-number of data used for regression and *p* value. * 5% significance level and ** 1% significance level (F Test).

(1st *S*-2000/2001 harvest) were those that had the fewest explanations for multiple regression variability with 95% significance levels for *TSS* as well as for *BMT* with, values of 0.59 and 0.37, respectively, demonstrating *TSS's* and *BMT's* low explanation ability for the orbital spectral data. On the other hand, the models for the second harvest (2nd *S*-2001/2002 harvest) for *TSS* and *BMT* had much higher r^2 values than those from the 1st*S* for both dependent variables and in both cases the regressions used the *NDVI* and *SAVI* indexes as independent variables. *B3* and *RVI* were part of the models for *TSS* and *B4* was part of the *BMT* regression. For the *TSS's* regression, the entry of the *B3* variable and *RVI* confirms what was already observed in Figure 3 and Table 4, the high correlation of this band and this index with *TSS*. In the case of *B4*, this variable was part of the regression due to the high correlation with the amount of the leaf biomass of the crop (Wiegand et al., 1991).

The coefficients of determination of the models for both harvests had intermediate values between the 1st*S* and 2nd*S* data, with values of 0.44 and 0.50, respectively, for *TSS* and *BMT*. The models for *TSS* and for *BMT* were comprised of the same variables, *NPM*, *B3* and *SR*. Curiously, the *NPM* variable was included in the models, even though it showed low correlation with *TSS* and *BMT*. This could be the result of using all the data and not only the average data as shown in Table 4. When data from both harvests were used the *NPM*, together with *B3* and *SR*, began to have greater correlation with *TSS* and *BMT*, explaining approximately 0.50 of the variation in the data, thus justifying why they were included in the models.

CONCLUSIONS

Orbital spectral data were different from the field spectral data (spectroradiometry). The pixel sampling methods in orbital images, the 4-pixel window sampling points (PtA) and the average field data (DMt), did not present differences.

The temporal behavior for the *B4* band and the *SAVI* index were not statistically explained by any of the tested mathematical models, but the *B3* band and the *SR*, *RVI* and *NDV*I indexes demonstrated temporal behavior represented by cubic exponential, quadratic, cubic and cubic exponential regression models, respectively.

B3 and the *SR* indexes were the orbital spectral data that best demonstrated the correlations with the agronomic and sugarcane growth variables. The resulting multiple linear regression models generated for the *DMt*, the 1st*S*, the 2nd*S* and the *2S* had 95% significance levels, which confirms the potential for applying orbital spectral data together with agronomic data for monitoring and accompanying sugarcane crop development.

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