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RESUMO-NOTAS/ABSTRACT-NOTES

This work has the objective to assess the performance of an yield estimation model for sugarcane (Saccharum officinarum). The model uses orbital gathered spectral data along with yield estimated from an agrometeorological model. The test site includes the sugarcane plantations of the Barra Grande Plant located in Lençóis Paulista municipality in São Paulo State. Production data of four crop years were analysed. Yield data observed in the first crop year (1983/84) were regressed against spectral and agrometeorological data of that same year. This provided the model to predict the yield for the following crop year i.e. 1984/85. The model to predict the yield of subsequent years (up to 1987/88) were developed similarly, incorporating all previus years data. The yield estimations obtained from these models explained 69%, 54%, and 50% of the yield variation in the 1984/85, 1985/86, and 1986/87 crop years, respectively. The accuracy of yield estimations based on spectral data only (vegetation index model) and on agrometeorological data only (agrometeorological model) were also investigated.

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AGRICULTURAL YIELD ESTIMATION OF SUGARCANE BASED ON AGROMETEOROLOGICAL-SPECTRAL MODELS

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This work has the objective to assess the performance of an yield estimation model for sugarcane (Saccharum officinarum). The model uses orbital gathered spectral data along with yield estimated from an agrometeorological model. The test site includes the sugarcane plantations of the Barra Grande Plant located in Lençóis Paulista municipality in São Paulo State. Production data of four crop years were analyzed. Yield data observed in the first crop year (1983/84) were regressed against spectral and agrometeorological data of that same year. This provided the model to predict the yield for the following crop year i.e. 1984/85. The model to predict the yield of subsequent years (up to 1987/88) were developed similarly, incorporating all previous years data. The yield estimations obtained from these models explained 69%, 54%, and 50% of the yield variation in the 1984/85, 1985/86, and 1986/87 crop years, respectively. The accuracy of yield estimations based on

<u>spectral data only (vegetation index model) and on agrometeorological data only (agrometeorological model) were also investigated.</u>

Introduction

The adequate planning of the activities related with food, fiber, and renewable fuel production is dependent on reliable and timely prognostic information.

Agricultural production of a crop is dependent on several factors which are most of the time very difficult to be estimated because they are dependent on seasonal and yearly variations with very complex interactions among them. The technique of remote sensing has great potential not only to identify the crop planted and as consequence to estimate the planted area but also to estimate yield (Tucker et al., 1980; Richardson et al. 1982; Hatfield, 1983; Jackson et al., 1983; Rudorff, 1985; and Bauer, 1985).

The current advance of the remote sensing technology indicates that in the near future very capable Earth observing systems will be available for monitoring the dynamics of the agricultural activity in a broad range of the electromagnetic spectrum with a much better temporal resolution than is available today. Brazil is currently having direct access to Landsat, SPOT, and NOAA satellites which are capable of improving current methods for crop yield estimation.

Yearly fluctuation in yield are in most cases related to prevailing meteorological conditions throughout the growing season although many other environmental factors in addition to agronomic practices and economic variations may be also very important to explain yield variation especially from place to place. The quantification of the effect of some of these factors may be established through models that modulate the effect of these factors on yield.

Models based on meteorological variables to estimate crop yield have been extensively used (Doorembos and Kassam, 1979; Barnett and Thompson, 1982; Richardson et al. 1982; and Rudorff and Batista, 1988, among others). Landsat data when transformed into vegetation indices can be used to express the collective effect of several factors on crop yield (Rudorff, 1985).

In recent years, several studies were carried out using Landsat data for crop yield estimation. The significant correlations between crop reflectance factors and agronomic parameters related with yield have encouraged the use of spectral data in crop yield models (Pearson and Miller, 1972; Ashley and Rea, 1975; Tucker et al., 1980; Tucker and Holben, 1981; Richardson and Wiegand, 1977; Richardson et al., 1982; Wiegand et al. 1979, Hatfield, 1981, 1983; Rudorff, 1985; and Rudorff and Batista, 1988; among others).

The majority of these works have been developed in experimental fields using portable radiometers. Wiegand et al. (1979) however, indicated that orbital remote sensing could be a promising technique to relate spectral variables with crop yield for large areas. Unfortunately, there are no efficient methods that make the numeric relationship between satellite acquired data and yield independent of atmospheric variation and sensor calibration.

Recent studies as the ones developed by Richardson et al. (1982), Barnett and Thompson (1982), Rudorff (1985) and Rudorff and Batista (1988), used Landsat in conjunction with agrometeorological data and obtained better results than the use of any of these data sets independently. The model developed by Rudorff and Batista (1988) to estimate yield of sugarcane based on both meteorological and Landsat data explained 72 percent of the variation in yield for three crop years.

This paper reports on a long term research project which has the objective of assessing the potential of high spatial resolution orbital data (Landsat) in conjunction with agrometeorological data to estimate sugarcane yield (total stems phytomass production per hectare) in several crop years based on a comprehensive agronomic data set provided by a well managed sugarcane plant in Brazil.

