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Wheat plays an important role in the Brazilian commodity production. Therefore, objective and reliable methods for yield estimation are needed specially at the farm level where several management actions have to be taken. TM Landsat and agrometeorological data were integrated in a mode for wheat yield estimation at the farm level for a test site in the south of São Paulo State. Landsat data for the crop years of 1986 (three acquisitions) and 1987 (two acquisitions), agronomic and meteorological data were related to yield estimates at the field level (200 fields approximately) Results have shown that vegetation index derived from TM Landsat explained 60 and 40 percent of wheat yield variability for the two crop years analyzed. The joint use of both vegetation index and agrometeorological data in a single model improved significantly the results as compared to either vegetation index or agrometeorological data separately. The proposed model is to be validated for future crop seasons nevertheless it provided objective and reasonably accurate results for wheat estimation on the two crop seasons analyzed, (R^2 = 0.65 with a standard error of 339 kg/ha).

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TITLE PAGE

WHEAT YIELD ESTIMATION AT THE FARM LEVEL USING LANDSAT TM AND AGROMETEOROLOGICAL DATA

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ABSTRACT Wheat plays an important role in the Brazilian commodity production. Therefore, objective and reliable methods for yield estimation are needed specially at the farm level where several management actions have to be taken. TM Landsat and agrometeorological data were integrated in a model for wheat yield estimation at the farm level for a test site in the south of São Paulo State. Landsat data for the crop years of 1986 (three acquisitions) and 1987 (two acquisitions), agronomic and meteorological data were related to yield estimates at the field level (200 fields approximately). Results have shown that vegetation index derived from TM Landsat explained 60 and 40 percent of wheat yield variability for the two crop years analyzed. The joint use of both vegetation index and agrometeorological data in a single model improved significantly the results as compared to either vegetation index or agrometeorological data separately. The proposed model is to be validated for future crop seasons nevertheless it provided objective and reasonably accurate results for wheat estimation on the two crop seasons analyzed, (R^2= 0.65 with a standard error of 339 Kg/ha).

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Wheat yield estimation at the farm level

1. INTRODUCTION

The availability of accurate information on crop yield is essential in different sectors of agriculture. Correct decisions are dependent on timely and accurate information. Crop yield models are designed to represent in a simple manner the relationship between the crops and their environment (Baier 1979). At present, the existing growth models are not suitable to simulate perfectly the overall impact of meteorological and cultural factors on crop yield. On the other hand, it is difficult to obtain timely and precise field observation on crop information over large areas to estimate potential yield (Colwell 1979). Recent studies have been performed on the suitability of digital Landsat data to estimate crop yields. The high correlation between spectral reflectance of crops and agronomic variables encouraged the application of those data on crop yield models (Tucker et al. 1980, 1981; Richardson et al. 1982; Wiegand et al. 1979; Hatfield 1981, 1983; among others). Although most of those studies have been performed on experimental fields using ground based radiometers, Wiegand et al. (1979) suggested that remote sensing data from satellite are ready to be used in crop yield estimation models.

However, improvement in the relationship between Landsat data and yield is dependent on research aiming the suppression of atmospheric effects and radiometric calibration. The several meteorological and cultural factors which affect the crop yield are indirectly observed through the vegetation index which is a transformation of the visible and infrared spectral bands able to express crop growing conditions and crop yield. Previous findings (Richardson et al. 1982; Barnett and Thompson 1982; Rudorff 1985; among others) show that the use of spectral data along with agrometeorological data provide better crop yield estimate as compared to those derived from just agrometeorological data.

This study was performed to assess the improvement on wheat yield estimation at the farm level by using vegetation index derived from Landsat data in addition to agrometeorological data.

2. METHODOLOGY

The study area is located at the main wheat production area in São Paulo state. The geographical coordinates of the area are 22° 30'S and 50o 30'W. The weather is wet, warm, and without a dry season, with 350mm of average total precipitation from April to September. The average temperature for the warmest month (January) is over 24°C and for the coldest month (July) is less than 17°C (Setzer 1966).

