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SPECTRAL RESPONSE OF WHEAT AND ITS RELATIONSHIP WITH AGRONOMIC VARIABLES IN THE TROPICAL REGION

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RESUMO-NOTAS/ABSTRACT-NOTES

The spectral behavior of three varieties of wheat (Anahuac, IAC-24, and BH-114) was analyzed using field radiometry throughout the 1988 growing season, in the region of Assis, SP. The field radiometric data were obtained in the visible and near infrared portion of the electromagnetic spectrum of 30 sampled fields distributed in commercially planted fields of four farms. The radiometric data were transformed into vegetation indices which are expected to represent crop growing conditions and development. These indice were related to agronomic variables (grain yield, green phytomass, dry phytomass, canopy height, etc) obtained in ten measurement missions carried out weekly beginning at initial stages of growing (30 days after planting approximately) until harvesting. the main objetive of this work was to verify the potential of spectral data to estimate grain yield of wheat growing in tropical region. It was observed that the vegetation index obtained at booting to beginning of flowering stages was quite well related to the final grain yield and correlation coefficients of 0.82 to 0.93 were obtained. The radiometric data were analyzed multitemporally also, where the vegetation indices were integrated throughout the growing cycle and related to the final yield. Another analysis, included the incorporation of spectral data into an yield estimation model denominated agrometeorological-spectral model. This model was developed to provide an assessment of the growing conditions of a crop through meteorological and spectral variables. Results obtained clearly indicated that the reflected energy at certain stages of the crop development and at certain wavelength bands are well related to the final grain yield. Therefore, spectral data, transformed into vegetation indices have great potential to be used in yield predicting models for wheat growing in tropical regions.

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SPECTRAL RESPONSE OF WHEAT AND ITS RELATIONSHIP WITH AGRONOMIC VARIABLES IN THE TROPICAL REGION

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SPECTRAL RESPONSE OF WHEAT AND ITS RELATIONSHIP WITH AGRONOMIC VARIABLES IN THE TROPICAL REGION

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The spectral behavior of three varieties of wheat (Anahuac, IAC-24, and BH-1146) was analyzed using field radiometry throughout the 1988 growing season, in the region of Assis, SP. The field radiometric data were obtained in the visible and near infrared portion of the electromagnetic spectrum of 30 sampled fields distributed in commercially planted fields of four farms. The radiometric data were transformed into vegetation indices which are expected to represent crop growing conditions and development. These indices were related to agronomic variables (grain yield, green phytomass, dry phytomass, canopy height, etc) obtained in ten measurement missions carried out weekly beginning at initial stages of growing (30 days after planting approximately) until harvesting. The main objective of this work was to verify the potential of spectral data to estimate grain yield of wheat growing in tropical region. It was observed that the vegetation index obtained at booting to beginning of flowering stages was quite well related to the final grain yield and correlation coefficients of 0.82 to 0.93 were obtained. The

radiometric data were analyzed multitemporally also, where the vegetation indices were integrated throughout the growing cycle and related to the final yield. Another analysis, included the incorporation of spectral data into an yield estimation model denominated agrometeorological-spectral model. This model was developed to provide an assessment of the growing conditions of a crop through meteorological and spectral variables. Results obtained clearly indicated that the reflected energy at certain stages of the crop development and at certain wavelength bands are well related to the final grain yield. Therefore, spectral data, transformed into vegetation indices have great potential to be used in yield predicting models for wheat growing in tropical regions.

Introduction

The technology of remote sensing is quite useful for evaluating the conditions of large extensions of the Earth surface in a timely basis, especially if the acquisition of data is through Earth observation satellites. In agriculture, remote sensing has been an important tool for estimating crop production of large areas (Henderson and Badhwar, 1984). However, in spite of the proved potential of spectral data to estimate agronomic parameters used in yield estimating models, there are no reliable methods that use these data operationally. The instability of the relationship between spectral data and agronomic parameters caused by calibration problems and by variation of the atmospheric layer are the major limitations to the use of remote sensing for crop production forecast. The next decade will see a multitude of sensor systems that will be launched aboard of orbital platforms. There will be a great demand for methods that are able to integrate the various factors that affect crop yield.

Agricultural production is subject to fluctuations caused by several interactive factors. The effect of these factors on yield variation is difficult to be quantified for large areas. However, as remote sensing allows the acquisition of data over extensive areas and can be used to estimate agronomic parameters which may be obtained from the reflected energy by the crop in certain wavelengths, this technique have great potential to contribute for yield predicting models.

Wheat has been subject of several studies that have the objective of estimating agronomic parameters from the spectral energy reflected by the crop. This fact is probably due to the importance of this grain for food in the international community, and therefore it is very important to have reliable and timely information on the production of this commodity. However, the majority of the studies have been conducted in temperate regions. Very little has been done to understand the relationship between agronomic parameters and spectral response of wheat cultivated in tropical regions.

The objective of this work was both to analyze the spectral behavior of wheat throughout its development cycle and to study the relationship of the reflected energy by the crop with agronomic parameters. This study was conducted at the field level, using field radiometry over sampled fields of commercial farms of an important wheat production region of Brazil.

Remote Sensing and Yield Models

Crop yield at field conditions depends on several factors such as: soil fertility, pests and disease control, planting stands, temperature, available water, radiation, etc. These factors affect the reflectance of the canopy which in turn is related with final yield (Wiegand et al., 1979; Thompson and Wehmanen, 1979; Brakke and Kanemasu, 1979; Rao et al., 1982; Richardson et al.,1982; and Wiegand, 1984).

The significant correlation between reflectance factors of the crop with agronomic parameters related to yield such as leaf area index (LAI), phytomass, absorbed photosynthetic active radiation (APAR) has induced the use of spectral data in yield predicting models (Pearson and Miller, 1972; Ashley and Rea, 1975; Tucker et al., 1980, 1981; Richardson and Wiegand, 1977; Richardson et al., 1982; Wiegand et al. 1979; Hatfield, 1981, 1983; Rudorff, 1985; Rudorff and Batista, 1988, 1989a, 1989b; among others).

Idso et al. (1980) estimated the yield of wheat using a vegetation index to assess the senescence rate of the crop assuming that plants under stress senesce earlier and consequently have a lower yield than healthy plants. Following this research, Pinter Jr. et al. (1981) proposed a new technique to estimate yield of wheat under water stress. The authors plotted the trajectory of the vegetation index (NDVI) throughout the growing cycle of the crop and verified that the area under the spectral trajectory was closely related to the final yield. This occurs because the highest the LAI and the period that it remains high, the highest is the yield. As LAI is closely related to crop reflectance, the same should be expected to occur with the vegetation index.

The spectral response of a crop represents the overall effect of several factors over its development condition and final yield (Badhwar and Henderson, 1981). On the other hand, yield models based on both spectral and meteorological data give better results than the models that utilize either data separately (Richardson et al., 1982; Barnett and Thompson, 1982; Rudorff, 1985; and Rudorff and Batista, 1988, 1989a, 1989b). The high temporal frequency of the meteorological data in connection with the high spatial resolution of the spectral data are complementary and therefore, can provide improved results.

Transformation of Spectral Bands into Vegetation Indices

Linear transformations of spectral bands are used to express physically the characteristics of the spectral behavior of crops and natural vegetation emphasizing its growing conditions and are usually called vegetation indices.

Ideally, a vegetation index should be quite responsive to vegetation and not to the background variations (soil and shadow), in addition it should not be much affected by the atmosphere as suggested by Jackson et al. (1983). However, there is no such an index and the authors suggested the use of several indices to be able to assess the crop conditions throughout the growing cycle. Tucker (1979) concluded that the majority of the vegetation indices, commonly used, provided similar results for the estimation of the photosynthetically active phytomass.

Tucker et al. (1980) concluded that there is a close relationship between vegetation indices and wheat growing conditions and that these indices can explain a large part of the variation on crop yield.

Study Area

The study area is located in the municipality of Assis, São Paulo, in the Center-South region of Brazil which comprises the States of Paraná, São Paulo, and Mato Grosso do Sul and is one of the most important wheat production regions of Brazil responsible for 70 percent, approximately, of the national production. The coordinates of the center of the study area are 22^{o} 45′ S and 50^{o} 15′ W.

The major soil types of this region are Dark Red Latosol, Dusky Red Latosol, and "Terra Roxa Estruturada", in the Brazilian classification system which correlate approximately with Orthox, Eutrorthox, and Alfisols in the U. S. Soil Taxonomy according to Sanchez (1976). These are amongst the most fertile soils that occur in Brazil and presents low reflectance especially in the near infrared due to iron absorption bands (Baumgardner et al., 1985).

Wheat

Wheat (Triticum spp.) is one of the most important grain in human nutrition. This crop is quite well adapted, being cultivated from the equator up to 60^{o} of latitude (north and south); however the majority of the cultivated areas are concentrated between 30^{o} and 50^{o} of latitude (north and south) and the yield varies from lower than 1,000 kg/ha up to 10,000 kg/ha (Scheeren, 1986). Brazil was among the major importers of this commodity in the world market, and only in the 1987 and 1988 growing seasons the national production was close to the consumption. In 1987 the national production was 6.1 million tons and in 1988 it was 5.5 million tons for a consumption estimated in 6.3 million tons (FGV, 1988).

Selection of Sampled Fields

In the southwest part of São Paulo State wheat is planted from late April to beginning of May after harvesting the soybeans planted in the same field during the summer growing season. In this region the most commonly planted varieties are Anahuac, BH-1146, and IAC-24. The first is more productive but requires high soil fertility and plenty of available water and its cycle lasts for 120 days. The remaining two varieties are less productive but are more tolerant and therefore indicated for soils of low natural fertility and the duration of the cycle is around 100 days.