Study Area

The study area is located in Lençóis Paulista municipality, São Paulo State, comprising the sugarcane plantations of the Barra Grande Plant with 40,000 ha of cultivated fields encompassed by the following coordinates: $22^{o}00$ S to $23^{o}00$ S and $49^{o}00$ W to $49^{o}30$ W (Fig. 1)

FIGURE 1

The major soils of the study area correspond in the Brazilian classification system to "Latossolo Vermelho Escuro" and "Areia Quartzosa" (Orthox and Quartzipsamments approximately in the US Taxonomy system, according to Sanchez, 1976). The remaining soil types are in the Brazilian system classified as: "Latossolo Vermelho Amarelo", "Latossolo Roxo", and "Terra Roxa Estruturada" (Haplorthox, Eutrorthox, and Paleudalf approximately in the US soil taxonomy, according to Sanchez, 1976 and Oliveira et al. 1981). These soils represent 6 percent, 4 percent, and 3 percent, respectively, of the total cultivated sugarcane areas (Nelli, 1983). The predominant land use classes of this region are: planted forest, agriculture, and areas of "Cerrado" (IF, 1975). The climate is hot and humid with a dry winter, the precipitation of the driest month is lower than 30 mm, and the monthly average of the temperature of the hottest month is greater than $22^{o}C$ and of the coldest month is lower than $18^{o}C$ (Setzer, 1966).

This test site was selected because the Barra Grande Plant has a very high technological standard and is one of the best managed sugarcane plants in Brazil and made available for this research an extensive and reliable data set. In addition this area is located in the core of the major sugarcane productive region of Brazil.

Sugarcane

The planted area to sugarcane (Saccharum officinarum) in the State of São Paulo was 1.73 million ha approximately for the crop year of 1987 that corresponds to 40 percent of the total cultivated sugarcane area of Brazil. In the 1987 crop year 130 million tons were produced in São Paulo corresponding to 48.5 percent of the national production (IBGE, 1988). Sugarcane is planted for sugar and alcohol production and São Paulo is responsible for 46 percent of the sugar production and for 66 percent of alcohol production in Brazil (Planalsucar, 1984).

Sugarcane is originated from Asia, probably from Assam and Bengal and was introduced in Brazil in the early 1530's. This crop is successfully planted between 35^{o} North and South. At high altitudes and lack or excess of water, sugarcane does not grow.

A field planted to sugarcane may be harvested for several years before replanting. The growth cycle is around 12 or 18 months depending on planting date. After the first cut, the ratoons take about 12 months to be harvested. Fig. 2 illustrates the dynamic of sugarcane cultivation in the study region, showing the accumulation of green matter along the growing cycle.

FIGURE 2

Sugarcane is a typical tropical crop and its vegetative production occurs at temperatures between 22°C and 30°C. At temperatures lower than 20°C growing is very limited and ceases at 10°C. Depending on the climate this crop requires from 1500 to 2500 mm of water throughout the growing cycle. In order to accumulate saccharose in the stems, a dry season or a thermal deficit is required. This crop is not stringent in terms of rich soils, however, grows better when over 1 m of depth, good porosity, and well-drained soils are available. The ideal pH is around 6.5 however, grows well in soils with pH varying from 5.0 to 8.5. For a productivity of 100 ton/ha, 100 to 200 kg/ha of nitrogen, 20 to 90 kg/ha of phosphorous, and 120 to 160 kg/ha of potassium per year are required depending on soil fertility. Row spacing are usually between 1.1 to 1.4 m.
Usually sugarcane yield is expressed in terms of mass of stems per hectare, however, the rate of saccharose in relation to fresh weight is very important because this determines the total sugar or the alcohol production per ton of sugarcane.

Among the major varieties of sugarcane planted in the State of São Paulo there are: NA56-79, CB41-76, IAC52/150, SP70-1143, IAC48/65, and IAC51/205 which correspond to 78.7 percent of planted area (Planalsucar, 1984). In the study area, the predominant varieties are: NA56-79, SP70-1143, IAC51/205, IAC52/150, and SP70-1078. From the total area to NA56-79 variety. The variety SP70-1143 increased from 10 percent in 1983 crop year to 30 percent in 1986 gradually replacing the CB41-76, IAC52/150, IAC48/65, and IAC51/205 varieties.

Saccharose accumulation in the stems are also dependent on the variety. A variety is considered of short, medium, or long cycle according to the time it accumulates the maximum percentage of saccharose in the stems. The NA56-79 is a short cycle variety because it reaches the maximum of saccharose in the first months of harvesting. Basically for the first five months of harvesting only this variety is harvested followed by the medium cycle varieties (IAC52/150 and SP70-1143). Finally, the long term varieties which the maximum of accumulated saccharose is reached only at the end of the harvesting period are harvested (IAC51/205).

Sugarcane Production Forecast at the Plant

Sugarcane harvesting in the Center-South region of Brazil starts on April and ends on November of the same year. In order to plan the activities of sugar and alcohol production during that period it is very important to have an estimation of the volume of sugarcane stems to be industrialized before harvesting starts. This information at the plant level is used for cut and transportation planning having an important economic and managerial impact. In the case of the Barra Grande plant this estimation is done by the Agricultural Department which sends technicians out in the field to visually assess the productivity. The accuracy of this estimation is dependent on the experience of the technician.

As the plant has a rigorous control of the planted area and does not depend on other sugarcane suppliers, the estimation of production is obtained by multiplying the estimated yield by the planted area.

Data Available from the Barra Grande Plant

The agricultural areas of the Barra Grande plant are subdivided in farms which are subdivided in fields. A field is cultivated to the same variety and at the same development stage (first cut or ratoons) which is identified over planialtimetric charts that contain the spatial distribution of the planted areas. For each field a list is available containing information on variety, development stage, soil type, areal extent, production, planting date, and dates of the last two cuts. Other data concerned with industrial production are also available. The available information were concerned with the crop years of 1983/84, 1984/85, 1985/86, and 1986/87. Table 1 shows a summary of production and yield data for the analyzed crop years.