In Brazil wheat is planted as a winter crop and the states of Rio Grande do Sul, Paraná, Mato Grosso do Sul, and São Paulo are the major producers (Scheeren 1986).

In the study area, the wheat is generally planted after the soybean harvest from late April to early May. The two most planted varieties are Anahuac and BH-1146. The first is more productive but sensitive to water supply and soil fertility with a cycle of 120 days. The second is less productive but tolerant to dryness and lower soil fertility, its cycle is 100 days long.

In the study area 125 and 127 farms were selected during the crop year of 1986 and 1987, respectively. Crop field size in those farms varies from 10 ha to 50 ha. For each crop field the following data were collected: planting and harvesting dates, variety, observed yield in kg/ha and field boundaries of each crop area on the image.

For the crop year of 1986 the following TM-Landsat overpasses were acquired: June, 8th, June, 24th, and July, 10th. For the crop year of 1987 the TM-Landsat dates used were June, 27th and July, 13th.

TM data were digitally processed on a multispectral image analyzer at the scale in the monitor of 1:50:000 (one pixel on the image corresponds to one pixel on the monitor display). The digital number average and variance of TM bands 3 and 4 were acquired for each crop field analyzed. The average digital number for each band was converted to reflectance using the approach described by Brian and Barker (1987). The reflectance values were then transformed into the RVI vegetation index, which corresponds to the ratio between the reflectance in band 4 by the reflectance in band 3. This index is supported by Tucker (1979) for crops with more than 50% of ground cover. No atmospheric corrections were applied to the analyzed images because there was no appropriate data available to implement correction procedures. Nevertheless, all images were taken in very clear sky conditions over the test site.

The vegetation index was correlated with the observed yield of selected farms including different varieties of wheat and planting dates. The vegetation index, per se gives yield estimation. However, best results are obtained when agrometeorological data are used along with radiometric data. An agrometeorological model using the approach suggested by Doorembos and Kassam (1979) was developed for wheat in the south of São Paulo state. The description of the model is reported in Rudorff and Batista (1988) along with its corresponding software. The model estimates the maximum expected yield as a function of temperature and radiation during the crop cycle assuming that all remaining factors such as soil fertility, seeds and disease control are adequate to the crop.

This maximum yield is then decreased as a function of a factor which modulates the water supply. To take into account the potential yield of different varieties, a factor was proposed to adjust the estimates to that potential yield of the main varieties present in the study area.

Finally the study model is developed by relating crop yield estimates derived from agrometeorological model and vegetation index with the observed yield of selected fields.

3. RESULTS AND DISCUSSION

The high spatial resolution of the multispectral data from TM allows one to estimate reflectance variability among small crop fields. The vegetation index expresses the balance between incident, absorbed, reflected, and transmitted radiation by a given crop. This balance varies according to different phenological stage of the crop.

The RVI resulting from the ratio between the reflectances of TM band 4 and TM band 3 will increase as crop reflectance increases in band 4 and decreases in band 3. In the band 4, the leaf cell structure and the number of leaf layers are the major responsible factors for the reflectance of the canopy, whereas in band 3 leaf pigments respond for the absorption of the incident radiation, resulting in lower reflectance. It is generally expected that increases in the vegetation index correspond to increases in the photosynthetic activity of a given crop, what causes higher grain yield. Thus, it is possible to relate vegetation index to crop yield. However, variations in that relationship along the crop cycle are not well known for winter wheat planted in tropical region. Considering the low frequency of Landsat overpass (16 days), high frequency of cloud cover and the quite short length of the wheat cycle (100 days), data availability for such analysis is limited.

3.1 - **VEGETATION INDEX - 1986**

Three cloud-free overpass during the length of the wheat growing cycle were acquired for the year of 1986. At the first acquisition date (June 08th , 1986), most of the wheat areas were 35 to 45 days after planting. The following overpasses were obtained at 16 day intervals according to the Landsat track pattern. Vegetation indices were produced for each of these dates and regressed against observed crop yield, after harvesting the entire field, and the results are shown in Table 1. Data from June 24th provided the best results with vegetation index explaining 64% of the yield variation. At that date almost all crop fields were 50 to 60 days after emergence, that is: end of stem extension and beginning of the heading stage (from 7 to 10.1 of Feek's wheat growth stage, after Scheeren 1986).