For this experiment, field radiometric data and agronomic measurements were obtained over 30 selected fields. These fields were distributed over four farms that represent the production system of the region. The plots were selected on areas with high, low, and average potential of yield as indicated by the farmers. This was a very important criterion, inasmuch as the objective of this work was to verify the relationship between yield variation and spectral data and therefore, it is necessary to have a large variation in yield. From the 30 selected fields, 17 were planted to Anahuac variety, 7 to IAC-24, and 6 to BH-1146. In each selected field planted for commercial production, a plot of 100 m^2 were outlined for the radiometric and agronomic measurements throughout the growing cycle. An area of 3 x 10 m was reserved for the destructive agronomic measurements and the remaining of the plot (7 m x 10 m) was used for the radiometric measurements. At the end of the crop cycle an area of 25 m^2 was harvested for yield estimation of the plot.

Radiometric measurements

To obtain the radiometric data a field portable spectroradiometer (SPECTRON SE-590) with two detector units (CE-390) was used. One of the detector units was pointed downward to the target (wheat) with a field of view of 15^{o} which captured the energy reflected (radiance) by the crop whereas the other unit with a cosine collector (180^{o}) was pointed upwards and captured the income solar radiation (irradiance). By relating appropriately these two measurements the reflectance factor of the target can be obtained.

Each detector unit has a diffraction filter and an array of photodiodes which allow to obtain the radiometric spectrum in 252 bands in a fraction of a second. The radiometer operation is controlled by a microprocessor (CE-500). The data is digitally recorded in a minicassette tape. The data recorded can be transferred through a RS232C interface to a microcomputer where the data can be analyzed with specially designed software.

During the field missions to obtain the spectral data the detector units were mounted in a portable support with 3 m of elevation which allow the capture of the reflected energy from an area of approximately 0.5 m^2 of the crop. A 35 mm camera was also mounted in this support to obtain a photographic record of each plot at each mission.

The missions started on May 19, 1988. At that time, the wheat areas were with 30 to 40 days, approximately, after plant emergence and ten missions were carried out throughout the growing cycle at approximately one week interval between missions. Fig. 1 shows the dates of the missions related to the development stages of wheat expressed in the Feeks-Large scale (Scheeren, 1986).

FIGURE 1

Over each plot four measurements of radiance and irradiance were obtained in order to estimate the plot reflectance. The measurements were always obtained under clear or almost clear sky conditions to avoid large variation in illumination conditions. As a consequence, in some of the missions was not possible to obtain these conditions for some plots and therefore, measurements were not taken in these plots.

In order to calculate the reflectance factor, the first step was to intercalibrate the two detector units. This intercalibration was done following procedure proposed by Duggin (1980) which applies the following equation:

$$REF_n = \frac{R_{target}}{I} * C_n * F_n \qquad (1)$$

where REF is the reflectance factor; n is the wavelength number which varies from 400 to 1100 nm in a total of 252;

R_{target} is the radiance reflected by the target; I is the solar irradiance at the measurement time; C is the estimated calibration factor; and F is the calibration factor of the barium sulfate plate.

The estimated calibration factor (C_n) is obtained through regression equations (one for each wavelength). This factor varies with the solar zenithal angle. To derive the regression equations, measurements with the two detector units, one with the cosine collector and the other pointed to a barium sulfate panel were obtained throughout an entire day beginning at 9:00 o'clock until 15:00 o'clock at intervals of 5 minutes between measurements (total of 72 measurements pairs). This way, it was possible to obtain the variation between these two measurements as a function of illumination conditions due to different angles of sun elevation.

Afterwards, a linear regression of the calibration factor on the cosine of solar zenithal angle was obtained for each wavelength. Based on the regression equations, it is possible to estimate C_n for the illumination conditions of the time of the field measurement. The cosine of the zenithal angle was calculated as a function of the time and location of the field measurements.

The calibration factor (F) of the barium sulfate panel used in the calibration procedure is obtained in the lab by relating the radiance from this panel to the radiance from a standard panel of the lab under the same conditions. The lab standard is made of pressed barium sulfate which is kept safely in the lab without suffering deterioration. This lab standard has naturally greater reflectance than the panel used in the calibration procedure and therefore, this factor will adjust the radiance values from the barium sulfate panel (R_{panel}) to the radiance values of the lab standard (R_{lab}) following the equation:

$$F = \frac{R_{panel}}{R_{lab}} \quad (2)$$

The analysis of the spectral data was done in a PC XT microcomputer using a special software package. Initially, the four measurements made at each plot in each mission were averaged and using the calibration parameters, the reflectance factors at each wavelength were computed. Based on a preliminary analysis of the reflectance spectrum, it was verified that the radiometer presented problems beyond the wavelength of 900 nm and therefore the quantitative analysis was restricted to wavelength shorter than 900 nm.

Spectral Data Transformation

The commonly used vegetation indices based on the spectral bands of TM, MSS, AVHRR, were not used due to the limitation presented by the radiometer near 900 nm and beyond. As a result the following spectral bands were proposed: EST1

(547 nm - 562 nm), EST2 (661 nm - 673 nm), EST3 (756 nm - 780 nm), and EST4 (786 nm - 823 nm). These bands are fairly narrow and were positioned at the peak of wheat reflectance in the visible (EST1), at the peak of wheat absorbance in the visible region (EST2), and in the peak of wheat reflectance in the near infrared (EST3 and EST4).

Based on these spectral bands the following vegetation indices were used:

$$IVEST = (EST1 + EST4) / EST2 \qquad (3)$$

$$ND = (EST4 - EST2) / (EST4 + EST2) \qquad (4)$$

Based on the technique proposed by Pinter Jr. et al. (1981) to estimate yield through spectral data obtained throughout the growing cycle of the crop, spectral data were transformed in the vegetation index ND (Eq. 4) and the values of this index were integrated along the growing cycle to obtain the integrated vegetation index (IND). As the spectral data were obtained at intervals of 7 days approximately, the values of ND were interpolated to generate estimated values for regular intervals of 5 days

Agronomic Measurements

Simultaneously to the radiometric data acquisitions, the following agronomic measurements were taken: green phytomass, dry phytomass, plant height, pests and diseases occurrence, and weeds infestation. The green phytomass was obtained by cutting the aerial parts of the plants of 0.5 m of three different sampled rows of the plot. The dry phytomass estimate was obtained by oven drying the material used for the green phytomass estimate. Plant height corresponds to the average height from the soil to the top of the canopy. Occurrence of pests and diseases and evaluation of the percentage of weed infestation were visually estimated. The percent soil cover was estimated from the 35 mm photographs obtained for each plot at each mission, along with the radiometric measurements.

In addition, the following observations were available for each plot: planting and harvesting dates, row direction, and slope. Row spacing and crop stands were basically constant for all plots.

The harvesting of the plots was manually done after plant maturation in an area of 25 m^2 of the plot. The grains were dryed to minimize moisture variations and the weight was multiplied by 400 to provide the final yield estimation in kg/ha.

The development stages of the crop at each mission were estimated based on the samples used for phytomass estimation using the Feeks-Large scale as described by Scheeren (1986).

Agrometeorological Model

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 and its corresponding software are reported by Rudorff and Batista (1989a). 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 the deficit of relative evapotranspiration.

The evapotranspiration of the sampled fields was not calculated due to agronomic and meteorological data lack. Considering that favouring climatic conditions prevailed throughout the growing season the assumption that water was adequately available for the plant was made, and therefore, the maximum yield was not penalized by lack of water. Thus, in the context of this work, the maximum yield was equal to the estimated yield.

The agrometeorological model calculates the dry matter production for every 10 days throughout the growing cycle. The average dry matter production of wheat throughout the growing cycle is approximately 50 percent of the maximum dry matter production according to Doorembos and kassam (1979). The maximum dry matter production is reached only when the crop is well developed, being relatively low for the initial and final growing stages of the crop. These authors suggested that the maximum dry matter production be multiplied by a factor of 0.5 to estimate the dry matter production throughout the growing cycle.

Differently, in this work, this factor was estimated by spectral variables measured throughout the growing cycle. The vegetation index IVEST (equation 3) which represents the energy reflected by the crop in the visible and near infrared, was used instead of the arbitrary factor of 0.5. In order to be able to use the IVEST as a growth compensation factor (GCF), the values of IVEST throughout the growing cycle taking in account all sampled plots were normalized to vary from 0 to 1 corresponding to the minimum and maximum values of IVEST, respectively. As the dry matter production was calculated for every 10 days, the GCF should correspond to growing conditions of these respective intervals. However, the spectral measurements were not taken at such intervals and therefore, a linear interpolation was necessary to estimate the GCF's for the 10 days intervals based on the IVEST obtained in the radiometric missions.

To convert the dry matter produced by the crop into yield which is expressed in kg/ha, the total dry matter was multiplied by a factor of agricultural productivity which arbitrarily was set as 0.31 in this work.

Results and Discussion

Spectral Response of Wheat

The 268 spectral curves obtained during the 10 radiometric missions of the 1988 growing season are presented in Rudorff et al. (1989c). Since the first radiometric mission the crop extensively covered the soil, as a result the spectral curves already presented the typical shape of a canopy reflectance curve which persisted until the eighth mission (July 14, 1988) and then the crop started to mature and the absorption of the energy in the red region began to decrease due to leaf senescence and the reflected energy in the near infrared decreased due to cell degeneration and to a decrease in leaf area index. Fig. 2 presents the reflectance factor curves for one of the sampled plots planted to Anahuac variety obtained at the first, sixth, and tenth radiometric missions. These curves illustrate well the general behavior just described.