TABLE 1

One of the factors that affect sugarcane yield is the time between cuts of a field which normaly is expected to be 12 months. Table 2 summarizes the percentage of areas that are harvested between 7 and 18 months of growth for the four crop years analyzed.

TABLE 2

Spectral Data

Spectral data were obtained from Landsat 4 and 5 in digital format (CCT's). As the Landsat 4 presented problems with TM data transmission, only MSS data were used in this work. In fact the spatial resolution of the MSS system of 59 m by 82 m is quite adequate for this type of study. Rudorff (1985) concluded in his work that the best acquisition period of Landsat data for sugarcane yield estimation is during the month of February, therefore about two months in advance of the beginning of harvest. Table 3 shows the characteristics of the Landsat data acquired.

TABLE 3

A sample of approximately 130 fields representative of the major varieties and development stages from the entire data set provided by Barra Grande Plant was selected at each crop year. This selection criterion determined that the number of fields of a specific variety/development stage in the sample corresponds to the proportion of that variety/development stage in the plant's total agricultural area.

Given the proportion of variety/development stage to be selected, the fields were randomly chosen. However, after the random selection, the fields were outlined over both the plant maps and the images in order to guarantee a good spatial distribution and unambiguously location of the fields on the Landsat images and to facilitate the acquisition of the digital spectral information.

To be able to extract the spectral information from the CCT's an interactive image analyzing system was used. The images were loaded into the system image display at the 1:100,000 scale in which each pixel of the monitor corresponded to one pixel of the image. Once a selected field was located on the monitor using a map transparency overlay, a variable size cursor was used to extract the spectral response (digital count) of that field using a software package which provides for each sample the number of pixels, the mean, and the matrix of autocorrelation of the spectral bands. Each selected field has a specific address in the monitor display, which was used to identify that field on the different acquisitions once the relative positions of the fields are kept from image to image. This procedure not only helped expedite the work but also helped to locate the same sampled area in the images of the different crop years.

Normalization of Landsat Data

The normalization of Landsat digital data is the transformation of digital counts obtained directly on the CCT's in reflectance values. Several works such as Robinove (1982), Middleton and Lu (1983), and Medeiros (1987) have shown the importance of this normalization. This is particularly important in a work that utilizes different satellites obtained in several years as it is the case of the present work. This normalization makes the data more stable for multitemporal analysis.

The variation on the digital count of different acquisitions of the satellite is not due solely to the variation on target reflectance but also to variations in the atmospheric layer, sun elevation angle, calibration of sensors, etc. Also, there may occur different gain assignment during CCT generation. Variations due to the atmosphere are very difficult to be corrected once the availability of data usually occurs only close to major airports.

To transform the digital counts in reflectance, the following equation used by Brian and Barker (1987) was applied:

$$\text{Reflectance} = \frac{d^2 \times ¶}{E \times \text{sen}\alpha} \times \left[\frac{DC}{DC_{MAX}} \quad (R_{MAX} - R_{MIN}) + R_{MIN} \right] \qquad (1)$$

Where:

E = irradiance on top of the atmosphere (Table 4)

α = sun elevation angle of the image (Table 4);

DC = digital count extracted from CCT;

DC_{MAX} = maximum digital count (equal to 127 for the MSS processed in Brazil);

R_{MAX} = maximum radiance measured by the detector (Table 4);

R_{MIN} = minimum radiance measured by the detector (Table 4);

d = distance between the sun and Earth in astronomic units (Table 4)

TABLE 4

Vegetation Index

Linear transformations of spectral bands in vegetation indices have the benefit of expressing the spectral behavior of crops and vegetation in a simplified manner, enhancing their growing conditions. Ideally, a vegetation index should be sensible to vegetation conditions and not to background variations (soil and shadow), in addition it should not be much affected by the atmosphere as suggested by Jackson et al. (1983). Unfortunately, there is no such an index and the different indices proposed in the literature may work better than others for specific situations or crop growing conditions.

Rudorff (1985) analyzed several indices revised by Jackson et al. (1983) and concluded that the ratio of the reflectance of the near infrared band by the red band (RVI), is among the best indices to relate spectral data and observed sugarcane yield. Jackson et al. (1983) recommended the use of RVI when the crop are covering more than 50 percent of the soil. By the time the Landsat data were acquired, the crop was at the end of its vegetative growth and therefore, covering almost completely the soil. Thus, the ratio vegetation index was used in this work according to the following equation:

$$RVI = MSS\ 4\ /\ MSS\ 2 \tag{2}$$

Where:

RVI = vegetation index;

MSS 4 = reflectance value in Landsat MSS band 4;

MSS 2 = reflectance value in Landsat MSS band 2.

Agrometeorological Model

An agrometeorological model using the approach suggested by Doorembos and Kassam (1979) was developed to estimate sugarcane yield as a function of climatic conditions and soil water availability. The description of the model, the data set used, and the corresponding software are reported by Rudorff and Batista (1989). The model estimates the maximum yield (Ym) of a well-adapted crop to the given growing environment, as a function of temperature and radiation during the crop cycle assuming that all remaining factors such as water, nutrients, pests, and disease are not limiting yield. This maximum yield is then decreased as a function of the deficit of relative evapotranspiration, according to the following equation:

$$(1 - Ye/Ym) = ky\ (1 - ETa/ETm) \qquad (3)$$

Where:

Ye = estimated yield;

Ym = maximum yield;

ky = yield response factor;

ETa = actual evapotranspiration;

ETm = maximum evapotranspiration.