To asses the impact of varieties and planting period on the relationship of the RVI and observed yield, a statistical analysis was performed on subsets of the data using the vegetation indices from the best acquisition date. The subsets of the data corresponded to the two most planted varieties Anahuac and BH-1146 planted at 8 planting periods. Although, significant improvements were obtained for both varieties especially for the planting period of April 21-25, which had the greatest number of samples, the overall results do not support the conclusion that homogenization of variety and planting period is necessary. Therefore, additional studies using field radiometry are recommended in controlled experiments using different varieties and planting periods.

June and July, 1986, were very dry. As a result, the planting date strongly influenced crop yield due to the lower availability of water for the fields planted in later periods (Figure 1a). The average of the vegetation index and the corresponding observed crop yield for each planting period, decreased following the delay in planting date periods except for the May 01-05 period.

3.2 - **VEGETATION INDEX - 1987**

The crop year of 1987 was also a nice year for cloud-free Landsat data availability. Based on the experience of the 1986 data analysis, only two overpasses were selected. June 27th and July 13th, which are almost anniversary dates in relation to the 2nd and 3rd overpasses of 1986.

Table 1 shows the results of the correlation between vegetation index and crop yield in 1987. The best results were found for June 27th, 1987 acquisition date. Data were also stratified according to planting date to assess the impact of this variable on the relationship between vegetation index for Anahuac variety and its observed yield. Results showed that the degree of correlation varied from one planting period to the other. For example, for fields planted in the period April 16-20, there was an increase in the correlation coefficient, whereas fields planted in the period May 06-10 displayed no significant correlation at 5 percent level.

During the crop year of 1987 there was a suitable rain distribution from seeding to maturation, followed by a dry period at the harvest, independent of the planting period. On Figure 1b one can observe some variation in yield for different planting periods with the vegetation index being sensitive to yield changes.

3.3 - VEGETATION INDEX - 1986 AND 1987

The availability of images at almost anniversary dates for both crop years allowed the comparison between the crop year of 1986 and 1987. Results have shown that the best acquisition date for 1986 was also the best for 1987. However, the values of vegetation indices are quite different from one crop year to the other, as indicated in Figure 1a and 1b. The average vegetation index in 1986 was 11% higher than that of 1987 whereas the average yield of 1986 is 28% lower than that of 1987. Pluviometric records for 1986 show that practically there was no rain during the 30 days previously to the Landsat overpass of June 24th. However, for 1987, intense rains were registered previously to the Landsat overpass of June 27th, 15thr (230 mm) and 23th (36 mm). The differences in rain distribution were the major factor that explained the instability of the relationship between vegetation index and crop yield for different crop years.

Atmospheric correction and sensor calibration could be performed in order to minimize the variations between the two dates. However, the major differences which could be visually observed on the color composite of the images are due to soil moisture content. At that growth stage of the crop (tillering to heading), the reflectance is also influenced by the soil reflectance, as a result, in overall, the image tonality became lighter in 1986 and darker in 1987 due to the higher soil moisture content in 1987.

In spite of the existing differences in vegetation indices between dates which are not related to the crop, an analysis involving all the data from both crop years was performed and resulted in 48 percent of the variation in the observed yield being explained by the RVI with a standard error of estimate of 414 kg/ha.

3.4 - AGROMETEOROLOGICAL MODEL

The agrometeorological model calculates the maximum yield for wheat as a function of radiation temperature from seeding to the harvest. This maximum yield was then decreased as a function of water availability what resulted in the estimate yield for generic wheat variety. To adjust this yield to potential yield for different wheat varieties, a multiplication factor derived from ground information was applied for the planted varieties as follow: Anahuac = 1.30, BH-1146 = 0.90, IAC 5 = 1.00, IAC 18 = 1.00 and PAR 281= 0.65. As a result, the agrometeorological model produced different yields as a function of seeding date, wheat variety, radiation, temperature and soil water availability.

