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ANALYSIS OF CROP PRODUCTION IN ZAMBIA WITH THE HELP OF REMOTE SENSING, METEOROLOGICAL DATA AND MATHEMATICAL MODELS

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CONTENTS

1. Introduction

Allocation of land for agriculture (arable and permanent crops) in Zambia has been increased from the Independence (1964), reaching nowadays the 7% (5188000 ha) of the total land area (74072000 ha) of Zambia in 1985 (Anonymous, 1987). However, these 5 millions of hectares allocated for arable and permanent crops refer to land under temporary crops, temporary meadows or pasture, greenhouses ferand land temporarily fallow or lying idle. The last cathegory of land allocation can be very significant when fallow land resulting from shifting cultivation system is included. Indeed, according to table 1, the entire crop production of Zambia in 1984-85 was cultivated only on the 15% of the total arable land while fallow land generated by shifting cultivation practice occupied practically 85% of the total arable land in Zambia.

Table 1. Agricultural area in Zambia in 1984-85 crop season.

	Area [1000 ha]	
Arable crops	5180	(FAO)
Permanent crops	8	(FAO)
Annual crops	785	(MAWD)

(FAO) source : Anonymous, 1987
(MAWD) source : Anonymous, 1985

In conclusion, according to table 1, only 1% of the total land area contributed to the actual crop production of the whole country in crop season 1984-85. Agricultural land is administratively divided in agricultural camps, which are groups of one or more villages. The density of land allocated for agriculture can be also indicated via the number of agricultural camps present in a district or province.
Analysing more in detail four provinces of Zambia which have high number of agricultural camps, some provinces e.i. Eastern and Southern provinces, shows higher percentage of cultivated land in crop year 1984-85 (table 2), compared to the average agricultural land in the whole country.

Table 2. Land area and agricultural area in four zambian provinces, respectively Central, Eastern, Southern and Northern provinces in crop year 1984-85. Data of agricultural area are collected from Anonymous, 1985

Provinces	Land area [ha]	Cultivated agric. area [ha]	Ratio agric.area/ land area
Central	11629000	164968	1.4%
Eastern	6910000	245893	3.6%
Southern	8528000	201090	2.3%
Northern	10700000	67267	0.6%

Production in the zambian rainfed agriculture is closely bound to the yearly amount and time distribution of precipitation.
Only 20000 ha of arable land profit from irrigation practice (Anonymous, 1987) while the unirrigated arable land (in 1985, 97.5%) remains the greatest portion of cultivated land. Consequently, amount of crop production is strictly related to the amount of rainfall.
A challenging target is to find a method which, by means of remote sensing, is able to correlate quantitatively crop production to the yearly evolution of vegetation, both factors influenced by the amount of yearly rainfall.
In particular, monitoring of vegetation resources has been attempted by means of remote sensing techniques, by using vegetation indices (Curran, 1980 and 1981; Prince, 1986; Tucker et al., 1985). Methods using both meteorological data and satellite data have also been able to assess vegetation condition (Seguin, 1985; Glick et al., 1983; Taylor et al.,1985; Boatwright et al.,1986; Johnson et al.,1987).
The aim of this study is actually to analyse jointly meteorological data, simulated crop production via mathematical models and remote sensing data in order to compare them with statistical data of production obtained by the Statistics Section of the Ministry of Agriculture in Zambia.

2. Materials and methods

2.1 MATERIALS

2.1.1. Satellite data

Two years, respectively 1983-84 and 1984-85 of NDVI 10 day composite images from NOAA-AVHRR (7.6 km. of resolution) have been provided by FAO (Rome). The data set for year 1983-84 was complete (36 decades) while for year 1984-85 only 29 images were available (table 3) .The set of these NDVI 10-day composite images covers the whole territory of Zambia.

Table 3. List of available satellite images

Satellite/Sensor	Frame/Row	Dates
NOAA-AVHRR		from 22nd decade 1983 to 21st decade 1984
		from 22nd decade 1984 to 9th decade 1985
		from 17th decade 1985 to 21st decade 1985
LANDSAT-MSS	172/70	31 August 1984
	172/67	31 August 1984
	172/71	8 September 1984
	170/70	25 August 1984
LANDSAT-TM	170/70	29 November 1984
		16 January 1985
		9 April 1986

Four LANDSAT-MSS cct's (resolution 79x56 mt) have been acquired as table 3 shows. The selection of these MSS images has privileged the locations where more agricultural camps are present (Berkhout et al., 1988). Location of the chosen LANDSAT-MSS images is shown in Fig.1.

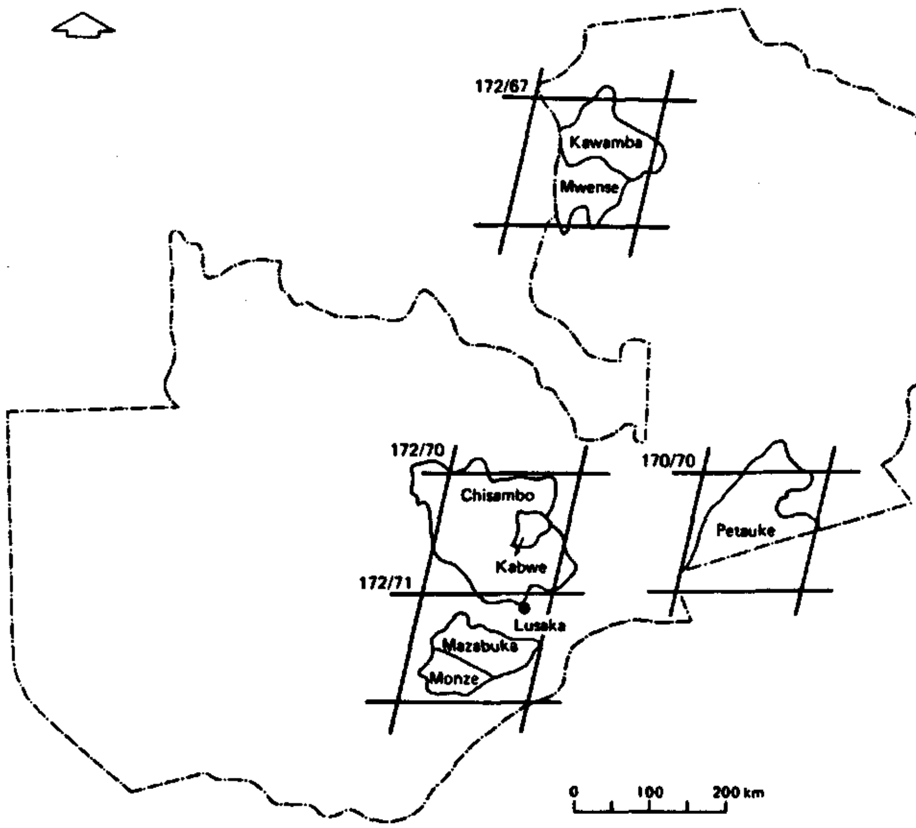

Figure 1. Selected LANDSAT-MSS frames and zambian districts where the pilot areas of MARS project are located (from Berkhout et al., 1988)

Three LANDSAT-TM cct's (II quadrant of frame 170/70 in three different dates) have been also acquired (table 3). They are located in the Eastern province and cover 80% of Katete and part of Petauke districts. Pixel resolution of LANDSAT-TM image is 28.5x28.5 mt.

2.1.2. Meteorological data

Rainfall data were considered for years 1983-84-85 in the following provinces: Southern, Central, Eastern and Northern. These data, collected from several meteorological stations dislocated in each considered province, were analysed in form of 10 day records and averaged for each provinces by means of the isohyetal method. Table 4 shows the considered meteorological stations for four provinces.

Table 4. List od meteorological stations in four zambian provinces.

Province	Meteorological station
Northern	Mbala
	Misamfu
	Mpika
	Isoka
	Kasama
Central	Mumbwa
	Kabwe rural
	Kabwe urban
	Serenje
Eastern	Petauke
	Chipata
	Mfuwe
	Lundazi
	Msekera
Southern	Magoye
	Kafue Polder
	Choma
	Livingstone

2.1.3. Statistical data

Statistical data of annual crop production and of cultivated area were collected for the crop years 1983-84 and 1984-85. Source of such data is the Agricultural Statistics Bulletin of the Ministry of Agriculture and Water Development of Zambia in which yearly statistical data are divided for province and for main cultivated crops.