FIGURE 2

The analyses of all reflectance factor curves show that there is systematically a steady fall of the energy reflected by the crop beginning at the 900 nm wavelength, independently of the development stage. The exam of reflectance curves of wheat reported in the literature does not support this steady decrease in the reflectance between 900 nm and 1100 nm and therefore, this decrease was attributed to a lack of sensitivity of the spectroradiometer used at this wavelength interval. As a result, the reflectance factors beyond 900 nm were not considered in this work.

Relationship between Spectral Data and Agronomic Variables

From the reflectance spectra covering the wavelength interval of 400 nm to 1100 nm (252 spectral bands), four spectral bands (EST) as described in previous sections were selected. To express the growing conditions of the crop a vegetation index called IVEST (Eq. 3) was used after a preliminary analysis of the correlation between several vegetation indices and agronomic variables. The vegetation indices presented similar results, however as the IVEST uses bands in the green, red, and near infrared wavelengths it presented consistently slightly better results in expressing crop growing conditions as compared with the other vegetation indices tested.

Table 1 shows the correlation coefficients between IVEST and grain yield, green phytomass, dry phytomass, canopy height, percent soil cover, and number of heads, for each radiometric mission. Fig. 3 shows the correlogram of vegetation index (IVEST) with grain yield, green phytomass, and dry phytomass along the radiometric missions. In addition, Fig 4 shows the relationship between the vegetation index and grain yield for each mission.

TABLE 1

FIGURE 3

FIGURE 4

It can be observed that the best relationship between spectral measurements and yield was obtained in the second fortnight of June, when the crop fields were in the end of the booting stage and the fields were with about 60 days after planting. Similar results were obtained by Rudorff and Batista (1989a) which analyzed the vegetation index (IVEST) extracted from Landsat TM (bands 2,3, and 4) data and related with grain yield of commercial fields in the crop years of 1986 and 1987 in the same study area.

Since the first mission the most productive fields were with a soil cover greater than 70 percent and therefore the spectral response of the plot was primarily from the crop rather than from the soil. On the other hand, the less productive fields presented approximately 50 percent of soil cover and as a result they had a low vegetation index. Thus, even though the best relationship between vegetation index and yield was found when the crop were with 60 to 70 days after planting, good relationships were found since the crop were with 30 to 40 days after planting (mission 1). However, in the last three missions, the relationship between spectral data and yield was quite low and tended to decrease as the crop matured and senesced. Table 2 illustrates these observations and shows that the regression coefficients between observed yield and vegetation index were quite stable, except for the last three missions.

TABLE 2

Based on these observations it may be concluded that the period from 30 to 70 days is quite appropriate to estimate yield from spectral data for the studied varieties which has a growing cycle of 100 to 120 days. This is a quite encouraging result because spectral data could be obtained in a large period (40 days) early in the growing season.

The relationship between the vegetation index with either green or dry phytomass presented lower correlation coefficients than with yield basically in all missions, as can be seen in Fig. 3. Examining the correlation between vegetation index and phytomass it may be noticed that the largest coefficients were observed in the first mission what is in accordance with Richardson et al. (1982) who stated that as the growing cycle of a crop progresses there is an increase in phytomass of the plant as a whole while the vegetation index is more related with the quantity of leaves

(LAI) which are responsible for photosynthesis and as a consequence with the final yield.

Table 1 also shows that the vegetation index is poorly correlated with percent soil cover, plant height, and number of heads. Table 3 presents the correlation coefficients of final yield with both green and dry phytomass. Fig. 5 shows that the correlation coefficients of final yield with vegetation index (IVEST) are greater than the correlation coeficients of final yield with both green and dry phytomass. This is also a very encouraging result because the vegetation index could be obtained by satellites over extensive areas with high spatial resolution in an objective and non destructive manner. Table 3 also shows the correlation coefficients between green and dry phytomass.

TABLE 3

FIGURE 5

Multitemporal Analysis of the Vegetation Index

Fig. 6 shows as an example, the trajectory curves based on index ND (Eq. 4) since 50 percent of the plants were at the heading stage until maturation for 6 sampled plots. It can be observed that the area under the curves are strongly related with final yield. The final yield is dependent not only on the intensity of the photosynthetic activity but also on the period that the LAI remains high. In order to eliminate from the vegetation index components not related with photosynthetic activity, a baseline was empirically established under which the photosynthetic activity was considered negligible. Thus, a baseline value (0.55) was subtracted from the vegetation index before deriving the integrated index (IND). The 0.55 value corresponds to the value of the vegetation index of the most productive plot at maturation stage. Fig. 6 also shows that the use of the vegetation index obtained at just one time may lead to errors in yield estimation and the integrated index based on spectral data obtained throughout the growing cycle might provide robust estimation of yield.

FIGURE 6

The values of the IND index were obtained by adding up the vegetation index (ND) after subtracting the baseline beginning at the 40th day for the BH-1146 and IAC-24 varieties and at the 50th for the Anahuac variety when 50 percent of the plants were at the heading stage and ending when the plants were completely senesced (100 to 110 days). The differences in the integrating periods are due to differences in the duration of the growing cycles of these varieties. The relationship between the IND index and final yield was expressed in the following equation:

$$\text{Estimated Yield} = 474 + 491 \times \text{IND} \qquad (5)$$

This equation had a determination coefficient of 0.66 and an estimation standard error of 364 kg/ha.

It is quite evident that the spectral response of the IAC-24 variety is not well related with its final yield (Fig. 7a). However, the number of samples of this variety was small and therefore this observation cannot be conclusive. In spite of that, IND was regressed against final yield omitting the IAC-24 variety plots (Fig. 7b) which resulted in a determination coefficient of 0.92 and an estimation standard error of 208 kg/ha. This relationship was expressed by the following equation:

$$\text{Estimated Yield} = 275 + 624 \times \text{IND} \qquad (6)$$

This result is quite similar to the one reported by Pinter Jr. et al. (1981) who suggested the use of this technique for wheat yield estimation.

FIGURE 7

Yield Estimation by the Agrometeorological-Spectral Model

The agrometeorological-spectral model proposed in this work uses synergistically meteorological, agronomic, and spectral data. The model calculates the potential yield as a function of climatic conditions and a few compensation factors. One of the compensation factors takes in account the variation in growth of the crop as a function of the development stage and is called growth compensation factor (GCF) which is intended to modulate the LAI variation throughout the growing cycle.

In this work this factor was estimated through spectral data expressed by the vegetation index, IVEST, described previously. As the spectral data started to be obtained by the time that the fields were with 30 to 40 days after planting it was attributed the value of zero to GCF at the planting date and a linear interpolation was applied to estimate the GCF for 10 days intervals from planting to harvest, because the model estimates yield at each 10 days periods. The interpolated index was plotted across the growing cycle of the crop and three illustrative curves are presented in Fig. 8. It can be observed that the shape of the curves is very similar to the expected LAI throughout the growing cycle. The variation in yield estimated by the agrometeorological-spectral model is basically dependent on the variation in GCF obtained from the spectral data. The agrometeorological variables were obtained from a single climatic station and the variation in yield among the fields was due to the slight climatic variation caused by differences in planting dates which in fact, varied very little for the studied fields.

FIGURE 8

To estimate net dry matter production, the model uses a respiration factor equal to 0.5, assuming that 50 percent of the total dry matter production is consumed in the respiration process of the plant. To convert net dry matter production in grain yield a factor of 0.31 was empirically used.

Fig. 9a shows the relationship between observed and estimated yield obtained by the agrometeorological-spectral model where it can be oserved that the model explains 69 percent of the observed yield variation with a standard error of the estimation of 355 kg/ha. Fig 9b shows the same relationship excluding however the plots from the IAC-24 variety, as previously discussed. In this case, the model explained 84 percent of the observed yield variation with a standard error of estimation of 289 kg/ha. The exclusion of the IAC-24 plots from the analysis improved significantly the results.

FIGURE 9

The incorporation of spectral data to the agrometeorological model using the GCF is a preliminary proposition which might prove to be useful for yield estimation in the future, at a regional level (e.g. municipal or county level) where the spectral data could be obtained from environmental satellites (e.g. NOAA AVHRR) with high temporal resolution. Meteorological data are more available at the regional level than at the farm level and in the near future they might be estimated from satellite data.

Summary, Conclusions, and Recommendations

The reflectance curves presented sistematicaly an abrupt fall beginning near the 900 nm wavelength, independently of the crop development stage. This fall in the reflectance factor was attributed to lack of sensitivity of the spectroradiometer used and therefore, the reflectance factors beyond this wavelength were not considered in this work.

The best relationship between vegetation index and yield was obtained in the second fortnight of June when the crop was in the end of the booting stage with just over 60 days after planting. This is in agreement with results presented previously by Rudorff and Batista (1989a). However, good relationships were observed in a wide period (30 to 70 days after planting) what is quite encouraging because yield could be estimated well in advance of harvesting.

In the last three missions the relationship between spectral data and yield was quite low and tended to decrease as the development stage advanced due to crop maturation and senescence.

The relationship between yield and both green and dry phytomass had lower correlation coefficients than the relationship between yield and vegetation index.

Percent soil cover, canopy height, and number of heads per hactare had low correlation coefficients with vegetation index.

The vegetation index (IND) explained 66 percent of the observed yield variation with a standard error of estimation of 364 kg/ha. By excluding the plots from the IAC-24 variety the explained variation increased to 92 percent and the standard error decreased to 208 kg/ha. This result is similar to the one reported by Pinter Jr. et al. (1981) who suggested the use of this method for wheat yield estimation. The integrated vegetation index represents well the intensity and the duration of the photosynthetic activity of the crop throughout the growing cycle and as a result this index was highly correlated with the final observed yield.