The agrometeorological model can be applied for both local and regional scales. Comprehensive meteorological data used in this work were provided from a single meteorological station, except for the pluviometric data which were available in three different stations. Because of that, the model was not sensitive to variation in yield among different crop fields.

The estimated yield produced by the agrometeorological was regressed against the observed yield, resulting in an explained variation of only 33% and 18% and in with a standard error of estimate of 495 kg/ha and 355 kg/ha for 1986 and 1987, respectively. The regression using combined data from both years (86 and 87) resulted in an explained variation of 43% and a standard error of 434 kg/ha.

3.4 - **THE PROPOSED MODEL**

The agrometeorological model used was not able to explain, the variation in yield caused by meteorological variations within the study area due to its low spatial resolution (only one meteorological station and three precipitation gauges). On the other hand, the vegetation index could not explain variation in crop growing condition that might occur along the crop cycle since it was available for only few and specific acquisition dates.

By combining the high temporal resolution of meteorological data and high spatial resolution of Landsat data a new model was derived based on the regression of the observed yield on the vegetation index and the estimated yield by the agrometeorological model (AGRO):

$$\mathrm{YIELD}_{\mathrm{est}} = -676.0 + 253.5 * \mathrm{RVI} + 0.52 * \mathrm{AGRO}$$

The parameters of this model were derived using data from both crop years 1986 and 1987.

The results of this proposed model, when applied to the same set of data, increased the explained variation from 43% (agrometeorological model) and 48% (vegetation index) to 65% (agrometeorological and vegetation index). The standard error of estimates decreased from 434 kg/ha to 339 kg/ha for an average yield of 1581 kg/ha.

4. SUMMARY AND CONCLUSIONS

Best results were obtained with the late June acquisitions in both years when the wheat fields were with 50 to 60 days after planting: end of stem extension and beginning of the heading stage (from 7 to 10.1 of Feek's wheat growth stage, after Scheeren 1986).

The agrometeorological model explained 33% and 18% of yield variation for 1986 and 1987, respectively and 43% when data from both crop years were analyzed together. Similarly, the vegetation index (RVI) explained 64% and 46% of the yield variation for 1986 and 1987, respectively, and 48% for both years.

The incorporation of the vegetation index to the agrometeorological model improved significantly the results of yield estimation at the farm level. The proposed model increased the explained variation to 71% and 53% for 1986 and 1987, respectively, and to 65% when pooling together the data for both crop years.

Further investigation, especially to understand the year-to-year stability of the RVI as a function of variation in solar radiation, atmosphere interference, sensor calibration, scene characteristics and the geometry of data acquisition is recommend before the proposed model can be used operationally.