When the water available to the crop is equal to its demand, ETa will be equal to ETm and Ym will not be penalized. However, when the demand for water by the crop is greater than the available water, ETa will be lower than ETm and Ye will be lower than Ym. The ky value equal to 1.2 was used in Eq. 3 as suggested by Doorembos and Kassam (1979) to relate a deficit in evapotranspiration to a decrease in yield.

Equation 3 can be rewritten as:

$$Ye = Ym\ (1 - ky\ (1 - ETa/ETm)) \qquad (4)$$

Or:

$$Ye = Ym * kp \qquad (5)$$

Where:

kp = 1 -ky (1 - ETa/ETm), penalizing factor and other variables are defined in Eq. 3.

Maximum yield (Ym) was calculated based on the concept of De Wit (1965) cited by Doorembos and Kassam (1979). Initially, the gross dry matter production of a standard crop in clear days (yc) and in cloudy days (yo), is calculated, taking into consideration the fraction (F) of the day which is cloudy. The rate of production (ym) for the crop being analyzed, is a function of local air temperature. The values of yc and yo are adjusted for a specific crop according to the following equations:

When $ym > 20$ kg/ha/hour,

$$Yo=F(0.8+0.01\ ym)\ yo+(1-F)(0.5+0.025\ ym)\ yc \qquad (6)$$

When $ym < 20$ kg/ha/hour,

$$Yo=F(0.5+0.025\ ym)\ yo+(1-F)(0.05\ ym)\ yc \qquad (7)$$

Ym is obtained by multiplying the value of maximum gross dry matter production of sugarcane (Yo) by three correction factors (cL, cN, and cH). The leaf area correction factor (cL) equal to 0.5 was used to generate mean values of Yo inasmuch as the crop has maximum production of dry matter only when it has maximum leaf area index. The dry matter production factor (cN) equal to 0.5 was used to generate the mean net dry matter production inasmuch as it was assumed that the crop consumes 50 percent of the absorbed energy in the process of respiration. To convert the mean net dry matter in agricultural yield of sugarcane, given in ton/ha, the harvest factor (cH), equal to 2.3, was used according to Ometto (1981).

In the present work the maximum yield was initially calculated for monthly periods, adding up later on the monthly values to obtain maximum yield for the entire crop cycle.

The estimation of ETm is based on the concept of reference evapotranspiration (ETo), which relates to ETm by an empirically determined crop coefficient (kc). The values of kc were derived from Planalsucar (1984). ETo was calculated using a practical method for the application of Penman method as proposed by Frere and Popov (1979).

ETa of a crop is kept equal to ETm until a fraction of the available soil water is consumed, and then, ETa becomes lower than ETm. Under this condition, ETa depends on both the estimated value of ETm and on the depth of remaining available soil water. The depth of remaining available soil water depends on the fraction of the available soil water, the soil water holding capacity, and on the root depth.

ETa is estimated following the description in Doorembos and Kassam (1979) in a monthly basis using a look up table based on the values of ETm, the depth of the remaining available soil water, and an available soil water index which depends on the depth of the remaining available soil water, the monthly value of ETm, the effective rainfall, and the actual depth of the available soil water at the beginning of the month for a specific root depth.

Ye was calculated in this work, from the planting date (for the first cut) or from the harvesting date (for ratoons) until the next harvest which was assumed to be in April, providing this way, a prognostic estimation since harvesting begins in April in this region.

The estimated yield (Ye) by the agrometeorological model represents the mean sugarcane yield of a standard variety, for a specific period, under certain climatic conditions. To take into account the yield potential of different varieties a correcting factor (kvs) was proposed according to the following equation:

$$kvs_{(X,\ Y,\ Z)} = \frac{Ymo\ (X,\ Y,\ Z)}{Yme\ (X,\ Y,\ Z)} \tag{8}$$

Where:

kvs = variety-stage correcting factor;

Ymo = mean observed yield provided by the sugarcane plant;

Yme = weighted mean yield estimated by the agrometeorological model (Eq. 9);

X = crop year; Y = variety; Z = stage.

The harvesting period starts in April and finishes in November. During this period some varieties are predominantly cut at the beginning, in the middle, or at the end of the harvesting period according to the growing cycles of the varieties. To take into consideration the impact of the date of harvesting on the estimated yield, Ye was weighted by the number of harvested areas in each month based on previous year's data, according to the following equation:

$$Yme_{(X,\ Y,\ Z)} = \frac{\sum_{i=APR}^{NOV} (Ye_{(i)} \times N_{(i)})}{\sum_{i=APR}^{NOV} N_i} \qquad (9)$$

Where:

Yme = mean estimated yield by the agrometeorological model, weighted by the number of areas planted or harvested in each month;

i = month of planting (first cut) or harvesting (ratoons);

N = number of areas planted or harvested of a given variety-stage in the previous year, for each month;

X = crop year, Y = variety, and Z = stage.

Finally, the estimated final yield by the agrometeorological model (Yek) in tons of sugarcane stems per hectare is given by:

$$Yek = Yme \times kvs \qquad (10)$$

Where:

Yek = final estimated yield by the agrometeorological model of a given variety, at a given stage, considering the period from planting or harvesting until April of the following year;

Yme = Eq. 9;

kvs = Eq. 8.

Proposed Yield Model

The yield model proposed in this paper combines the results obtained by the agrometeorological model with the vegetation index obtained from Landsat.

The high frequency of meteorological data collection allows the monitoring of the climatic conditions throughout the growing cycle by the agrometeorological model. On the other hand, spectral data from the Landsat have high spatial resolution and allows the observation of variations on the different crop fields inasmuch as the spectral response of a sugarcane plantation might reflect the collective effect of several factors on the crop growth. With the agrometeorological model, the effect of the major climatological factors on crop growth may be quantified. However, other factors such as soil, cultivation practices, diseases, pests, etc. also impact crop yield and these factors may not be quantified by the agrometeorological model.