The regression of the observed yield on the yield estimated by the agrometeorological-spectral model has shown that the model explained 69 percent of the variation on observed yield with a standard error of estimation of 355 kg/ha. Excluding the plots of the IAC-24 variety the model explained 84 percent of the observed yield variation with a standard error of estimation of 289 kg/ha.

The meteorological data were basically the same for all plots analyzed, there was however, a slight variation in climatic conditions due to the different planting dates of the plots. As a result, the meteorological data contributed very little to improve yield estimation through the agrometeorological-spectral model in comparison with the estimation using spectral data only.

The incorporation of spectral data to the agrometeorological model using the growth compesation factor (GCF) is a preliminary proposition which might prove to be useful for yield estimation in the future, at a regional level (e.g. municipal or county level) where the spectral data could be obtained from environmental satellites (e.g. NOAA/AVHRR) with high temporal resolution. Meteorological data are more available at the regional level than at the farm level and in the near future they might be estimated from satellite data.

Agronomic measurements such as dry phytomass, canopy height, weight per volume, and number of heads per hectare contributed very little to understand the relationship between spectral data and yield. On the other hand, measures of LAI, APAR, and available soil water should be considered in future experiments, especially if these experiments could be carried out in experimental stations.

Radiometric missions carried out weekly over commercially planted fields can be very job intensive due to the distance among the plots. To optimize resources it is suggested that the reflectance models proposed in the literature be calibrated for the crops growing in tropical conditions based on field experiments and afterwards be validated for commercially cultivated crops.

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TABLE 1 Correlation Coefficients between Vegetation Index and Agronomic Parameters

MISSION	DATE	NUMBER OF PLOTS	DAYS AFTER PLANTING	AGRONOMIC PARAMETERS					
				OBSERVED YIELD	PHYTOMASS GREEN	PHYTOMASS DRY	HEIGHT	PSC [1]	HEADS
1	05/19	15	30 - 40	0.82**	0.87**	0.83**	0.14	0.65**	0.60**
2	05/26	25	35 - 45	0.76**	0.75**	0.62**	0.33	0.75**	0.38**
3	02/02	30	45 - 55	0.81**	0.77**	0.58**	0.17	0.78**	0.31*
4	06/09	30	50 - 60	0.84**	0.77**	0.70**	0.17	0.70**	0.40*
5	06/16	30	55 - 65	0.82**	0.59**	0.41*	0.08	0.73**	0.40*
6	06/23	29	60 - 70	0.85**	0.72**	0.33	0.10	0.33	0.42*
7	06/30	25	65 - 75	0.93**	0.72**	0.52**	0.13	0.70**	0.49**
8	07/14	30	70 - 80	0.68**	0.70**	0.55**	0.10	0.62**	0.46**
9	07/22	25	75 - 85	0.81**	0.58**	0.31	0.29	0.37*	0.20
10	08/04	26	80 - 90	0.31	-	-	-	-0.34	0.76**

1Percent soil cover

** = 0,01

* = 0,05

<u>TABLE 2</u> Regression Equations and Respective Coefficients of Determination (r^2) of Yield (kg/ha) on Vegetation Index (IVEST)

MISSION	DATE	NUMBER OF PLOTS	REGRESSION EQUATION	r^2
1	05/19	15	YIELD = 97 + 95.1 * IVEST	0.66**
2	05/26	25	YIELD = 273 + 87.3 * IVEST	0.58**
3	06/02	30	YIELD = 166 + 94.7 * IVEST	0.67**
4	06/09	30	YIELD = 302 + 92.3 * IVEST	0.69**
5	06/16	30	YIELD = 236 + 94.3 * IVEST	0.68**
6	06/23	29	YIELD = 334 + 101.0 * IVEST	0.72**
7	06/30	25	YIELD = 251 + 115.0 * IVEST	0.86**
8	07/14	30	YIELD = 796 + 127.0 * IVEST	0.46**
9	07/22	25	YIELD = 172 + 360.0 * IVEST	0.63**
10	08/04	26	YIELD =1056 + 267.0 * IVEST	0.10**

** = 0.01
* = 0.05

TABLE 3 Correlation Coefficients between Agronomic Parameters

MISSION	DATE	NUMBER OF PLOTS	GREEN PHYTOMASS X OBSERVED YIELD	DRY PHYTOMASS X OBSERVED YIELD	GREEN PHYTOMASS X DRY PHYTOMASS
1	05/19	15	0.69**	0.64**	0.93**
2	05/26	25	0.51**	0.48**	0.90**
3	06/02	30	0.59**	0.35*	0.90**
4	06/09	30	0.68**	0.61**	0.95**
5	06/16	30	0.52**	0.44*	0.84**
6	06/23	29	0.74**	0.47**	0.75**
7	06/30	25	0.77**	0.61**	0.82**
8	07/14	30	0.73**	0.75**	0.94**
9	07/22	25	0.73**	0.64**	0.90**

** = 0.01
* = 0.05

FIGURE LEGENDS

Figure 1. Development stage of wheat (Feeks-Large scale) and corresponding dates of the radiometric missions.

Figure 2. Reflectance factor of plot 8, Anahuac variety, planted on April 15, 1988, for four selected missions showing the unexpected fall in the reflectance factor at the 900-1100 nm interval.

Figure 3. Correlation coefficients of vegetation index (IVEST) with observed yield, green phytomass, and dry phytomass across the radiometric missions.

Figure 4. Relationship between vegetation index (IVEST) and grain yield for each radiometric mission.

Figure 5. Correlation coefficients of observed yield with vegetation index (IVEST), green phytomass, and dry phytomass across the radiometric missions.

Figure 6. Spectral trajectory of six selected plots and their respective grain yield.

Figure 7. Relationship between observed yield and vegetation index (IND) for a) 30 sampled plots; b) excluding the IAC-24 variety.

Figure 8. Growing compensation factor (GCF) throughout the growing cycle of four selected plots.

Figure 9. Relationship between observed yield and estimated yield by the agrometeorological-spectral model for a) 30 sampled plots; b) excluding the IAC-24 variety.

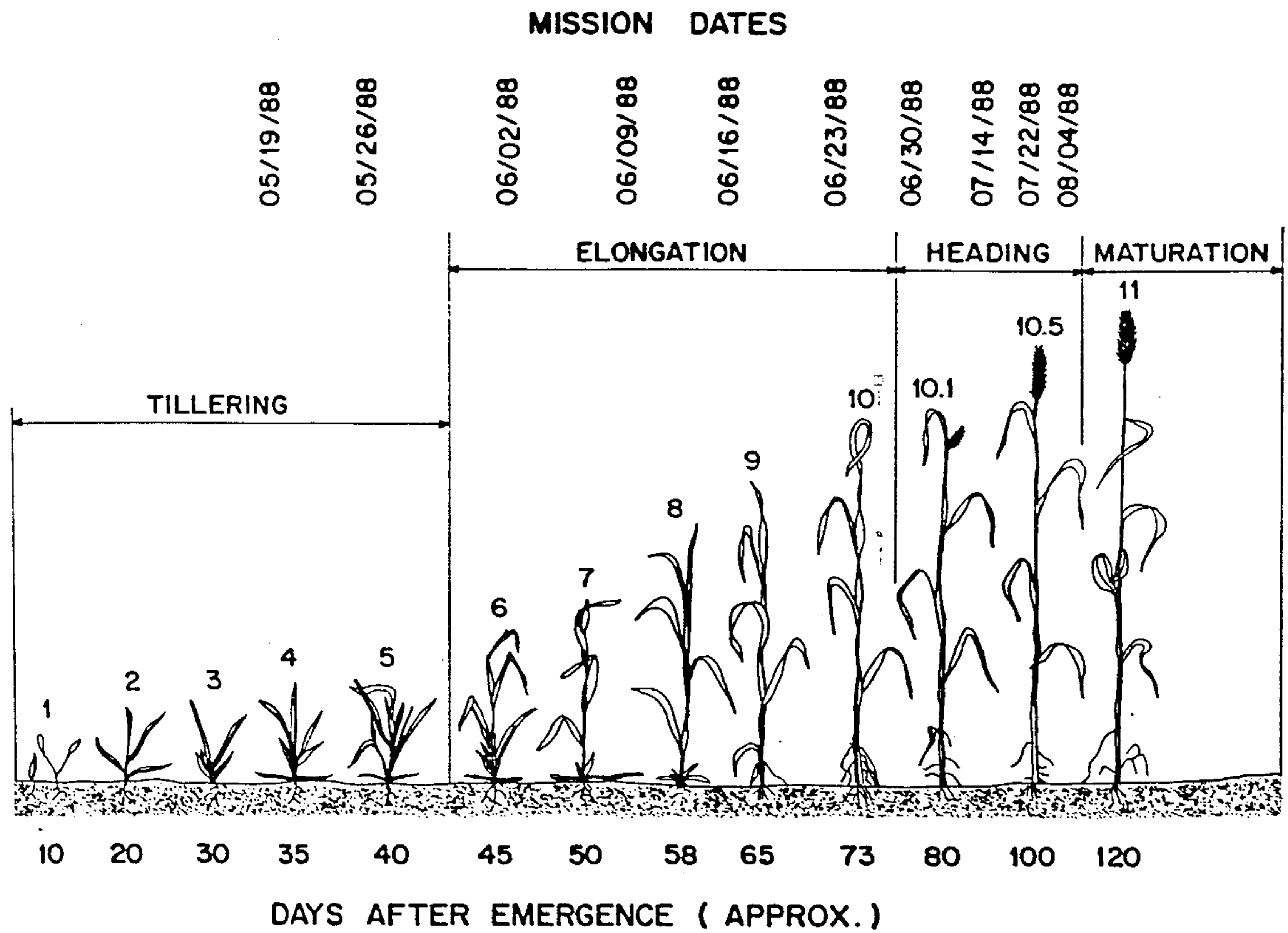

MISSION DATES
05/19/88
05/26/88
06/02/88
06/09/88
06/16/88
06/23/88
06/30/88
07/14/88
07/22/88
08/04/88
TILLERING
ELONGATION
HEADING
MATURATION
1
2
3
4
5
6
7
8
9
10
10.1
10.5
11
10
20
30
35
40
45
50
58
65
73
80
100
120
DAYS AFTER EMERGENCE (APPROX.)