2.2. RESULTS

2.2.1. Satellite data analysis.

The NDVI-10 day composite images of NOAA-AVHRR for crop years 1983-84 and 1984-85 were analysed as described in Berkhout et al.,1988. NDVI of each 10-day composite data were averaged within each province to obtain the time-serie of the mean NDVI.
Fig. 2. shows NDVI time-series plots of Northern, Southern, Eastern and Central provinces for the crop season 1983-84, where the time profiles exhibit wide fluctuations of NDVI values.

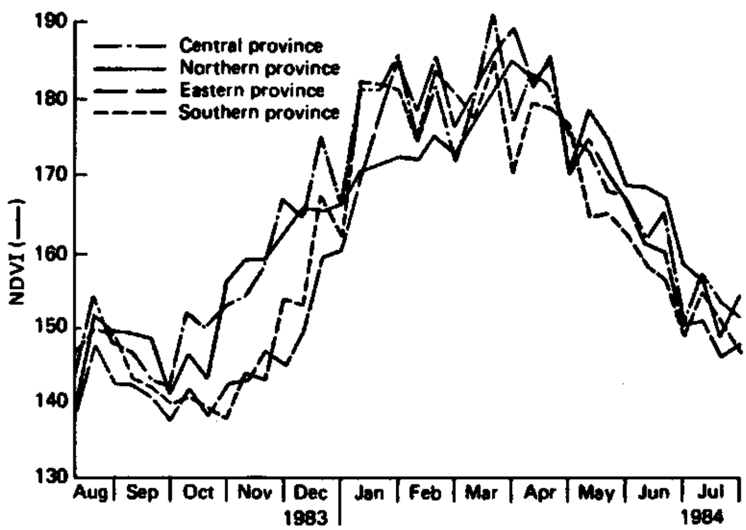

Fig. 2. NDVI time-series plots of Northern, Southern, Eastern and Central provinces for the crop season 1983-84.

To eliminate random fluctuations, the obtained profile has been smoothed and consequently a better interpretation of NDVI time series data profiles was performed. For this purpose NDVI time series data were analysed by means of a statistical package calculating the cubic spline data smoother (van Doorne, 1983) and the results plotted in the graphs shown in figures 3 and 4.

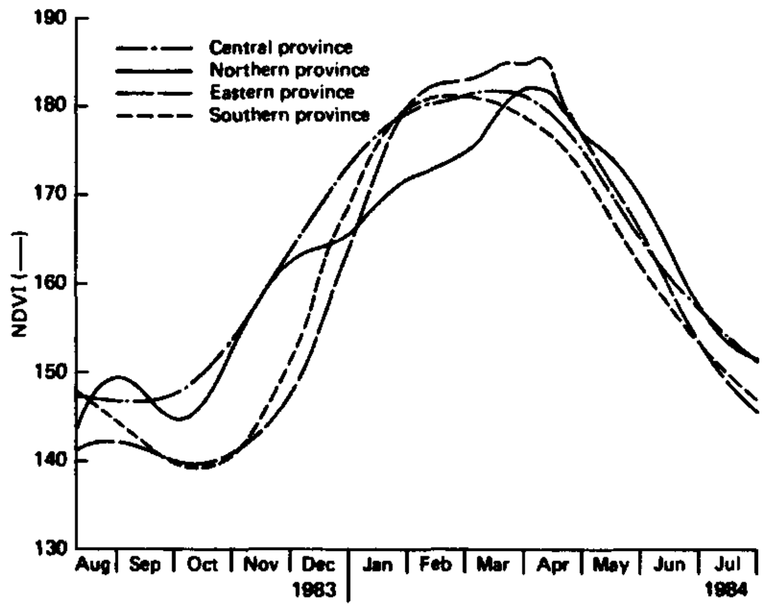

Fig. 3. NDVI time-series plots after the smoothing of Northern, Southern, Eastern and Central provinces for the crop season 1983-84.

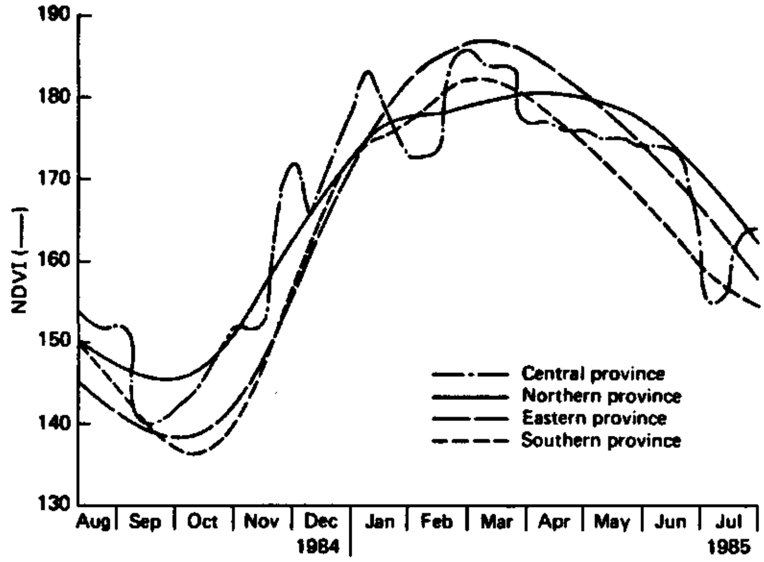

Fig. 4 NDVI time-series plots after the smoothing of Northern, Southern, Eastern and Central provinces for the crop season 1984-85.

Four zambian districts, respectively Kawambwa, Kabwe urban, Mazabuka and Petauke, were closely analysed by means of the four acquired LANDSAT-MSS images. For part of each MSS image a standard colour composite product (bands 7-5-4) was performed in order to visualize exactly where the agricultural areas of the chosen districts are located.
Furthermore, part of Petauke and Katete districts were carefully analysed in a multitemporal sequence of three acquired LANDSAT-TM images. Such analysis already performed and widely described in Berkhout et al., 1988 was slightly modified as follow :

- the LANDSAT-TM images of 16-1-85 has been rectified at full resolution
- a second landuse classification was performed using the maximum likelihood method on the rectified full resolution TM quadrant (band 5) where training sets have been chosen to define the following classes : maize, fallow+savanna, wood, water
- following the method described by Menenti et al.,1986, crop classification was also performed assigning a characteristic interval for each crop and for the considered reflectance values of bands 3, 4 and 5.

The Transformed Vegetation Index (TVI) was also taken into account in the calculation of the characteristic interval. The whole TM quadrant was then classified and such results compared with those of the maximum likelihood classification (Azzali, 1988).

2.2.2 Meteorological data analysis

The cumulative curves of the average rainfall data recorded in four chosen zambian provinces are the results of the precipitation data analysis for the years 1983-84 and 1984-85 (Figs. 5 and 6).

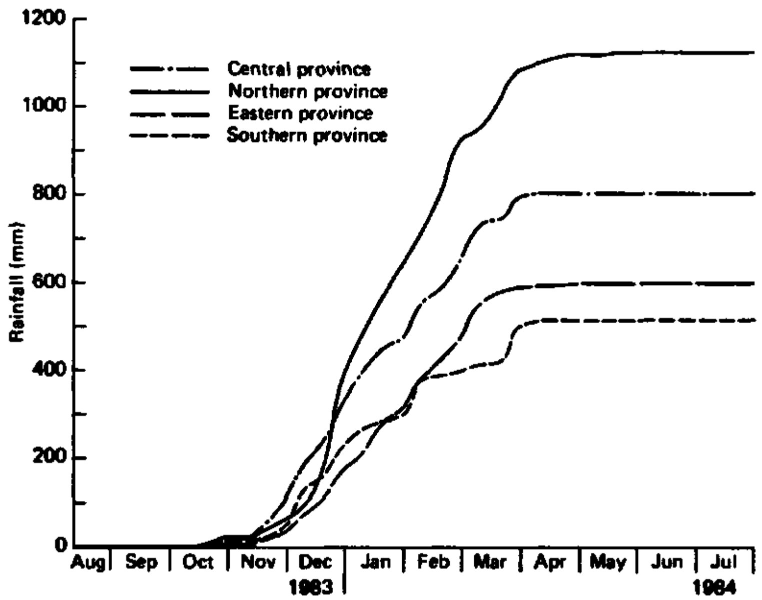

Fig. 5. Cumulated monthly rainfall amount for Northern, Eastern, Central and Southern provinces in crop year 1983-84