The integration of spectral data transformed into vegetation index with the agrometeorological model cannot be made in a multiplicative way because the vegetation index is not independent of factors used in the agrometeorological model. In fact, the climatic effect on crop growth is also represented in the vegetation index.

Based on the work of Barnett and Thompson (1982), regression technique was used to integrate vegetation indices obtained from Landsat data with estimated yield data obtained by the agrometeorological model to generate the proposed model for sugarcane yield estimation.

The first crop year analyzed (1983/84) was used to generate the model (regression equation) which represents the best fit of the observed yield with both vegetation index and estimated yield by the agrometeorological model. This model was used to estimate the yield for the following crop year (1984/85). The model for subsequent years were based on all previous years data since 1983/84 crop year.

Results and Discussion

Agrometeorological Model

The agrometeorological model was used to estimate sugarcane yield of the crop planted from December to April and for the crop harvested from April to November. Table 5 shows the results of this model for the four crop years analyzed.

TABLE 5

The estimated yield is a function of climatic conditions between planting or last cut and beginning of the current harvest (April) for a standard variety. However, as the different varieties-stages has different yield potentials, a correcting factor (kvs) was applied according to Eq. 8.

The kvs for the crop year of 1984/85 was derived based on data of 1983/84 crop year whereas for the subsequent crop years all previous data since 1983/84 crop year, were used.

Table 6 shows the mean estimated values of yield of the entire agricultural area of the sugarcane plant obtained by the agrometeorological model with and without the variety-stage correcting factor and the percent estimation error based on observed yield information.

TABLE 6

The variety-stage correcting factor improved very little the estimation of mean yield by the agrometeorological model. This occurred because the variations among observed and estimated yield was not constant from year to year.

Table 6 also shows the accuracy results of the regression analysis of observed yield on yield estimated by the agrometeorological model with and without the variety-stage correction factor. It can be observed that both coefficient of determination and the standard error of the estimation were not improved significantly by the correction factor. Probably the variation in yield not explained by the agrometeorological model is due to some other factors (e.g. soil, fertilization, harvesting date, etc.) which are not taken into consideration in this model, and therefore, the correcting factor (kvs) should be further investigated in additional crop years before its use could be recommended.

Thus, the kvs was not used in the remaining analyses reported in this paper.

Vegetation Index Model

A regression analysis of the observed yield on the vegetation index was run to verify the potential of spectral data for sugarcane yield estimation. Based on the data set of 1983/84 crop year, the regression model for 1984/85 was generated. Models for the subsequent crop years were obtained based on all previous years data since 1983/84. The resulting models for the different crop years are presented in Table 7 along with their accuracy figures. It can be noticed that the percent relative error of this estimation is lower than the agrometeorological model estimations.

TABLE 7

Proposed Model

The agrometeorological model explains a large portion of the variation in yield. However, the estimation from this model is just a function of the climatic conditions prevailing from planting or last cut until April (beginning of harvest). This way, other factors such as variety, stage of cutting, fertilization, pests, and diseases are not taken into account by this model and their effect on yield is not easy to be determined.

The agrometeorological model allows the monitoring of climatic effect on crop yield based on monthly averages of meteorological parameters whereas the vegetation index obtained at the final phase of the vegetative growth of the crop (February-March), reflects the collective effect of several factors on the growth of the crop. Thus, the high temporal frequency of parameters used in the agrometeorological model is complemented by the high spatial resolution of the spectral Landsat data.

Based on data from the 1983/84 crop year, a regression of the observed yield (Yo) with vegetation index (RVI) and estimated yield by the agrometeorological model (Ye) was run to generate the proposed model for the 1984/85 crop year. Similarly, based on all previous data since 1983/84 crop year the proposed models for the subsequent crop years were generated and results are presented in Table 8.

TABLE 8

Table 8 shows that the model explained 69 percent of the observed yield variation for the 1984/85 crop year. For the crop years of 1985/86 and 1986/87 the model explained 54 and 50 percent respectively, of the observed yield variation. The scatter plots of the relationship between observed and estimated yield by the proposed models are presented in Fig. 3.

FIGURE 3

If only mean yield is examined the model based on just the vegetation index gave the best results in terms of relative difference (Table 7). On the other hand, the agrometeorological model gave systematically underestimations of the mean yield what suggest that some improvements in the parameterization of this model could have improved the results. In addition to the simplicity of this model, it allows yield estimations independent of satellite images.

The proposed model based on both spectral and agrometeorological data improved results especially for the 1984/85 and 1985/86 crop years as indicated by the coefficients of determination and the standard errors of estimation.

The superiority of the proposed model in comparison with the vegetation index model is also apparent on the stability of the regression coefficients. The coefficients of the vegetation index model are quite variable (Table 7). This instability is probably due to atmospheric and sensor response fluctuations which interfere in the spectral reflectance of the crop.

The regression technique used to generate the proposed model requires that the vegetation index (RVI) and estimated yield by the agrometeorological model (Ye) be fairly independent. Even though both RVI and Ye are independently well related with observed sugarcane yield, the correlation coefficients between these variables for the 1983/84, 1984/85, 1985/86, and 1986/87 crop years were 0.25, 0.48, 0.03, and 0.18, respectively, and therefore, the assumption required for the regression analysis seemed to be reasonably met.

Summary, Conclusions, and Recommendations

The agrometeorological model explained 64, 28, 37, and 49 percent of the observed yield variation in the 1983/84, 1984/85, 1985/86, and 1986/87 crop years, respectively.