Figure 1

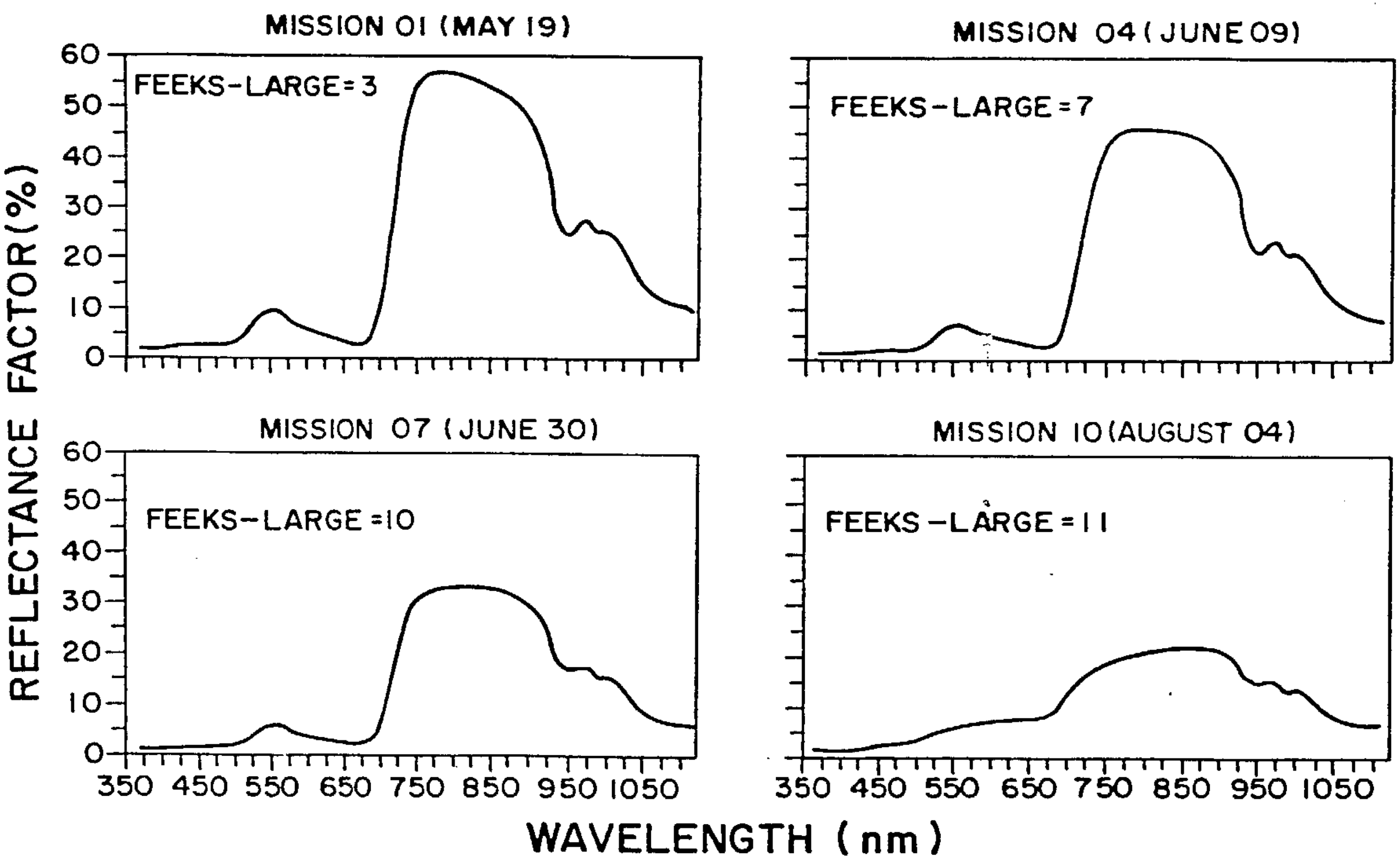
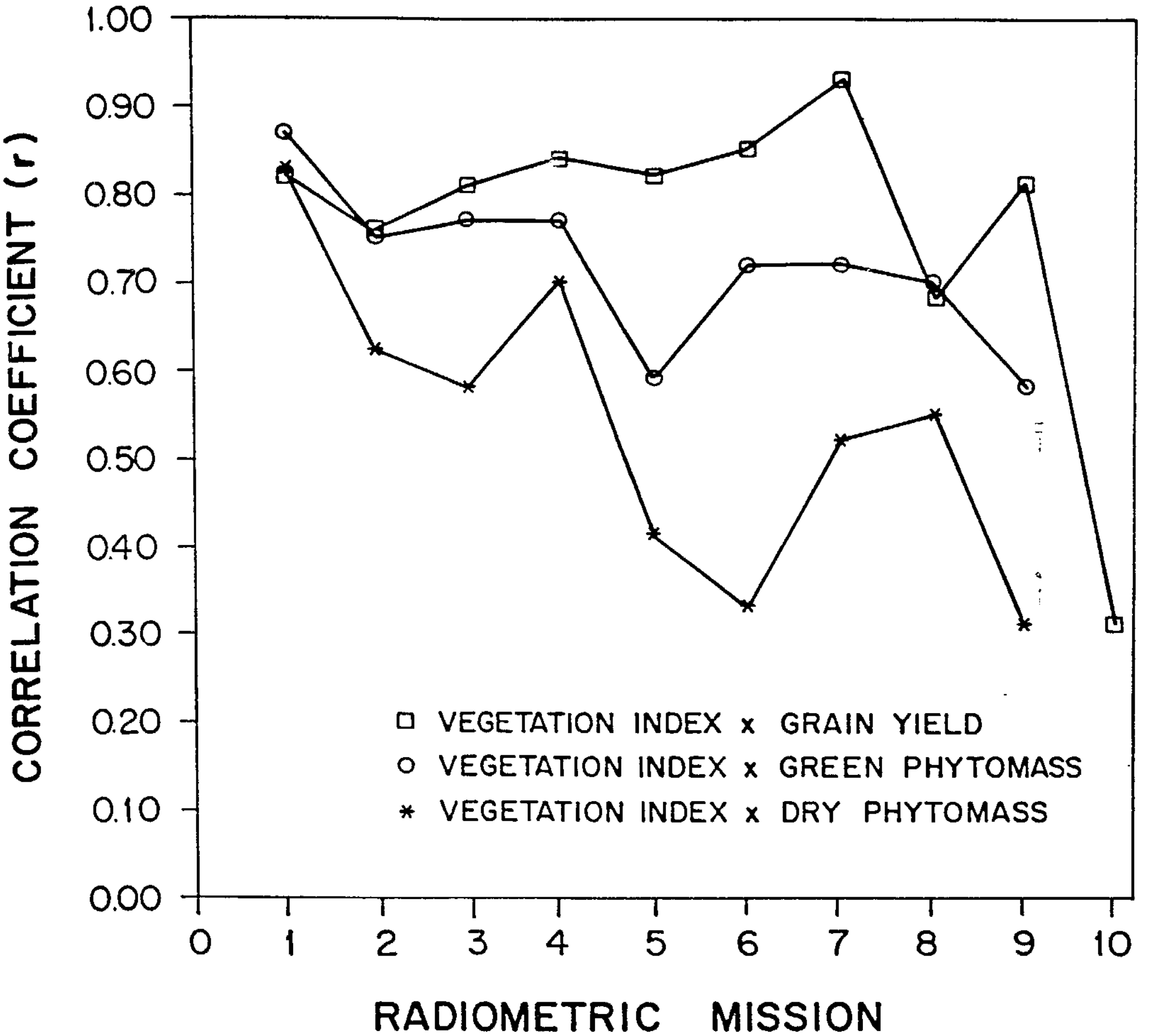

MISSION 01 (MAY 19)
FEEKS-LARGE=3
MISSION 04 (JUNE 09)
FEEKS-LARGE=7
MISSION 07 (JUNE 30)
FEEKS-LARGE=10
MISSION 10 (AUGUST 04)
FEEKS-LARGE=11
REFLECTANCE FACTOR (%)
0
10
20
30
40
50
60
350
450
550
650
750
850
950
1050
WAVELENGTH (nm)

Figure 2


CORRELATION COEFFICIENT (r)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
7
8
9
10
RADIOMETRIC MISSION
□ VEGETATION INDEX x GRAIN YIELD
○ VEGETATION INDEX x GREEN PHYTOMASS
* VEGETATION INDEX x DRY PHYTOMASS