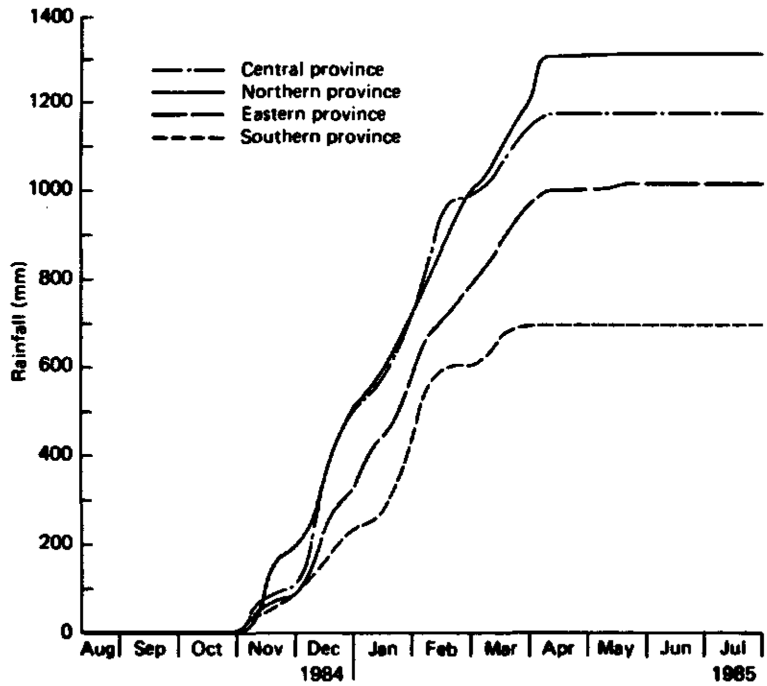

Fig.6 Cumulated monthly rainfall amount for Northern, Eastern, Central and Southern provinces in crop year 1984-85

2.2.3. Statistical data analysis

From Southern, Northern, Eastern and Central provinces the following statistical data were elaborated concerning the crop years 1983-84 and 1984-85 (from Anonymous, 1985) :

- actual cultivated crop area (table 5)
- maize cultivated area (table 6)
- crop production (table 7)
- maize production (table 8)
- yield, as obtained by dividing crop production by crop area (table 9)

Table 5. Actual crop cultivated area in four zambian provinces in the crop years 1983-84 and 1984-85, ratio between the cultivated area in the considered two years.

Provinces	Cultivated area for annual crops [ha] 1983-84	1984-85	Ratio 83-84 cult. area/ 84-85 cult. area
Central	144360	164968	88%
Eastern	264460	245893	108%
Southern	144610	201090	72%
Northern	61645	67267	92%

Table 6. Actual maize cultivated area in four zambian provinces, ratio between maize cultivated area and total annual crop cultivated area, crop years 1983-84 and 1984-85.

Provinces	Maize cultivated area [ha]		Ratio maize area/ crop area	
	1983-84	1984-85	1983-84	1984-85
Central	101000	118700	70%	72%
Eastern	214000	206000	81%	84%
Southern	90000	134000	62%	67%
Northern	42400	46800	69%	70%

Table 7. Crop production in four zambian provinces in 1983-84 and 1984-85, ratio of production between the two considered crop years.

Provinces	Production [1000 kg]		Ratio 1983-84 prod./
	1983-84	1984-85	1984-85 prod.
Central	289768	326895	89%
Eastern	330332	358570	92%
Southern	182947	329219	56%
Northern	108089	117535	92%

Table 8. Maize production in four zambian provinces during crop years 1983-84 and 1984-85, ratio of maize production between the two considered crop years.

Provinces	Production [1000 kg]		Ratio 1983-84/
	1983-84	1984-85	1984-85
Central	248310	285480	87%
Eastern	298710	330174	90%
Southern	144630	277758	52%
Northern	90000	96651	93%

Table 9. Productivity per hectare of annual crop production in four zambian provinces during the crop years 1983-84 and 1984-85, ratio between the two crop productivities.

Provinces	Productivity [1000kg/ha]		Ratio 1983-84/
	1983-84	1984-85	1984-85
Central	2.01	1.98	102%
Eastern	1.25	1.46	86%
Southern	1.27	1.64	77%
Northern	1.75	1.75	100%

3. Discussion of results

3.1. STATISTICAL RESULTS

Statistical data analysis shows that in crop year 1984-85, with the exception of Eastern province where less land was cultivated in 1984-85, land allocated for agriculture has remarkable increased between 8% and 28% referring to the previous year (table 5).

The same relative increase has been not found in the area cultivated with maize which remains rather stable between the two considered crop years (table 6), with the consequence that more land has been then allocated in 1984-85 for other types of crops. However, maize remains the predominant crop in Zambia (Table 6).

The comparison between the considered crop years shows that a higher production was recorded in 1984-85 (tables 7 and 8); see also Berkhout et al.,1988. However, if we compare the actual productivity per hectare between the two years, the bumper harvest year 1984-85 was only recorded for the Southern and ,in modest tone, for Eastern provinces, while Central and Northern provinces did not show any higher productivity (table 9).

3.2. COMPARISON BETWEEN RAINFALL, NDVI AND STATISTICAL DATA : CONTRADICTORY RESULTS

The lowest amount of total rainfall was recorded in the Southern province, in 1983-84 only 517 mm against 700 mm of rain in 1984-85.

Then a shortage of 30% of rainfall in crop year 1983-84 has also influenced the productivity level which has been reduced of the 23% in the Southern province (Table 9).

In Eastern province, during 1983-84 the total amount of rainfall was equal to 600 mm. against the 1016 mm. of 1984-85. However a difference in rainfall of 40% did not influenced so much the productivity which was reduced by only the 14% (Table 9). Moreover, in the Central province different

amount of rainfall recorded in both years , respectively 805 mm. and 1175 mm , did not hamper at all the productivity.
In order to explain different amounts of productivity correlated to different amount of rainfall, a dynamic model called WOFOST (van Diepen et al.,1988), which simulates agricultural production on the basis of physical and agronomic informations, was applied. Maize was chosen as crop in the model simulation.
The results of the model WOFOST shown that limited water had hampered maize production only in Southern province in 1983-84, which was calculated as 50% less of the maize production in 1984-85. In the other three provinces, the recorded amount of rainfall was not a limiting factor for the simulated maize production.
Relative reduction of production recorded both by statistical data in table 9 and by simulating crop production in 1983-84 in Southern province should be very evident in the NDVI time-series plots shown in fig.7

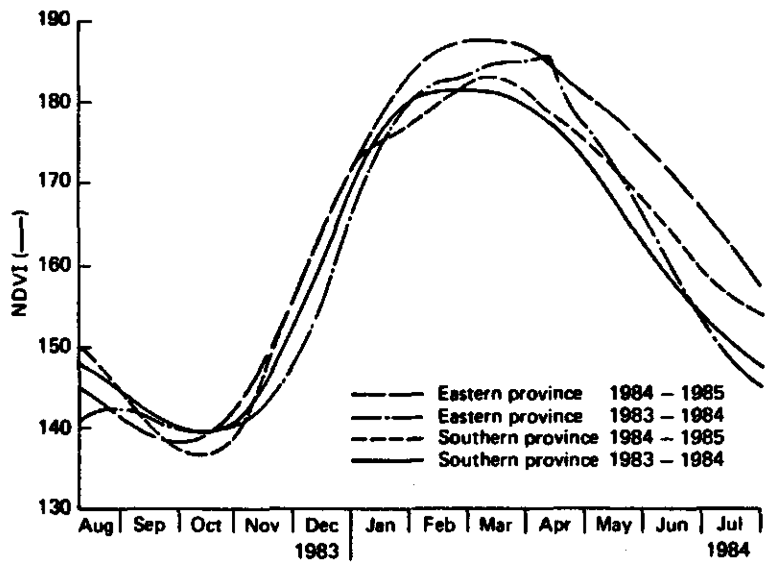

Fig. 7 NDVI time-series plots of Eastern and Southern provinces in the crop seasons 1983-84 and 1984-85.

Nevertheless the NDVI profiles of Southern province did not show up a large difference of values between the two years. On the contrary, remarkable differences in NDVI values between 1983-84 and 1984-85 are visible in NDVI time-series profiles (Fig.7) of Eastern province. Reasons of such patterns of NDVI time profiles can be perhaps many but one seems to be more evident. Indeed, NDVI relative values increase more in Eastern province than in the Southern province within the considered years because the relative increase in rainfall amount is larger in the Eastern than in Southern province. However, it seems that in Eastern province there is not a direct correlation between the amount of rainfall and maize production (simulated maize production did not change in two years via WOFOST model), but such correlation exists between the amount of rainfall and rate of increasing of NDVI values.