The vegetation index models explained 59, 24, and 14 percent of the variation in observed yield for the 1984/85, 1985/86, and 1986/87 crop years, respectively.

The proposed models explained 69, 54, and 50 percent of the variation in observed yield for the 1984/85, 1985/86, and 1986/87 crop years, respectively.

The proposed models resulted in higher coefficients of determination and lower standard errors of estimation than the models that are just based on either vegetation index or agrometeorological variables, especially for 1984/85 and 1985/86 crop years. For the 1986/87 crop year, the contribution of the vegetation index was not significant and the proposed model had the same performance of the agrometeorological model. In addition, the proposed models had good stability of the equation coefficients on the four crop years analyzed.

The vegetation index models had good estimations of mean yield for the three crop years analyzed. However, their equation coefficients were quite variable from year to year. In addition, their coefficients of determination and standard error of estimation were low except for the 1984/85 crop year.

The incorporation of the variety-stage correction factor did not improve conclusively the yield estimated by the agrometeorological model and it is advised that this factor be tested for additional crop years before its use could be recommended.

The agrometeorological model systematically underestimated the sugarcane yield what suggests that improvements in the parameterization of this model might result in improved performance.

It is suggested that techniques to estimate some agronomic parameters (e.g. LAI) through spectral data, used in the agrometeorological model, be further investigated. Also, in order to attenuate the additive effects on the spectral data, atmospheric correction procedures should be used.

Even though this work has been developed using commercial fields plantations, where several interacting factors may determine variations in crop yield and even though the spectral data used have been gathered from an orbital platform having the entire atmospheric layer between the target and the sensor, results were very encouraging. Current results are comparable with conventional methods used at the plant level especially at the field by field basis, with potential for improvements.

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FIGURE LEGENDS

Figure 1. Location of the study area showing the areas planted to sugarcane in Brazil.

Figure 2. Growing cycle of the sugarcane plantation.

Figure 3. Scatter plot of the relationship between observed yield (Yo) and estimated yield by the proposed models for a) 1984/85; b)1985/86; and c)1986/87 crop years.