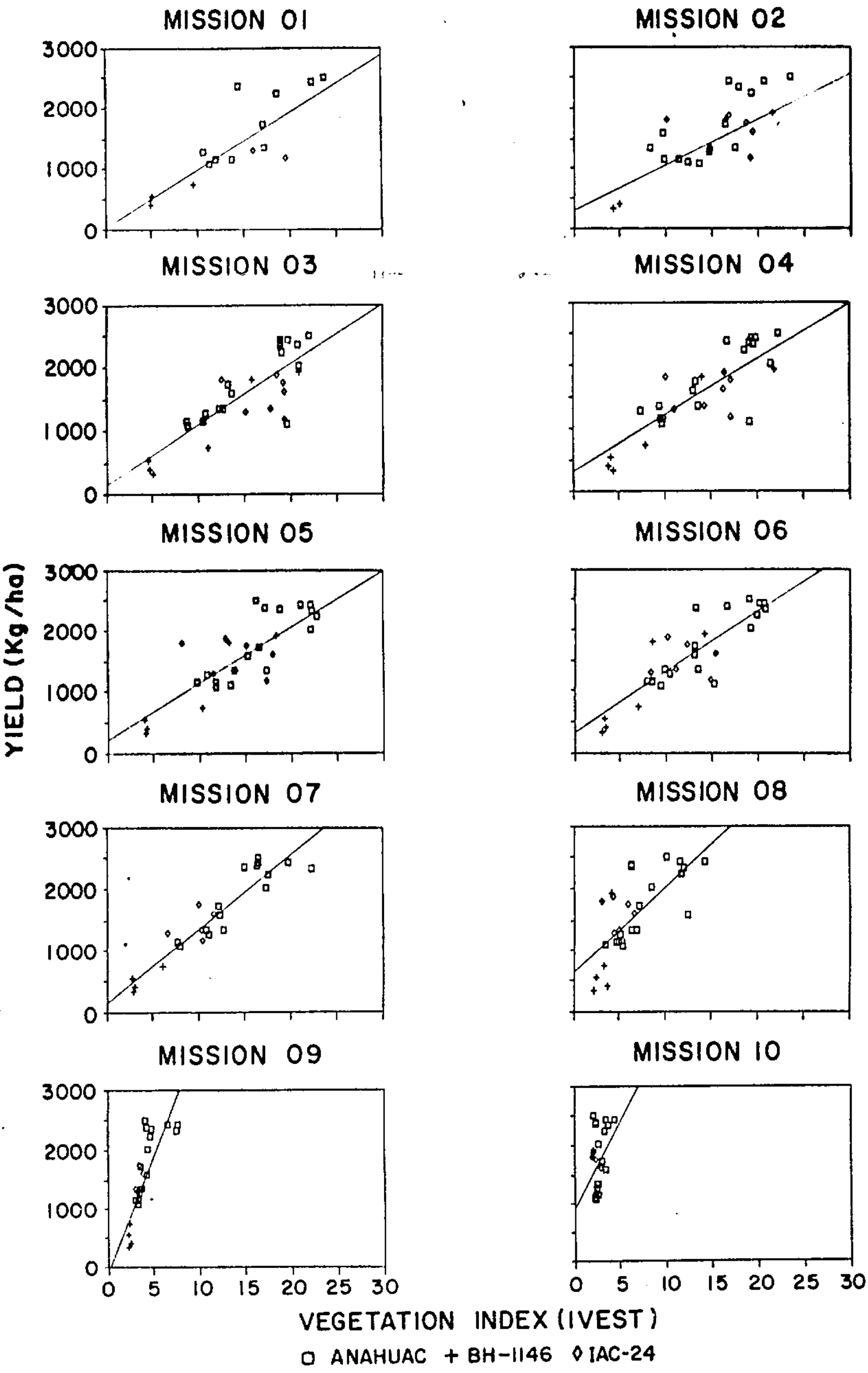
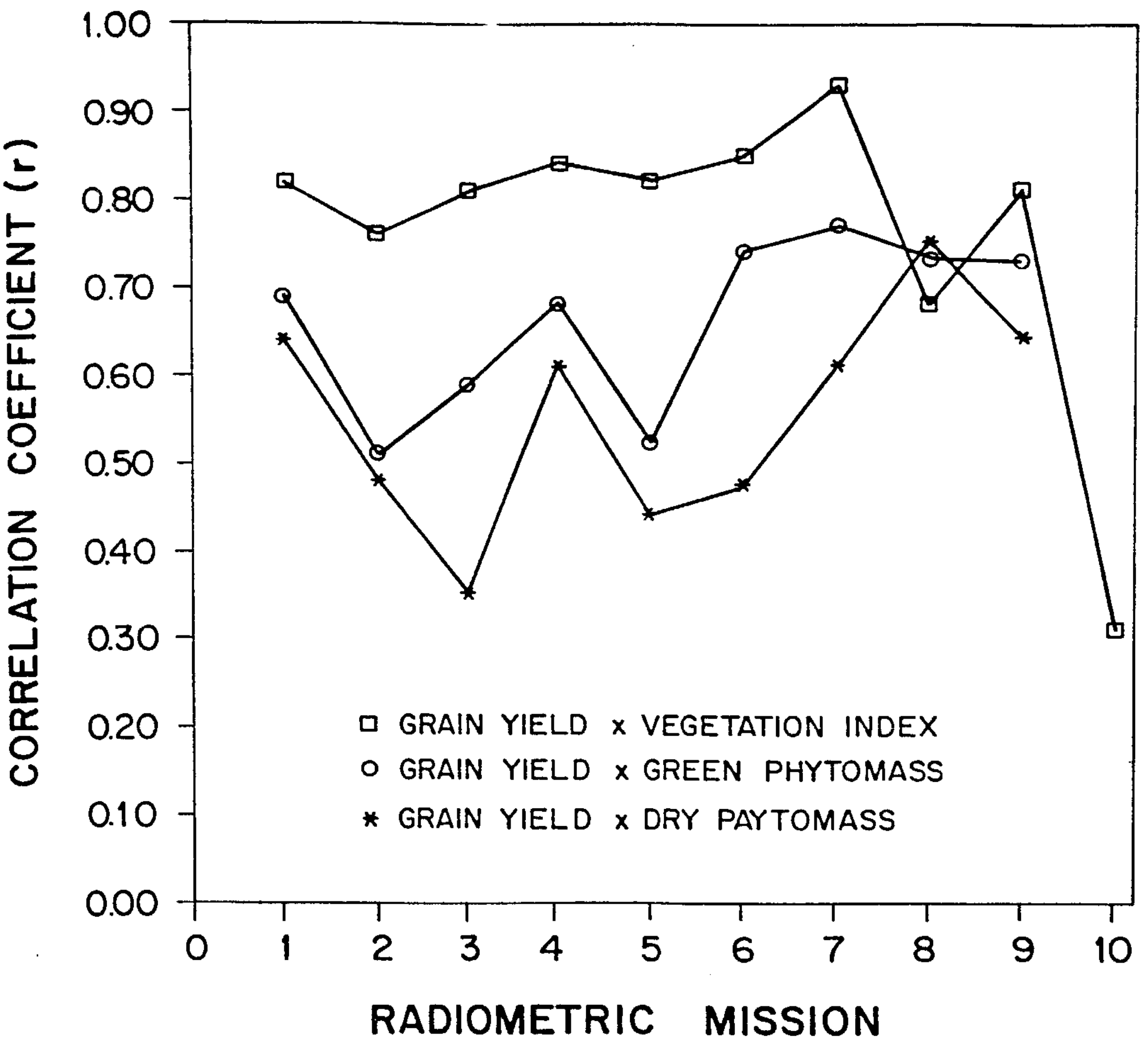

MISSION 01
MISSION 02
MISSION 03
MISSION 04
MISSION 05
MISSION 06
MISSION 07
MISSION 08
MISSION 09
MISSION 10
YIELD (Kg/ha)
0
1000
2000
3000
0
5
10
15
20
25
30
VEGETATION INDEX (IVEST)
□ ANAHUAC + BH-1146 ◊ IAC-24

Figure 4


CORRELATION COEFFICIENT (r)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
1
2
3
4
5
6
7
8
9
10
RADIOMETRIC MISSION
GRAIN YIELD x VEGETATION INDEX
GRAIN YIELD x GREEN PHYTOMASS
GRAIN YIELD x DRY PAYTOMASS