3.3. CORRELATION OF START OF THE RAIN SEASON WITH THE BEGINNING OF THE GROWING SEASON : CONTRADICTORY RESULTS.

From fig.3 the NDVI time-series plots referring to the year 1983-84 show that the spatial sequence of the start of growing season is : Central, Northern, Eastern and Southern provinces.

In general, the primary cause of different start of the growing season recorded in the four provinces is attributed to the different start of the rain season. Table 10 summarizes different time schedules related to the start and end of rain season for the four considered provinces; it shows, also, time schedules of two NDVI values respectively the date when the first increment of NDVI occurs after it has reached the minimum and the date when the maximum NDVI value occurs. The dates of beginning and end of rain season were defined when an amount equal or more than 4 mm. has occurred in a decade.

Considering the two analysed years, only in the Southern province (Table 10) NDVI has increased in 1983 during the first decade of November, just ten days later that the rain season has begun, while for the other provinces and years the increasing of NDVI is recorded before the rain season

Table 10. Start and end of rain season in years 1983-84 and 1984-85 for four Zambian provinces; date of NDVI increasing and occurring of profiles of Figs. 3 and 4 relative to years 1983-84 and 1984-85 for four zambian sub-areas

	1983 - 1984			
Province	Date increas. NDVI	Date start rainfall	Date max. NDVI	Date end rainfall
Northern	III dec. Oct.	III dec. Oct.	II dec. Apr.	III dec. May.
Central	III dec. Sep.	III dec. Oct.	III dec. Mar.	II dec. Apr.
Eastern	III dec. Oct.	I dec. Nov.	II dec. Apr.	II dec. Apr.
Southern	I dec. Nov.	III dec. Oct.	II dec. Mar.	II dec. Apr.

	1984 - 1985			
Province	Date increas. NDVI	Date start rainfall	Date max. NDVI/LAI	Date end rainfall
Northern	I dec. Oct.	I dec. Nov.	II dec. Apr.	I dec. Apr.
Central	I dec. Oct.	II dec. Nov.	I dec. Mar./ II dec. Jan.	II dec. Apr.
Eastern	I dec. Oct.	I dec. Nov.	II dec. Mar./ II dec. Jan.	III dec. May
Southern	III dec. Oct.	III dec. Oct.	II dec. Mar./ II dec. Jan.	I dec. Apr.

started. The expected pattern for rainfed agriculture should be, however, that the increase of NDVI (increasing of green vegetation) should occur after few weeks the rain season started, while the analysed results shown in Table 10 do not confirm such expected pattern.

In spite of such striking results obtained by the analysis of NOAA-AVHRR data in comparison with meteo- and statistical data, NDVI values analysed for four zambian provinces contain still plenty of usefull informations which have to be, actually, analysed in different way.

The NDVI values extracted for the four provinces are, de facto, an appropriate indicator of the average growing pattern of vegetation related to the whole province. For each province, clusters of different types of vegetation at different growing stages are, then, taken into account, averaged and explicited in one NDVI value for each considered decade.

Therefore, the type of vegetation, present in higher percentage is influencing NDVI values. In other words, the evolution of NDVI values within the considered years and in the four analysed provinces is reflecting the dynamic of vegetative growing of the type of vegetation there mostly represented.

Consequently, if we want to compare the evolution of NDVI values with the growing pattern of agricultural crops and try to extrapolate these results in a relationship which bounds NDVI values to crop production, we should look actually, for each considered province, at NDVI values extracted from areas where agriculture is the main land allocation. However, table 2 shows that agricultural land is between 0.6% to 3.6% of the total land of the four considered provinces. Therefore the mean NDVI values obtained from the whole province are not adequate to monitor the growing cycle of agricultural crops but they are able to monitor the growing of different types of vegetation.

3.4. ANALYSIS OF ZAMBIAN NATURAL VEGETATION BY MEANS OF REMOTE SENSING DATA

Natural vegetation in Zambia is mainly characterized by miombo woodland (White, 1983). According to the amount of rainfall two major miombo woodlands can be distinguished (Hough, 1986) :

1) wetter miombo with evergreen riparian forests (rainfall amount more than 1000 mm per year) and
2) drier miombo with deciduous riparian forest (less than 1000 mm rainfall per year) where, depending on soil characteristics and microclimates, canopy can be more or less thick (Howe, 1953).

Deciduous woodland is dominated by species as Brachystegia and Julbernardia (Hough, 1986), which roots can developed rather deeply in the soil intercepting water available in the groundwater storage in the dry season (Balek, 1977).

In particular, water balance studies have been performed in Zambia for small catchments (Balek, 1977), where large amount of water stored deep in the soil seemed to influence natural vegetation cycle, in supporting enough humidity to the root system of trees and bushes during the dry season.

It has been proven that in similar ecosystems as the zambian miombo woodland, respectively in Tanzania (Jeffers and Boaler, 1966) and in Zimbabwe (Ernst and Walker, 1973), flush of new leaves and flowering occur to trees and bushes before rain season starts. In fact flush of new leaves and flowering can be indipendent from the water supply given by rain if the groundwater storage is able to supply enough water to the plant rooting system. Then, if water is not a limiting factor, flush of new green vegetation is, in this case, dependent from increase of temperature and from absence of frost, which both two conditions occur in Zambia in the months of September and October (Muchinda, 1985; Hutchinson, 1974).

Therefore, new additional remarks can be made over the data shown in table 10, after such last analysis on zambian natural vegetation.

From table 10, we can see the flushing of natural vegetation (increasing of NDVI values) is, in both years, starting before the beginning of rain season. Moreover, the date of maximum value of NDVI reached in both years

between the months of March and April, shows that the largest amount of green vegetation is reached by the canopy during that period for the four provinces. Comparing these results with those obtained by Balek, 1977, on a study over the monthly evapotranspiration from grassland, woodland and transitive zone in Central African Plateau, we can see that also the values of actual evapotranspiration of woodland and transitive zone have their maximum during the months of March and April, which indicate that the considered vegetation systems have reached in that period full green canopy.
In order to prove the existence of green natural vegetation, able to flush up before rain season starts in Zambia, LANDSAT-MSS satellite images were analysed.
From MSS images available in dry season (table 3) - end August, begin September - it was possible to identify large areas where green vegetation is located. In particular, photos 1, 2, 3, 4, shows a standard colour composite product of sub-areas located respectively in Kawambwa, Petauke, Kabwe urban and Mazabuka districts, where red colour evidenciates the presence of green vegetation, attributed to woodland, bushes and irrigated agriculture, while gray-blue colour shows bare soil or dry vegetation.
Such sub-areas were chosen out of four provinces as the most representative areas for agriculture eventhough presence of natural vegetation is large mainly in Kawambwa and Kabwe urban districts (red colour in photos 1 and 2).
Analysing more closely the NDVI time-series plots of Fig.3 and 4, evolution of the vegetation types in Central and Northern provinces show a smaller fluctuation of NDVI profile values between dry and rain seasons. Such pattern can find an explanation in the massive presence of woodlands in the provinces which remains also greenish in the dry season (Photo 1 and 2).
Moreover, from figs. 3 and 4 the smallest minimum values of NDVI are recorded in Southern province, which reason can be found in the scarcity of woodlands and bushes (photo 4).

Photo 1

Photo 2

Photo 3

Photo 4

Photo 1. Colour coded (bands 7-5-4) MSS-image of a sub-area in Kawambwa district, Luapula province, Zambia, where full green vegetation is red, dry savannah and bare soil are blue to gray-blue; 31 August 1984, LANDSAT-MSS data

Photo 2. Colour coded (bands 7-5-4) MSS image of a sub-area in Kabwe urban district, Central province, Zambia, for coding see photo 1; 31 August, 1984, LANDSAT-MSS data

Photo 3. Colour coded (bands 7-5-4) MSS-image of a sub-area in Petauke district, Eastern province, Zambia, for coding see photo 1; 25 August, 1984, LANDSAT-MSS data

Photo 4. Colour coded (bands 7-5-4) MSS-image of a sub-area in Mazabuka district, Southern province, Zambia, for coding see photo 1; 9 September, 1984, LANDSAT-MSS data

4. DEFINITION OF NEW ANALYSIS OF SATELLITE DATA TO MONITOR CROP PRODUCTION

4.1. SETTING A NEW METHOD OF ANALYSING NOAA-AVHRR DATA

In order to analyse areas where agricultural camps are represented in high percentage, few pixels in the NDVI NOAA-AVHRR image-series were chosen out of the four provinces. From such selected pixels NDVI values were extracted and plotted in time-series graphs which represent mainly the growing pattern of agricultural crops during the two considered years.
These results should allow a better comparison with the statistical data of crop production instead of the earlier obtained results which analysed the average values of NDVI extracted from the whole province.