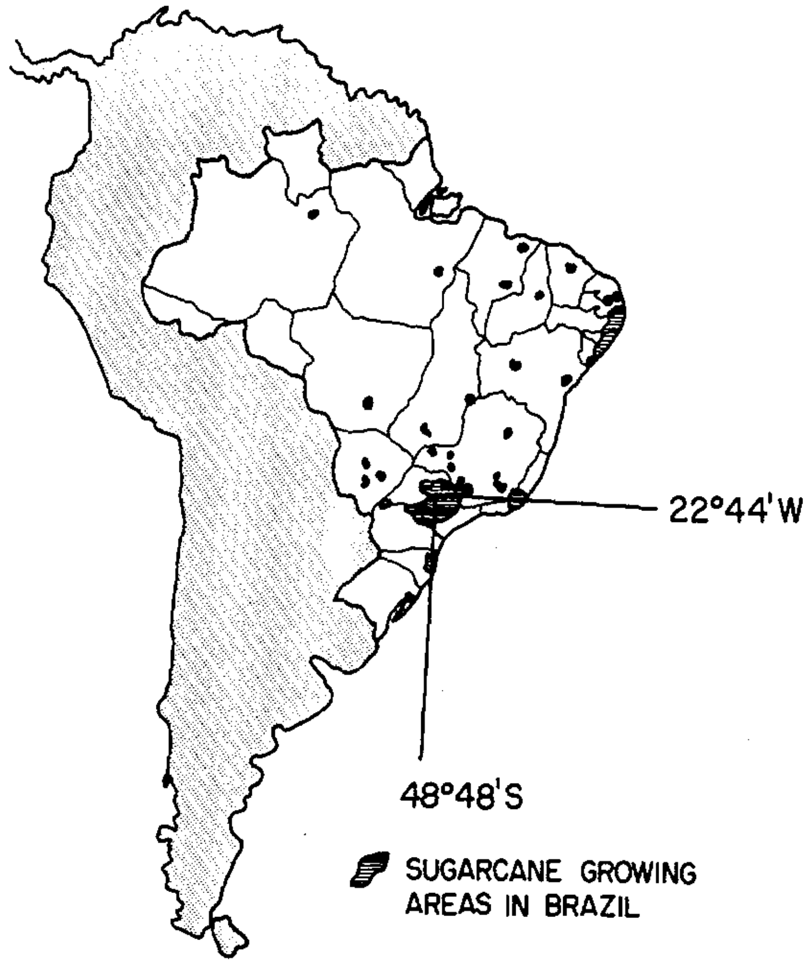


FIGURE 1

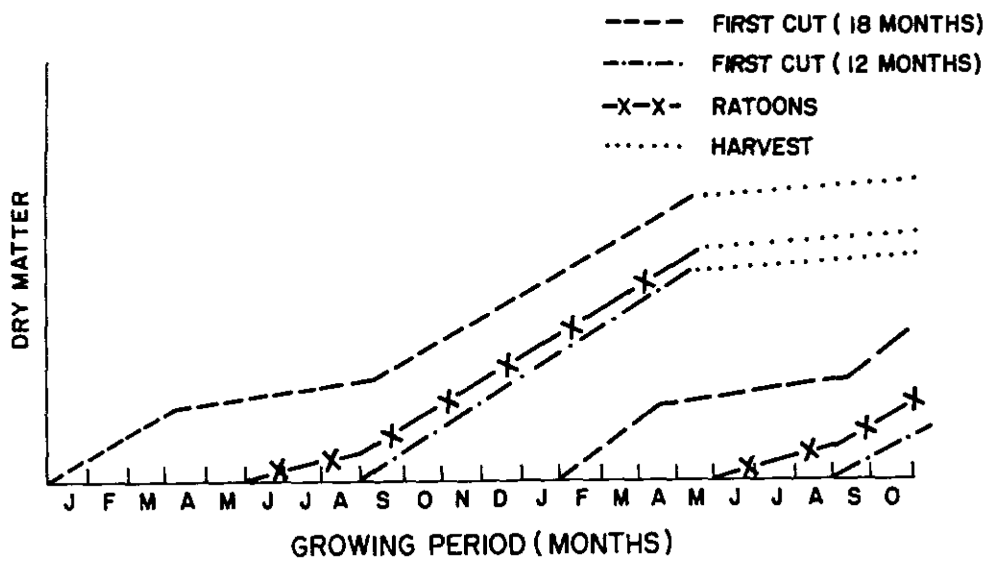
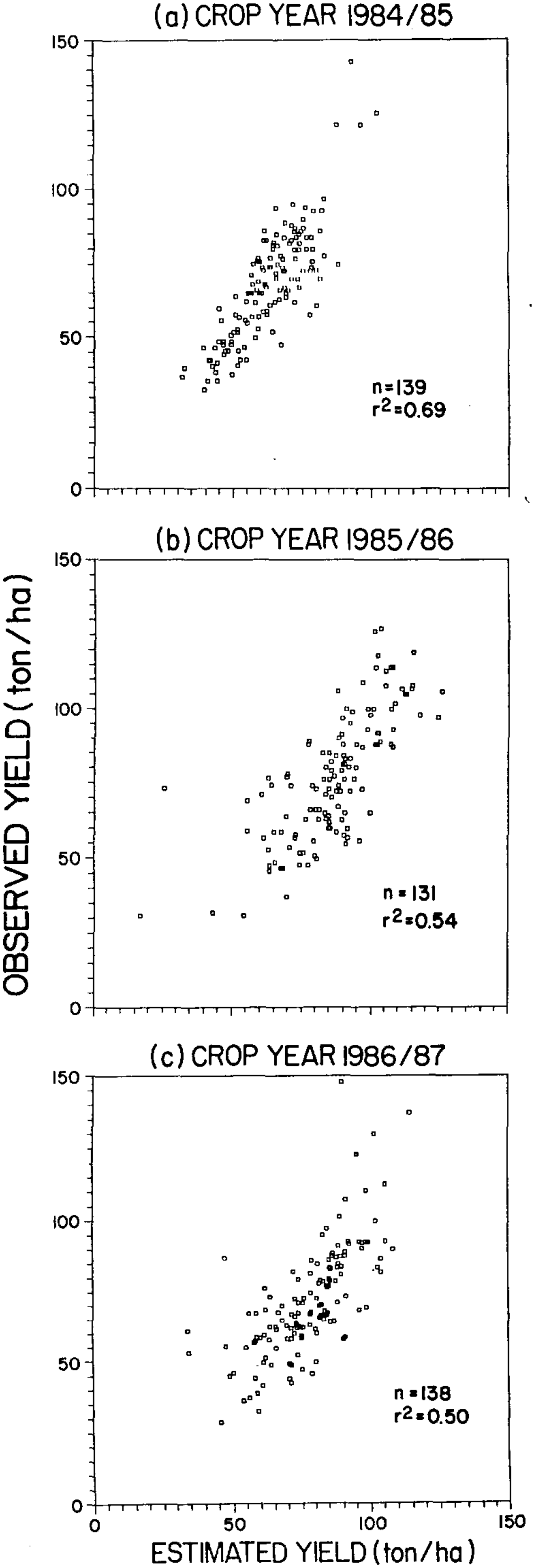


FIGURE 2



(a) CROP YEAR 1984/85
n=139
r2=0.69
(b) CROP YEAR 1985/86
n=131
r2=0.54
(c) CROP YEAR 1986/87
n=138
r2=0.50
OBSERVED YIELD (ton/ha)
ESTIMATED YIELD (ton/ha)
0
50
100
150

TABLE 1 Production and Yield Data for the Main Varieties on the Crop Years of 1983/84, 1984/85, 1985/86, and 1986/87 at the Barra Grande Plant Production Area

CROP YEAR	1983/84	1984/85	1985/86	1986/87
Yield (ton/ha) (first cut)	106.5	100.7	103.3	89.4
Yield (ton/ha) (ratoons)	70.3	65.0	73.0	67.0
Production (%) (first cut)	26.3	12.7	17.5	24.6
Production (%) (ratoons)	65.5	79.2	75.9	71.5
Yield (ton/ha) (analyzed varieties)	77.8	68.4	77.2	71.6
Yield (ton/ha) (overall for the Plant)	78.5	68.6	77.8	71.0

TABLE 2 Overall Percentage of Ratoons Harvested per Number of Months of Growth at the Barra Grande Plant Production Area

NUMBER of MONTHS of GROWTH	7	8	9	10	11	12	13	14	15	16	17	18
1983/84	1.3	1.3	1.6	3.4	12.6	30.3	22.5	13.8	8.8	2.4	1.0	0.9
1984/85	0.1	0.3	4.8	20.9	33.8	23.9	7.6	3.2	1.8	1.3	0.8	1.5
1985/86			0.4	1.0	11.7	26.4	27.8	15.5	10.6	4.1	1.7	0.7
1986/87		0.3	1.4	6.2	13.8	26.2	17.5	7.6	3.1	1.1	0.9	0.4