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TABLE 1

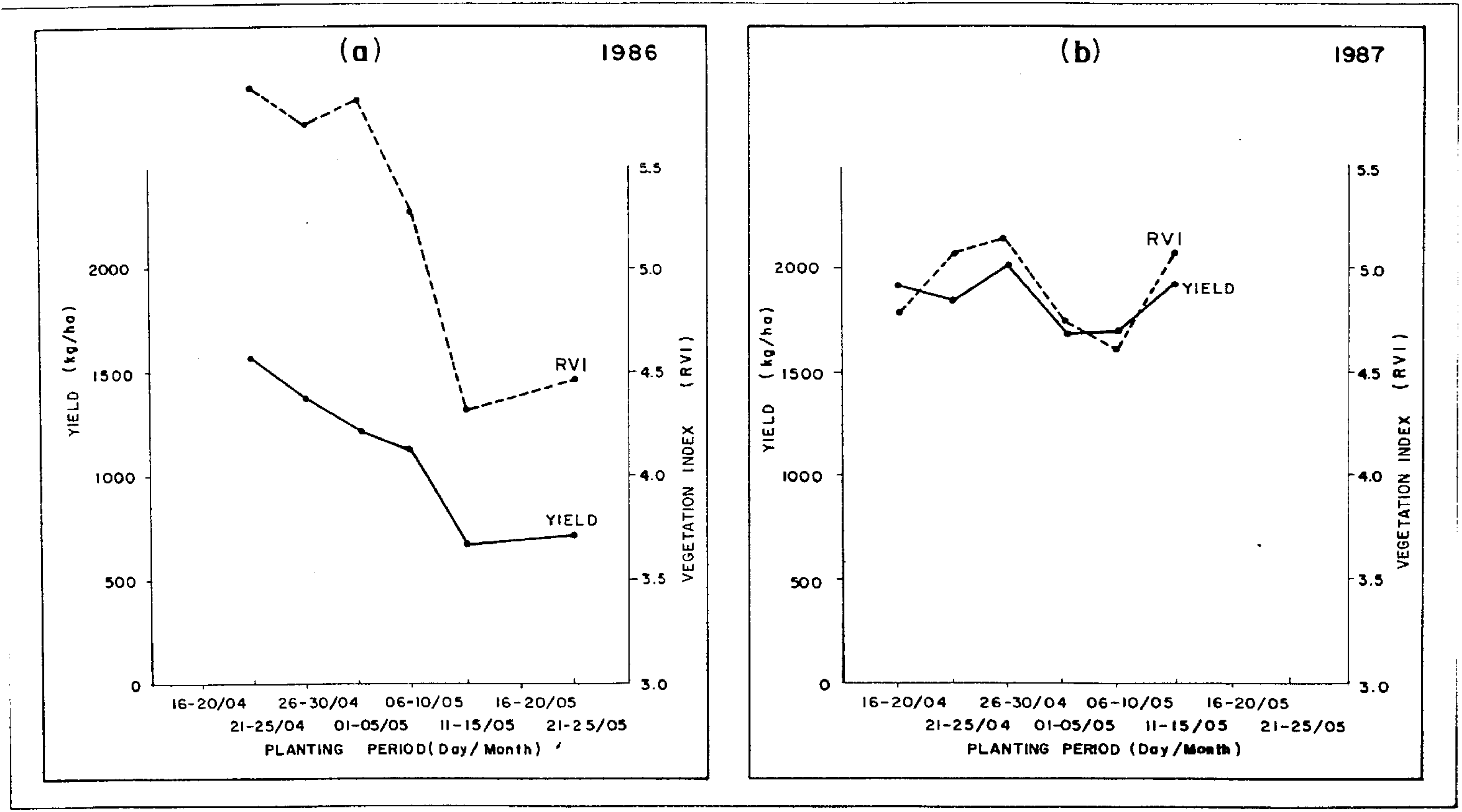
REGRESSION ANALYSIS OF OBSERVED YIELD AND VEGETATION INDEX (RVI) FOR 1986 AND 1987

YEAR	NUMBER OF SAMPLES	ACQUISITION DATES (MONTH/DAY/ YEAR)	CORRELATION COEFFICIENT (r)	COEFF. OF DETERM. (r2)	STANDARD ERROR (ton/ha)
1986	125	06/08/86	0,68	0.46	443
		06/24/86	0,80	0,64	366
		07/10/86	0,73	0,54	411
1987	127	06/27/87	0.67	0.46	290
		07/13/87	0.43	0.19	353

Figure 1 - Average of observed yields and average of vegetation indices as a function of planting period; (a) acquisition date of June 24th, 1986; (b) acquisition date of June 27th, 1987.

SHORT TITLE

Wheat yield estimation at the farm level


(a)
1986
YIELD (kg/ha)
0
500
1000
1500
2000
VEGETATION INDEX (RVI)
3.0
3.5
4.0
4.5
5.0
5.5
RVI
YIELD
16-20/04
21-25/04
26-30/04
01-05/05
06-10/05
11-15/05
16-20/05
21-25/05
PLANTING PERIOD(Day/Month)
(b)
1987
YIELD (kg/ha)
0
500
1000
1500
2000
VEGETATION INDEX (RVI)
3.0
3.5
4.0
4.5
5.0
5.5
RVI
YIELD
16-20/04
21-25/04
26-30/04
01-05/05
06-10/05
11-15/05
16-20/05
21-25/05
PLANTING PERIOD (Day/Month)