4.2. INTERCORRELATION BETWEEN SATELLITE IMAGES AT DIFFERENT RESOLUTIONS

The finest resolution of NOAA-AVHRR images have pixel dimension of 1.1 km. Sampling and compression of these data generate several cathegories of NDVI images having different spatial resolutions (Johnson et al., 1987). Data used for the NDVI time-series plots in this research have a pixel resolution of 7.6 km., which resolution does not allow to visualize features as, i.e., agriculture fields.
In order to localize agricultural areas in the NDVI pixels,LANDSAT-MSS images were used. For this purpose, standard colour composite products created from bands 7-5-4 of LANDSAT-MSS images were analysed (Photo 1, 2 3 and 4). In fact, given the higher resolution of MSS pixel, such products are able to show the location where agricultural fields are present.
In order to compare NOAA-AVHRR images with MSS images, the districts boundaries respectively of Kawambwa, Kabwe urban, Mazabuka and Petauke district were digitized on a map. Then four masks were created showing the districts boundaries and superimposed on the NDVI NOAA-AVHRR images (Berkhout et al., 1988). On four black and white photo products, showing

the entire areas of the considered LANDSAT-MSS frames (table 3), boundaries of the forewritten districts were drawn. Then, a grid, which each cell represented a NOAA pixel, was superimposed to the districts masks and visual comparison between the location of districts areas in the NOAA-AVHRR and LANDSAT-MSS images was performed. Consequently, "agricultural" pixels were selected from NDVI NOAA-AVHRR with the help of LANDSAT-MSS images, where, because of the better resolution, agricultural fields were clearly visible and easier to locate.
Furthermore with the help of LANDSAT-TM images it was possible to locate areas characterized by high numbers of agricultural fields.
From the set of two out of three LANDSAT-TM (Table 3) images, landuse classification was performed using band 5 of the LANDSAT-TM image of 16-1-1985 (Azzali, 1988). More in detail, two different methods of landuse classification were performed on band 5, which was previously geometrically and radiometrically corrected. In a rather intensive cultivated area (part of Petauke and Katete districts in Eastern province) allocated land for maize cultivation reached 3.4% of total area of the considered LANDSAT-TM quadrant. Such classification proves that looking at selected areas (i.e. part of Petauke and Katete districts or selected pixels in NOAA-AVHRR images) the percentage of area allocated for maize was, in 1984-85, higher in comparison with the maize cultivated area calculated for the whole Eastern province (3% of the total territorial area).

4.3 SELECTION OF "AGRICULTURAL" PIXELS : GENERAL RESULTS

Selected pixels were chosen (Table 11) and for each group of pixels a mean NDVI value was calculated for each decade and plotted in a temporal profile. Figures 8a,b; 9a,b; 10a,b; 11a,b; show both the time-series profiles of NDVI of the selected sub-areas and cumulative rainfall amounts in 1983-84 and 1984-85.

Table 11. Location and amount of analysed pixels of NDVI NDAA-AVHRR data referring to the years 1983-84 and 1984-85.

Province	District	N. of pixels	Hectares
Luapula	Kawambwa	3	17328
Central	Kabwe urban	5	28880
Eastern	Petauke	8	46208
Southern	Mazabuka	4	23104
Southern	Mazabuka	5	28880

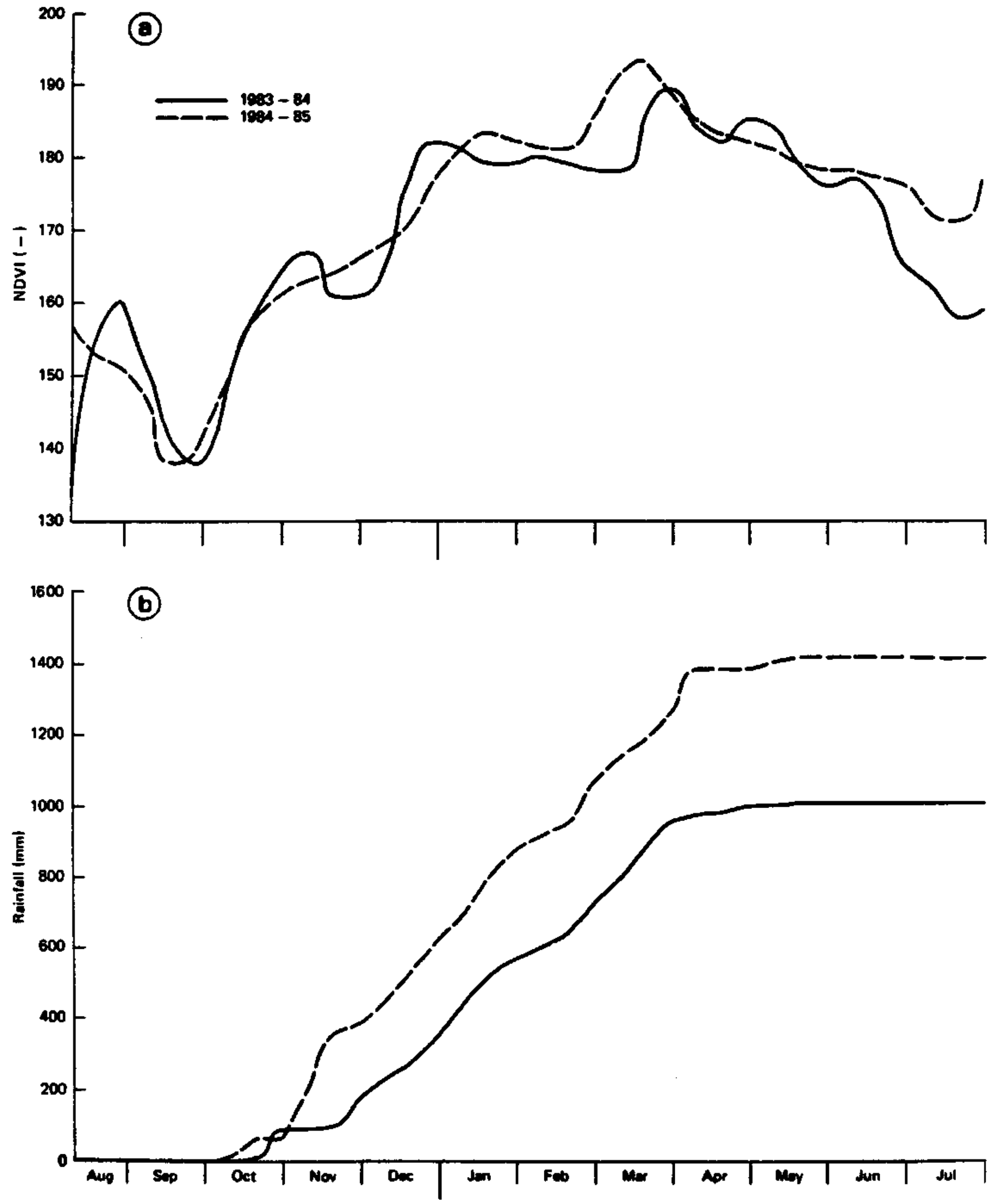

Fig. 8 a) NDVI time-series plots of NDVI mean values referring to three pixels located in Kawambwa district in the crop years 1983-84 and 1984-85

b) Cumulative decade rainfall amount recorded in the meteorological station of Kawambwa in 1983-84 and 1984-85