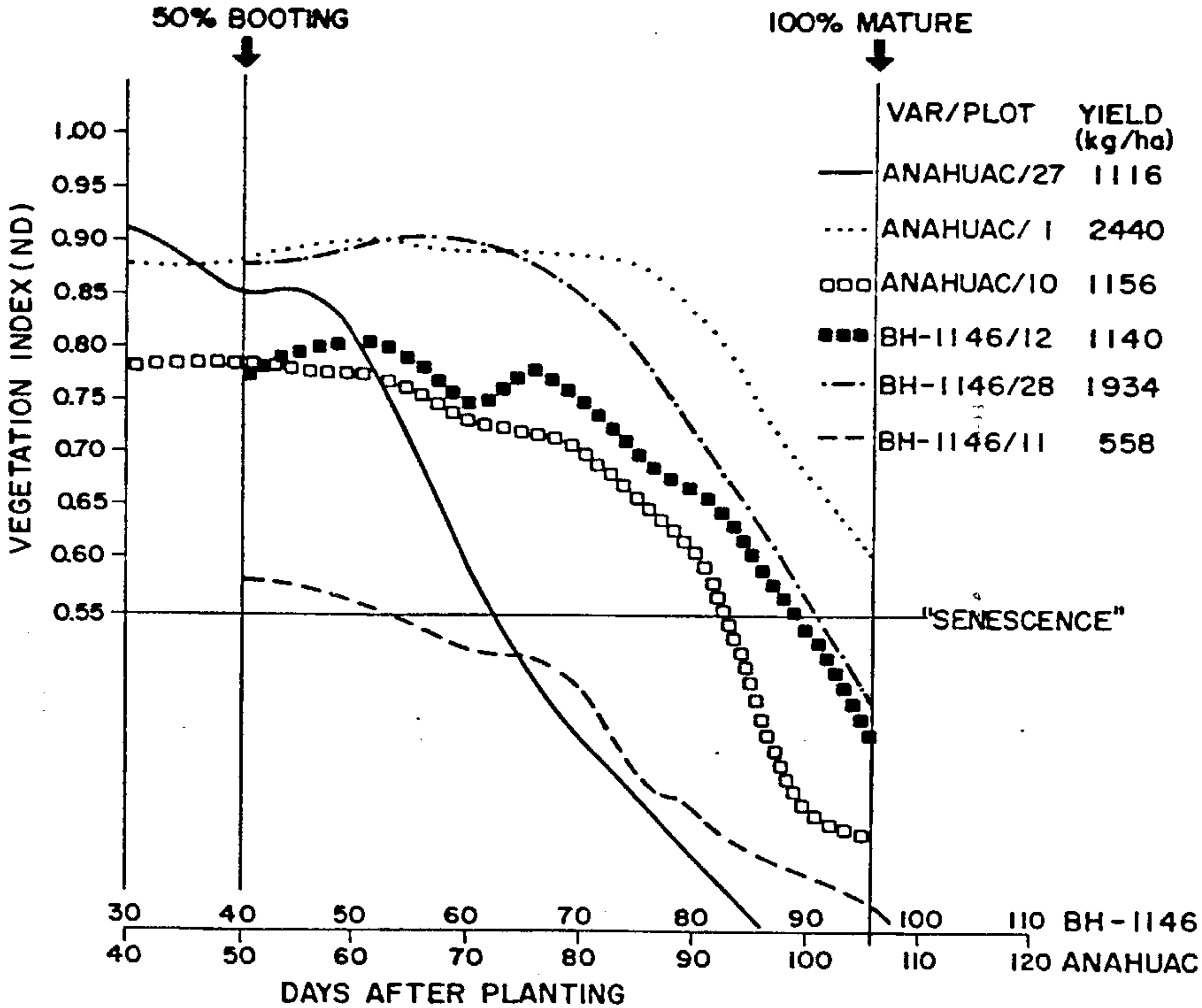

50% BOOTING
100% MATURE
VAR/PLOT YIELD (kg/ha)
ANAHUAC/27 1116
ANAHUAC/ 1 2440
ANAHUAC/10 1156
BH-1146/12 1140
BH-1146/28 1934
BH-1146/11 558
"SENESCENCE"
VEGETATION INDEX (ND)
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
30 40 50 60 70 80 90 100 110 BH-1146
40 50 60 70 80 90 100 110 120 ANAHUAC
DAYS AFTER PLANTING

Figure 6

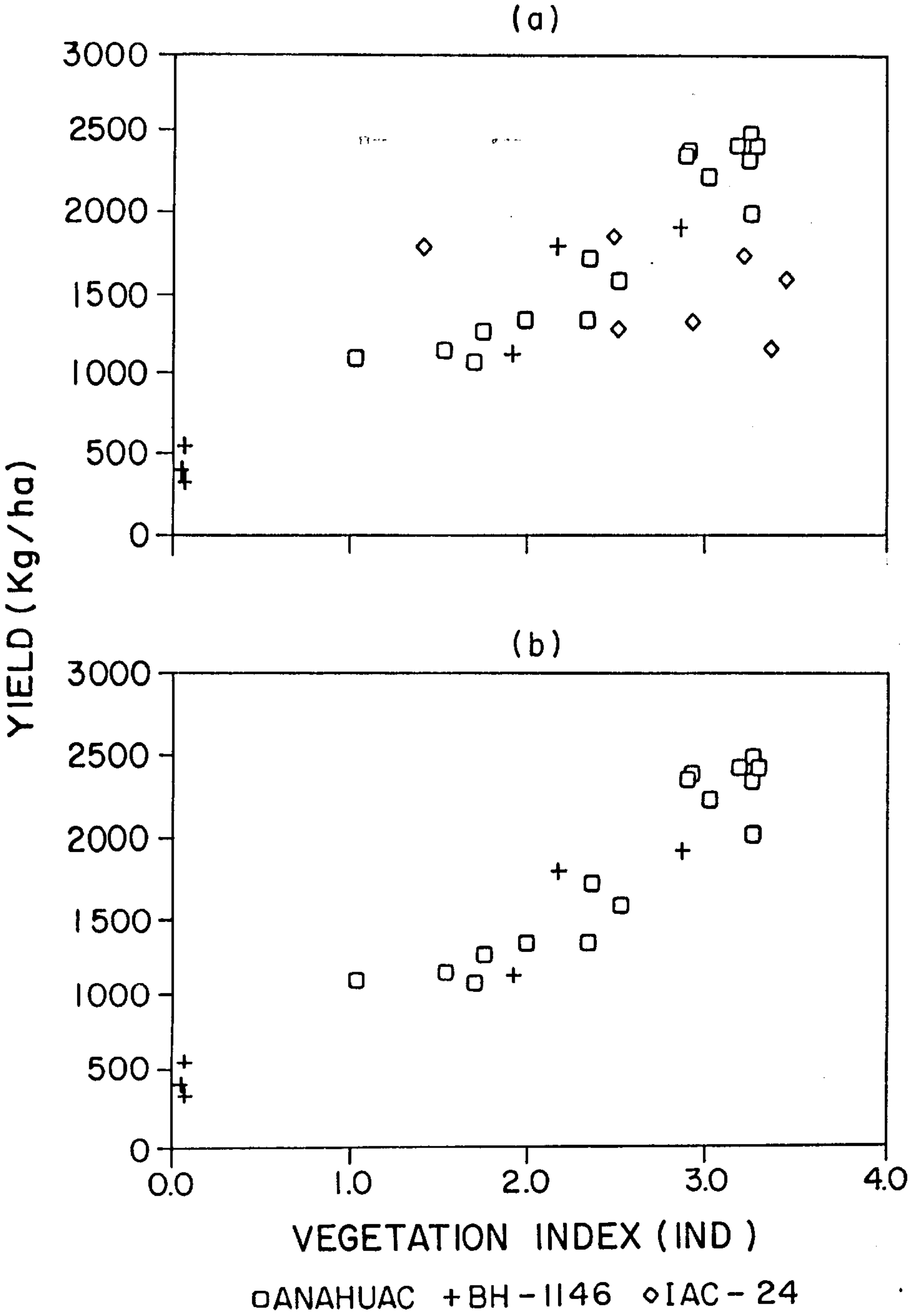
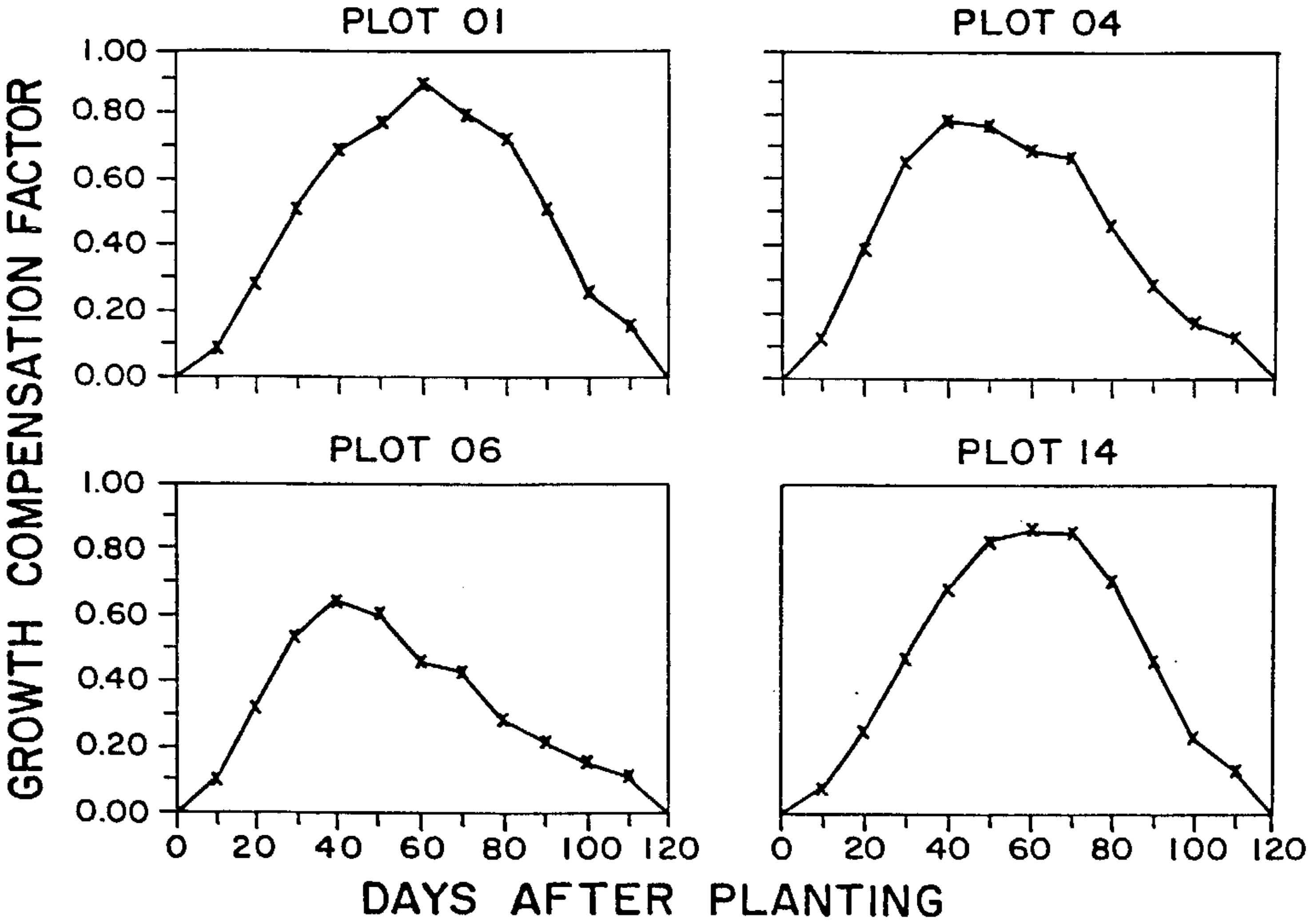