TABELA 3 Landsat Data

CROP YEAR	ACQUISITION DATE	SENSOR	LANDSAT	BANDS
1983/84	FEB/25/83	MSS	4	1, 2, 3, 4
1984/85	FEB/28/84	MSS	4	1, 2, 3, 4
1985/86	MAR/26/85	MSS	5	1, 2, 3, 4
1986/87	FEB/25/86	MSS	5	1, 2, 3, 4

TABLE 4 Maximum (Rmax) and Minimum (Rmin) Radiance, Irradiance on top of the Atmosphere (E), Sun Elevation Angle (α), and Sun-Earth Distance (d) for the analyzed Landsat MSS Images

IMAGE ACQUIS. DATE	MSS1			MSS2			MSS3			MSS4			α	d (a.u.)
	Rmax	Rmin	E	Rmax	Rmin	E	Rmax	Rmin	E	Rmax	Rmin	E		
02/25/83	23.0	0.2	185.1	18.0	0.4	159.3	13.0	0.4	126.0	13.0	0.3	87.8	48^{o}	0.9898
02/28/84	23.8	0.4	185.1	16.4	0.4	159.3	14.2	0.5	126.0	11.6	0.4	87.8	47^{o}	0.9905
03/26/85	26.8	0.3	184.9	17.9	0.3	159.5	14.8	0.5	125.3	12.3	0.3	87.0	45^{o}	0.9976
02/25/86	26.8	0.3	184.9	17.9	0.3	159.5	14.8	0.5	125.3	12.3	0.3	87.0	48^{o}	0.9898

Source: Brian and Barker (1987).

TABLE 5 Agrometeorological Model Estimations of Maximum Yield (Ym in ton/ha), Penalizing Index (kp), and Estimated Yield (Ye in ton/ha)

CROP YEAR		1983/84			1984/85			1985/86			1986/87		
DATE		Ym	kp	Ye	Ym	kp	Ye	Ym	kp	Ye	Ym	kp	Ye
PLANTING of FIRST CUT	DEC	122	0.86	105	116	0.80	92	130	0.82	106	128	0.72	92
	JAN	115	0.84	96	109	0.75	82	123	0.79	97	120	0.72	86
	FEB	106	0.83	88	102	0.75	76	113	0.74	84	112	0.73	82
	MAR	97	0.84	82	93	0.73	68	103	0.76	78	104	0.74	78
	APR	91	0.87	79	86	0.76	65	95	0.78	74	96	0.76	73
HARVEST of RATOONS	APR	91	0.89	81	86	0.74	63	95	0.83	79	96	0.76	73
	MAY	83	0.88	73	79	0.73	57	90	0.84	75	88	0.77	68
	JUN	77	0.87	68	75	0.73	54	83	0.83	69	83	0.79	65
	JUL	73	0.87	63	71	0.80	57	77	0.83	64	80	0.81	64
	AUG	67	0.88	59	56	0.77	51	71	0.84	60	76	0.81	62
	SEP	61	0.90	55	60	0.76	46	66	0.85	56	70	0.80	56
	OCT	54	0.89	48	56	0.77	43	59	0.86	51	62	0.86	53
	NOV	46	0.95	44	49	0.87	43	49	0.92	45	53	0.91	48

TABLE 6 Mean Estimated Yield (Ye) without (Yme) and with (Yek) variety-stage factor (kvs) by the Agrometeorological Model and Accuracy Figures of the Relationship between Estimated and Observed Yield

CROP YEAR	MEAN Ye (ton/ha)		RELATIVE DIFFERENCE(%)		STANDARD ERROR (%)		COEF. OF DETERMIN.	
	Yme	Yek	Yme	Yek	Yme	Yek	Yme	Yek
1983/84	65.1	——	-17.1	——	15.56	——	0.64	——
1984/85	52.5	61.3	-23.5	-10.6	16.06	15.39	0.28	0.34
1985/86	68.2	85.0	-12.3	+9.3	16.50	15.67	0.37	0.43
1986/87	65.2	78.1	-8.2	+10.0	14.10	14.03	0.49	0.49

TABLE 7 Vegetation Index Models for Sugarcane Yield Estimation (Y) and their Accuracy Figures

CROP YEAR	MODELS	MEAN YIELD (ton/ha)	RELATIVE DIFF. (%)	STANDARD ERROR (ton/ha)	COEFF. of DETERMIN.
1984/85	Y = -31.9 + 28.6 * RVI	72.1	5.1	12.2	0.59
1985/86	Y = -35.6 + 29.0 * RVI	83.8	7.7	18.1	0.24
1986/87	Y = -11.8 + 22.4 * RVI	75.5	6.3	18.6	0.14
1987/88	Y = -3.29 + 20.0 * RVI	——	——	——	——

TABLE 8 Proposed Models for Sugarcane Yield Estimation (Y) and their Accuracy Figures

CROP YEAR	P R O P O S E D M O D E L S	MEAN YIELD (ton/ha)	RELATIVE DIFF. (%)	STANDARD ERROR (ton/ha)	COEFF. of DETERMIN.
1984/85	Y = -43.4 + 17.1 * RVI + 0.862 * Ye	63.3	-7.1	10.5	0.69
1985/86	Y = -44.9 + 19.9 * RVI + 0.747 * Ye	87.2	12.1	14.1	0.54
1986/87	Y = -34.3 + 15.7 * RVI + 0.788 * Ye	78.1	10.1	14.0	0.50
1987/88	Y = -31.3 + 14.0 * RVI + 0.825 * Ye	——	——	——	——