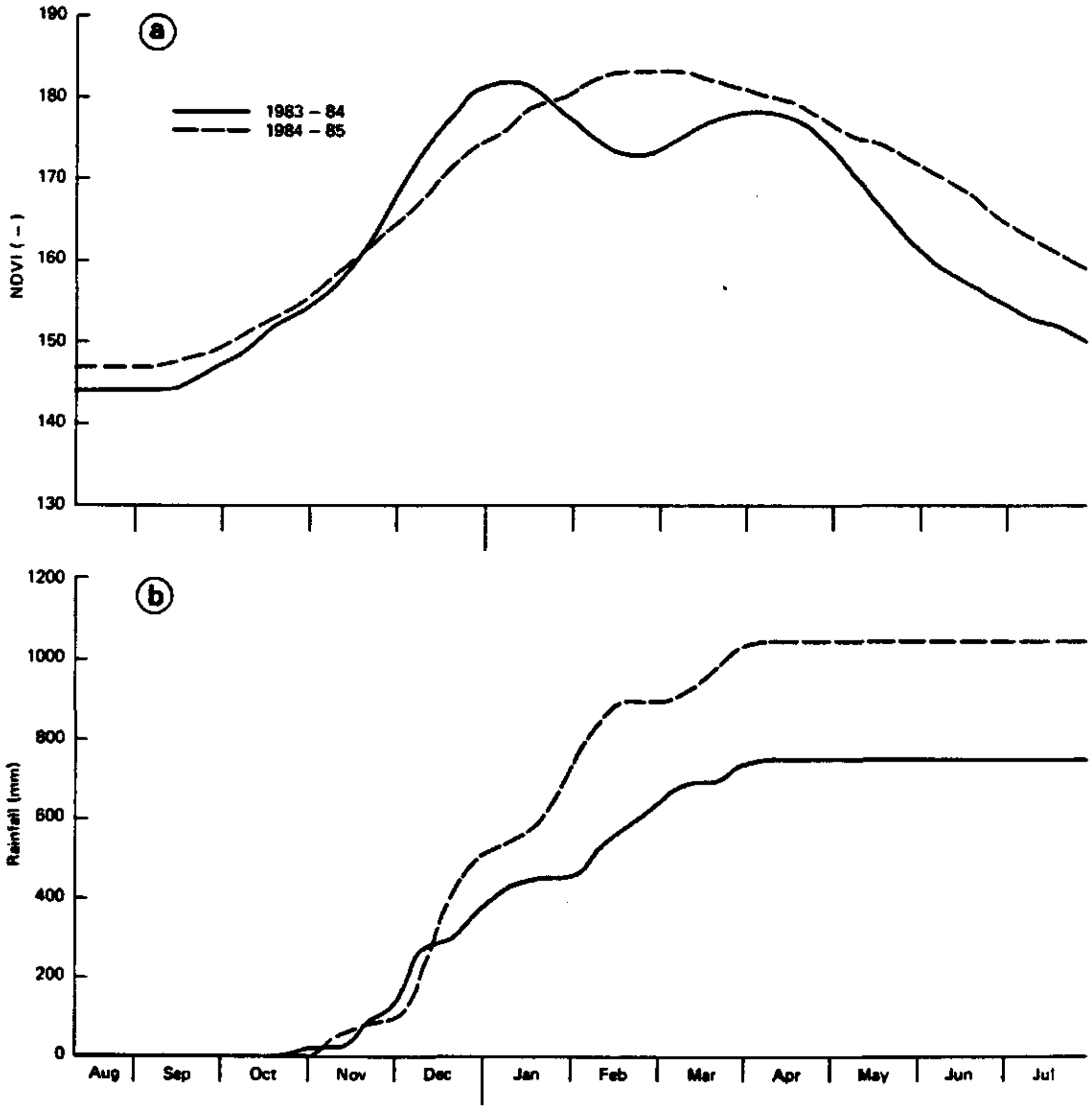

Fig. 9 a) NDVI time-series of NDVI mean values referring to five pixels located in Kabwe urban district for the crop years 1983-84 and 1984-85

b) Cumulative decade rainfall amount recorded in the meteorological station of Kabwe urban in 1983-84 and 1984-85

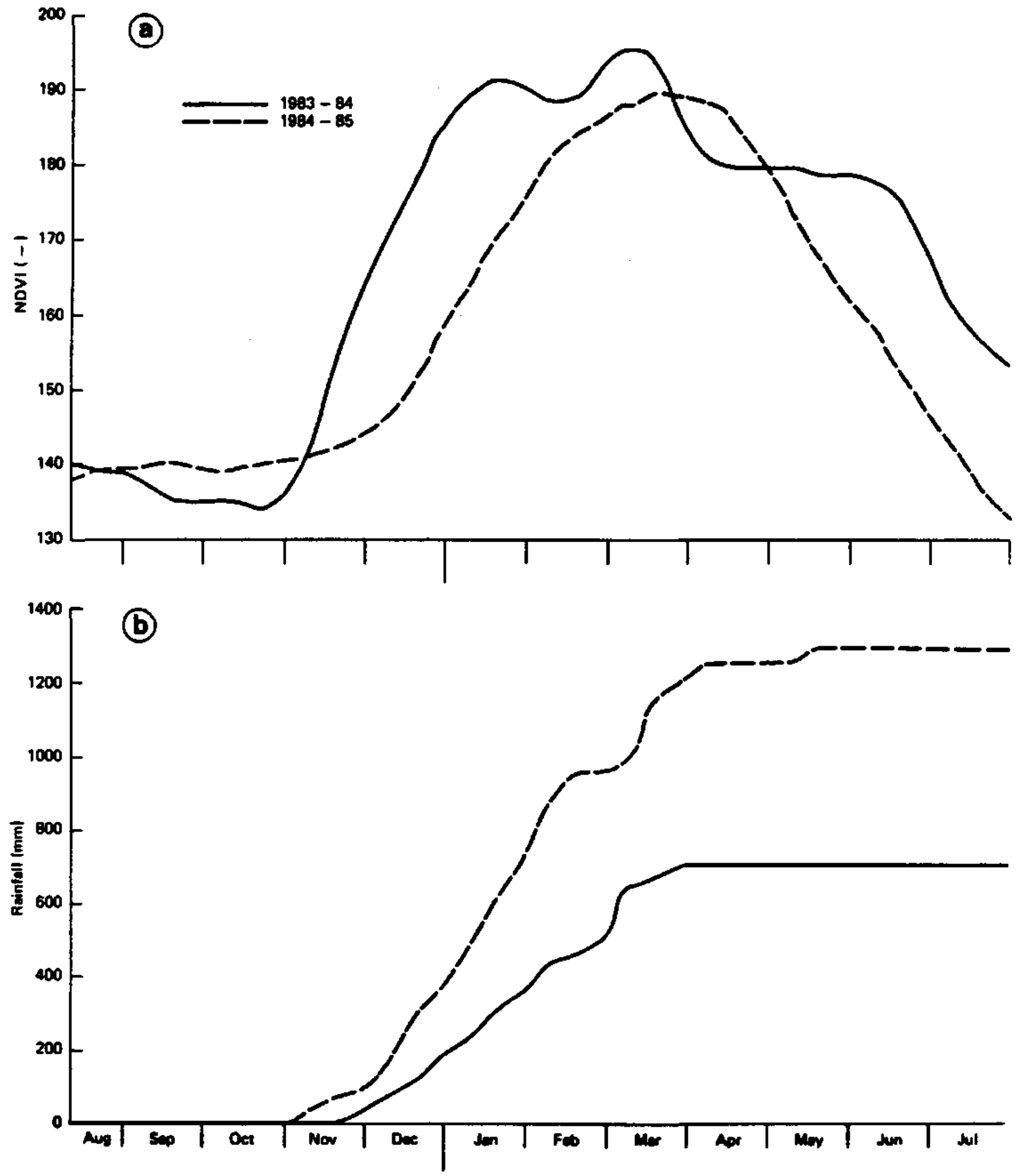

Fig. 10 a) NDVI time-series of NDVI mean values referring to eight pixels located in Petauke district for the crop years 1983-84 and 1984-85

b) Cumulative decade rainfall amount recorded in the meteorological station of Petauke in 1983-84 and 1984-85