(a)
(b)
YIELD (Kg/ha)
3000
2500
2000
1500
1000
500
0
0.0
1.0
2.0
3.0
4.0
VEGETATION INDEX (IND)
□ANAHUAC +BH-1146 ◇IAC-24

Figure 7



PLOT 01
PLOT 04
PLOT 06
PLOT 14
GROWTH COMPENSATION FACTOR
1.00
0.80
0.60
0.40
0.20
0.00
0
20
40
60
80
100
120
DAYS AFTER PLANTING

Figure 8

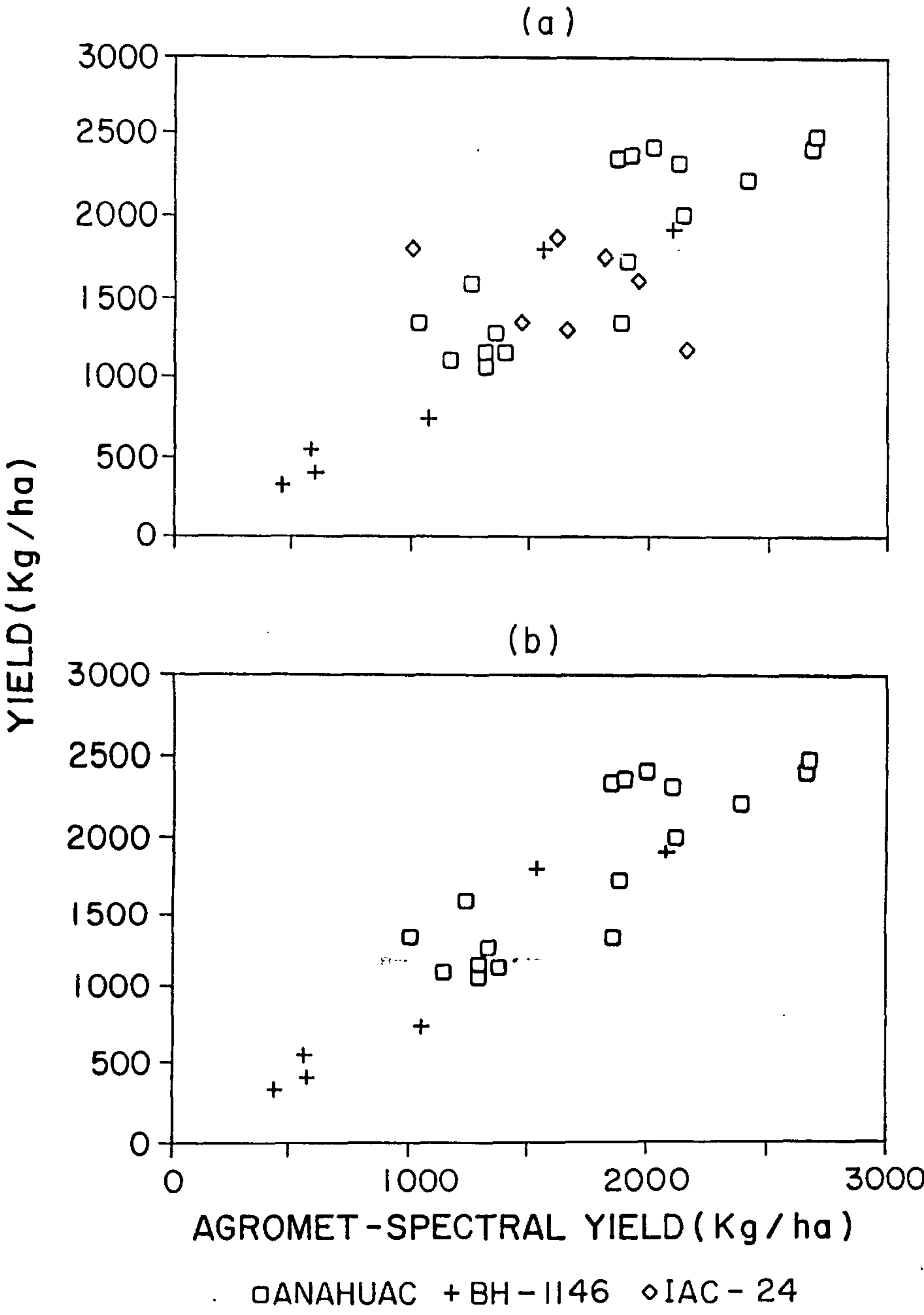

(a)
(b)
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
YIELD (Kg/ha)
AGROMET-SPECTRAL YIELD (Kg/ha)
□ANAHUAC + BH-1146 ◇IAC-24

Figure 9

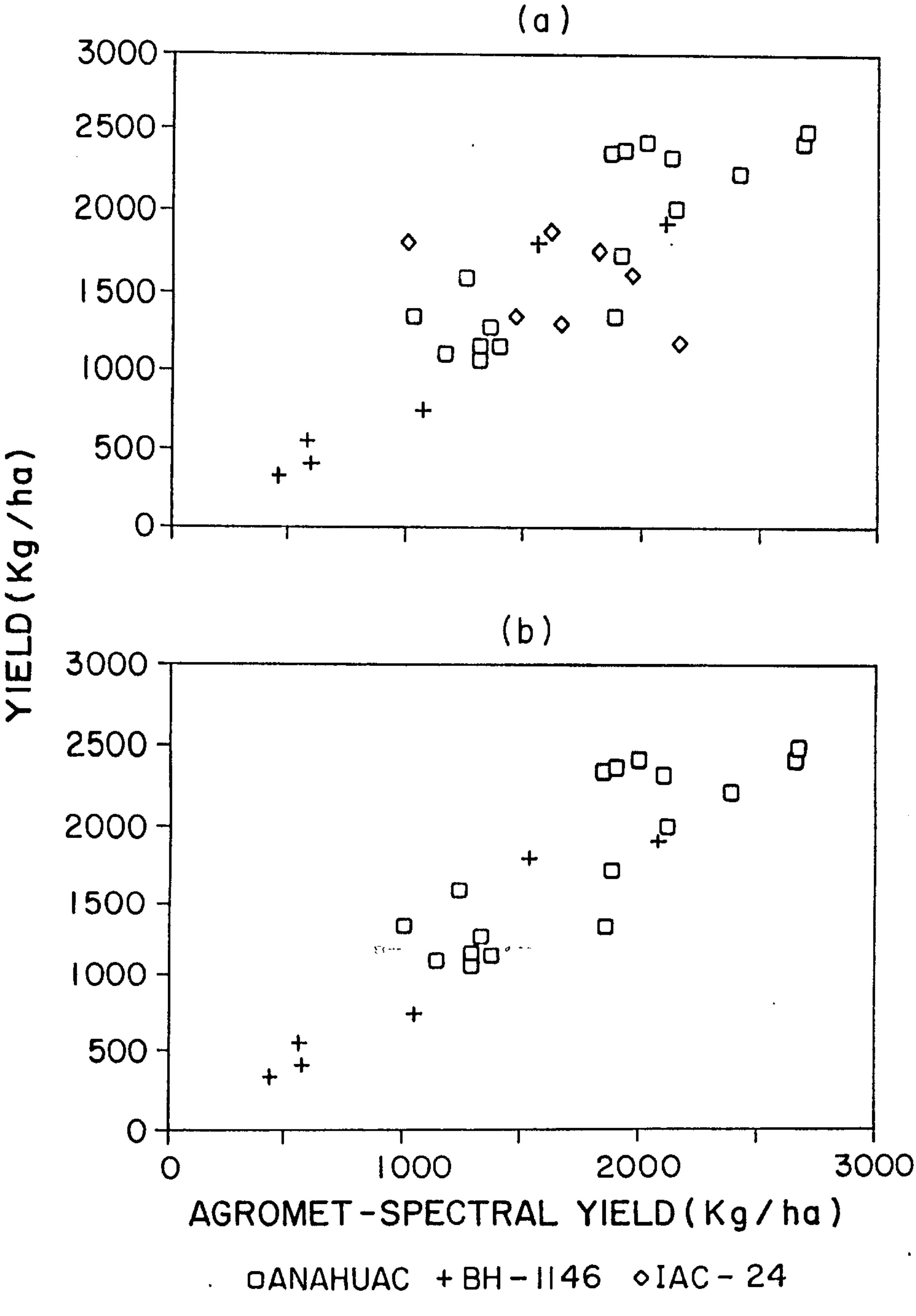

(a)
(b)
YIELD (Kg/ha)
3000
2500
2000
1500
1000
500
0
0
1000
2000
3000
AGROMET-SPECTRAL YIELD (Kg/ha)
□ANAHUAC + BH-1146 ◇IAC-24

Figure 9