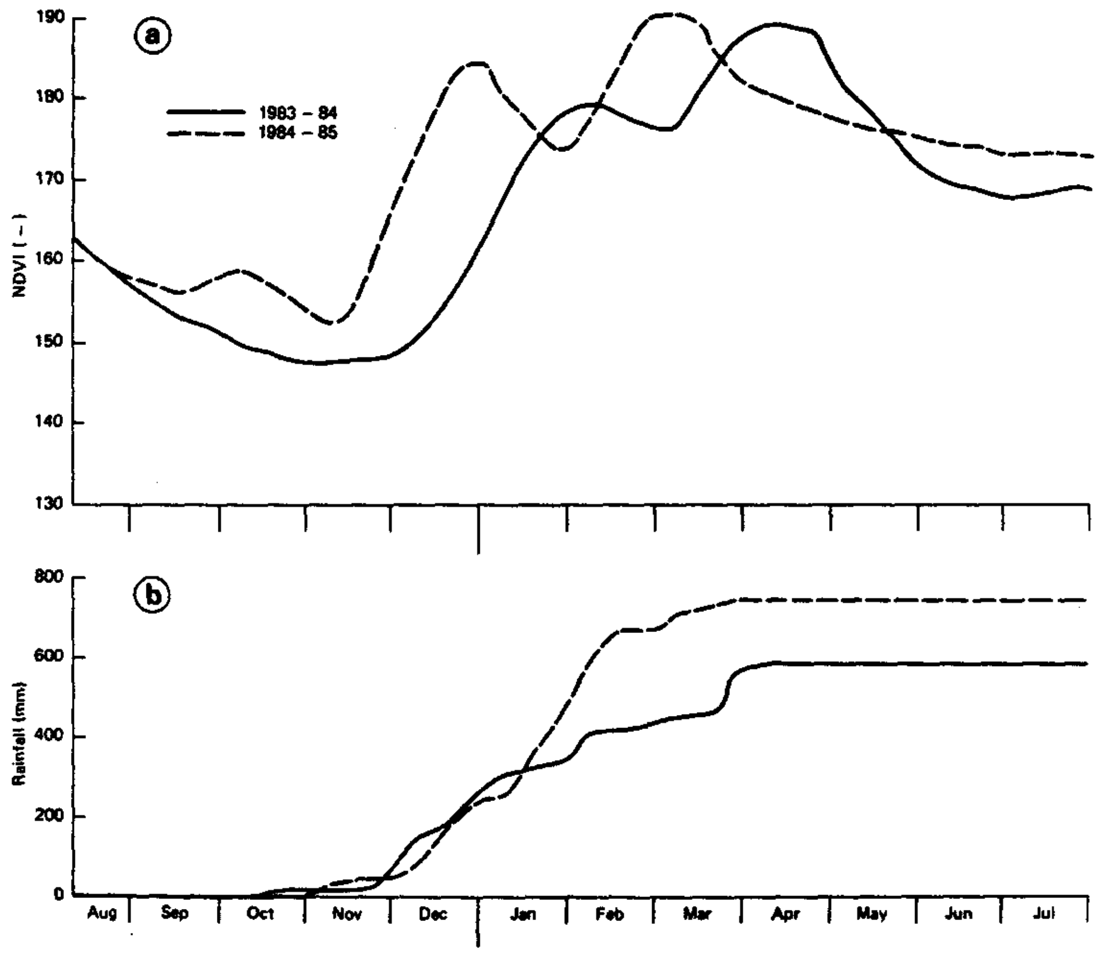

Fig. 11 a) NDVI time-series of NDVI mean pixels located in Mazabuka district for the crop years 1983-8 and 1984-85.

b) Cumulative decade rainfall amount recorded in the meteorological station of Magoye in 1983-84 and 1984-85

occurred in January. Being the NDVI a very sensible indicator of vegetation growing pattern, we can correlate the first maximum value of NDVI in 1984-85 (Fig.10a) to the maximum growing stage of annual crops, while the second maximum value in the same profile can be correlated with the growing patterns of woodlands and transitive zone where the highest evapotranspiration rates occur during March and April (Balek, 1977).

Moreover, analysing Fig.10a differences between the NDVI temporal profiles in the two years are rather large, which cause can be probably found in different

From the comparison between the NDVI values and the pattern of the rainfall amount on the graphs from fig. 8 to fig.11, some results are, so far, summarized in table 12 and described as follow :

1) the spatial sequence of the growing season in both years begins in Kabwe urban district, followed by Kawambwa, Katete districts and it ends in Mazabuka district.
2) Significative rainfall (>0.4 mm per day) starts in three sub-areas, respectively Kawambwa, Petauke and Kabwe urban, much later than the [illegible] of the growing season. Such results indicates that, eventhough

Table 12. Begin and end of rain season in years 1983-84 and 1984-85 for four Zambian meteorological stations; date of NDVI increasing and occurring of maximum values of NDVI extracted from the NDVI time series profiles of Figs. 8, 9, 10 and 11 relative to years 1983-84 and 1984-85 for four Zambian sub-areas.

	1983 - 1984			
district	Date increas. NVDI	Date start rainfall	Date max. NDVI	Date end rainfall
Kawambwa	I dec. Oct.	III dec. Oct.	I dec. Apr.	III dec. May.
Kabwe urban	III dec. Sep.	I dec. Nov.	II dec. Apr. II dec. Jan.	II dec. Apr.
Petauke	III dec. Oct.	III dec. Nov.	III dec. Mar.	I dec. Apr.
Mazabuka/ Magoye	I dec. Dec.	III dec. Oct.	II dec. Apr. II dec. Feb.	II dec. Apr.
	1984 - 1985			
	Date increas. NDVI	Date start rainfall	Date max. NDVI/LAI	Date end rainfall
Kawamba	III dec. Sep.	II dec. Oct.	III dec. Mar.	III dec. May
Kabwe urban	III dec. Sep.	II dec. Nov.	II dec. Mar.	II dec. Apr.
Petauke	I dec. Nov	I dec. Nov.	II dec. Mar. III dec. Jan.	III dec. May
Mazabuka/ Magoye	III dec. Nov.	II dec. Nov.	II dec. Mar. I dec. Jan.	I dec. Apr.

amounts of rainfall (Fig. 10b). In addition, correlating the NDVI temporal profiles with the maize productivity values for Eastern province (Table 9), we find a good correspondance between the two patterns, where at lower productivity (1.25 tons/ha) in 1983-84 the NDVI profile was smaller than the profile in 1984-85 (productivity = 1.46 tons/ha).
Nevertheless, simulating maize crop production via WOFOST model, water amount was not a limiting factor for crop production (in 1983-84 total rainfall amount was 739 mm, while in 1984-85 it was 1322 mm) in the considered years. In addition, it seems that in 1984-85 the huge amount of rainfall had influenced negatively maize production simulated via WOFOST model, which was 4% lower than that in the previous year (Huygen, personal communication).
From the 8-pixel sub-area a second sub-area of 3 pixels was also closely analysed in order to reduce the influence of natural vegetation over the agricultural area; however, the same results were obtained as before.
Such results confirm that the temporal profiles of NDVI values of fig.10a refer to mixed types of vegetation and they cannot used as direct indicator of growing patterns of agricultural crops in Petauke district sub-area.

4.4.4. Mazabuka district sub-area

Rainfall amounts, respectively 589 mm in 1983-84 and 749 mm. in 1984-85, recorded in Magoye meteorological station (Fig. 11b) were the lowest values between the other rainfall amounts recorded in the three considered meteorological station. Then, comparing the NDVI temporal profiles of a 4 pixel subarea from Mazabuka district (Fig. 11a) with the total amount of rainfall (Fig. 11b), we can see, in both years, a good correlation between the four curves. In particular, in 1983-84 the start of rain season (>0.4 mm per day) occurred on the third decade of October (Table 12), while increase of NDVI started only on the first decade of December, as consequence of a very scarce amount of rainfall dropped in November. Such cause has then delayed that growing season and, as consequence, NDVI (indicator of green vegetation) has reached its first maximum value on the second decade of February while the second maximum value was reached on the second decade of April.

Moreover the sensitivity of NDVI indicators are strictly correlated to large amounts of rainfall. In fact the NDVI values have promptly increased reaching the maximum values (Fig. 11a) as reaction to the relatively large amounts of rainfall which have occurred respectively on the first decade of February (70 mm) and on late March (105 mm) in 1983-84.
Simulating maize growing pattern via WOFOST model for this sub-area, the highest LAI was recorded on mid-January in 1983-84 and, comparing this LAI value with the first maximum value of NDVI (Fig. 11a) in 1983-84, a time lag of one month was found between the two occurrence dates.
However, simulation of maize production did show that in 1983-84, maize production was hampered because of water limiting in reason of 38% of the simulated maize production of 1984-85. Such result can be partly compared with the statistical productivity values shown in table 9 where Southern province had a very poor production year in 1983-84 compared with 1984-85.
Analysing also crop year 1984-85, a good correlation between NDVI temporal profile and amount of rainfall (Fig. 11a and b) can be found. In fact in 1984-85 significative rain has started a week before than the increasing of NDVI has been recorded (Table 12). Furthermore, the date of the first maximum NDVI value - Dec.84/Jan.85 - (Fig. 11a) matches with the date of LAI maximum value extracted from the simulated maize growing pattern via WOFOST.
The second maximum value recorded on mid-March '85 shows that the NDVI values extracted from the chosen sub-area are also influenced by some vegetation which reaches full green cover late in the season.
Rather interesting is the NDVI pattern recorded for two different sub-areas located in Mazabuka district (table 11), from which other NDVI time-series profiles were extracted (fig 12).

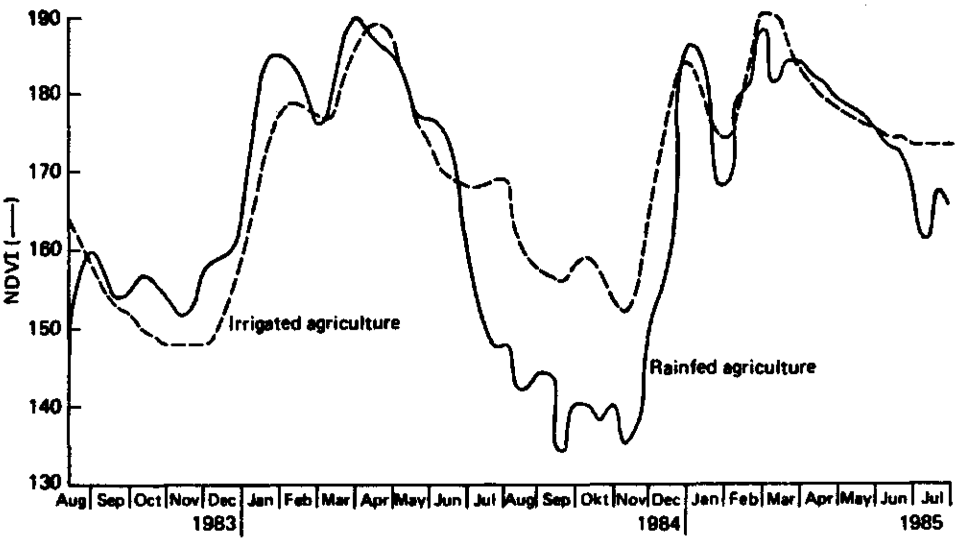

Fig. 12 NDVI time-series plots of NDVI averaged values referring to four respectively five pixels located in Mazabuka district for the crop years 1983-84 and 1984-85. Four pixel area refers to an irrigated farm while five pixel area refers to rainfed agricultural system

By analysing the colour composite product of MSS image 172/71 on 8 September 1984 (photo 4), it was possible to identify a very large farm which, even on that date, had plenty of green vegetation, which condition occurs only if crops are, in that period, under irrigation. The farm object of the analysis is a state farm located around Mazabuka city (Wisse and Marchand, 1982) and the farm irrigation water is supported by the Kafue Flats Irrigation Program. In fig. 12 the dashed line refers to the NDVI time-series profile of a 4 pixel sub-area comprehending the above mentioned state-farm (large 3 NDVI pixels) where, during summer 1984 NDVI values were much higher (irrigation practice) than those recorded in rainfed agriculture system (solid line of figure 12).

4.5. CORRELATION BETWEEN NDVI VALUES AND CROP PRODUCTION IN SUB-AREAS

The NDVI temporal profiles of the sub-areas extracted from four zambian districts have shown to be more closely correlated to the pattern of crop growing than the NDVI time profiles extracted from four zambian provinces. A method which will correlate annual production of agricultural crops with AVHRR-NDVI values extracted on the end of the crop growing season has been tried out.
More precisely, from each NDVI time series profiles of the selected pixels for Kabwe urban, Mazabuka, Petauke and Kawambwa for each crop season, the ending date of the crop growing season is so defined: it is the consecutive date after the last maximum value in the NDVI temporal profile has occurred. From such date till the 36th decade the NDVI cumulative decrement values were extracted for each profile and plotted on graph.
The lines (Fig. 13) extracted for each training area in 1983-84 show a good correlation with the productivity values recorded in table 9 for each province. In addition, the rate of decreasing of NDVI values at the end of growing season can be used as qualitative indicator of crop production.

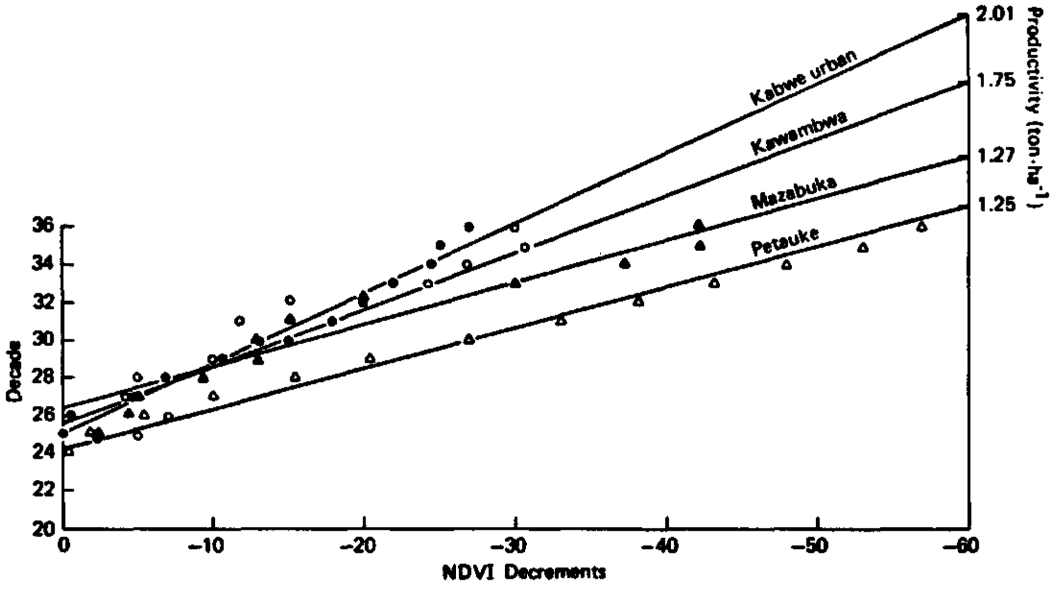

Fig. 13. Cumulative decrements of AVHRR-NDVI values extracted from selected sub-areas located respectively in Kawambwa, Kabwe urban, Petauke and Mazabuka districts, crop year 1983-84. Productivity values in tons/ha are extracted from table 9.

5. Correlation between NDVI, rainfall and production data in four zambian provinces : final results

Comparison between the NDVI data, rainfall data and production data obtained both via statistical data and via simulation model WOFOST was performed in four zambian provinces (Central, Northern, Southern and Eastern provinces) in the years 1983-84 and 1984-85. In order to compare such different data, four indicators were elaborated as follows :

1) rainfall data were elaborated calculating the increment of rain between the two considered years and then the percentage of such increment for each province was extracted referring to the amount of rainfall occurred in 1984-85;
2) both values of maize production from statistical data (Table 9) and those obtained from the WOFOST model were elaborated calculating the increment (negative or positive) between the two years and the percentage of these values were extracted referring to the productions respectively obtained in 1984-85;
3) cumulative decrements of NDVI values extracted from the four considered zambian provinces were calculated following the method described in par. 4.5 for both years. Then, for each province,difference between these decrements was calculated and from this result percentage value was extracted referred to the year 1983-84. This percentage value was then multiplied for 1/100.

The so obtained indicators allowed actually a more clear comparison between the different data referring to the four zambian provinces.
Very interesting results came up from Central and Southern provinces (Table 13) where the highest increment of rainfall (Central province) corresponds to the lowest increment of production confirmed by statistical, WOFOST and NDVI indicators.

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8. Glossary of Acronyms

AVHRR	NOAA Advanced Very- High Resolution Radiometer
FAO	Food and Agricultural Organization of the United Nations, Rome, Italy
GAC	NOAA Global Area Coverage
LAC	NOAA Local Area Coverage
LAI	Leaf Area Index
LANDSAT-MSS	LANDSAT Multispectral Scanner
LANDSAT-TM	LANDSAT Thematic Mapper
MARS	Monitoring Agroecological Resources using Remote Sensing and Simulation
MAWD	Ministry of Agriculture and Water Development, Lusaka, Zambia
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration, US
WOFOST	crop growth simulation model of the Centre for WOrld FOod STudies, Wageningen, The Netherlands