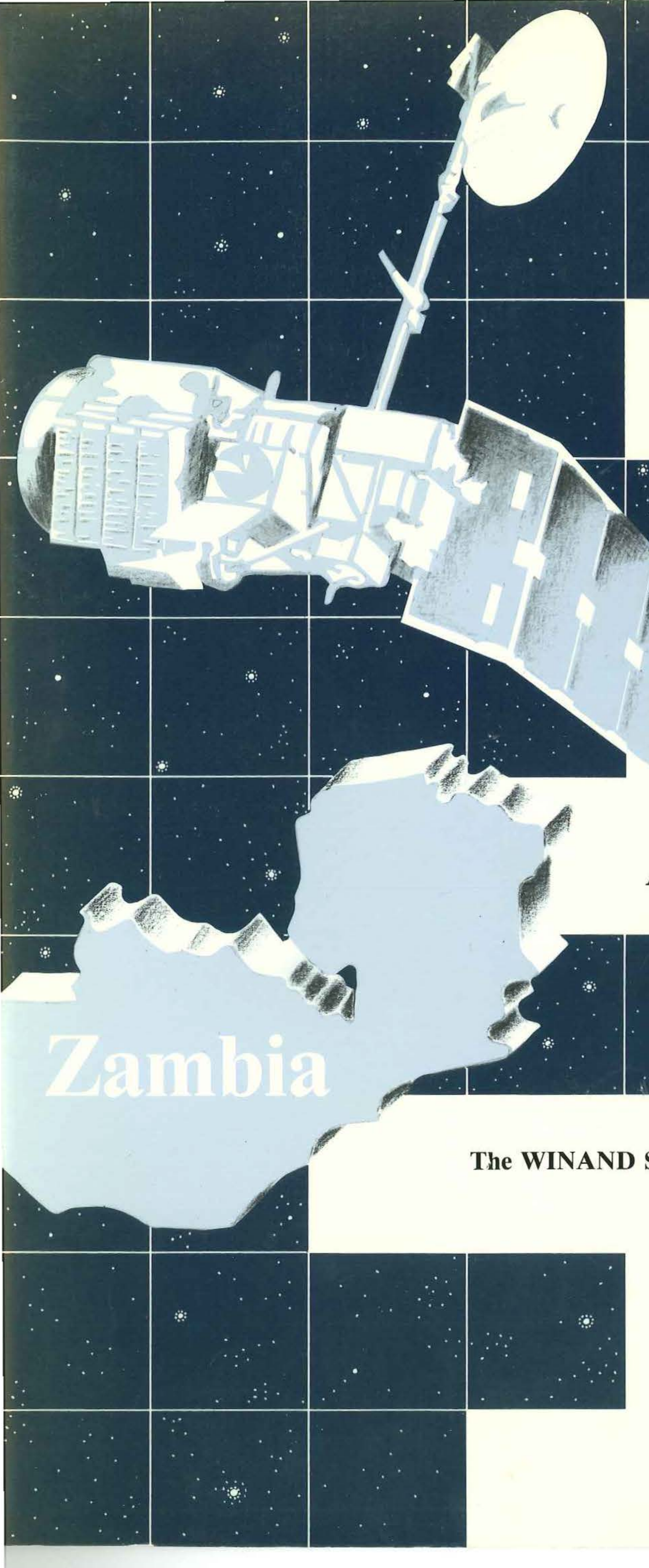

MARS

Monitoring Agro-ecological Resources with Remote sensing & Simulation

HIGH AND LOW RESOLUTION SATELLITE IMAGES TO MONITOR AGRICULTURAL LAND

REPORT 18

The WINAND STARING CENTRE, Wageningen (The Netherlands), 1990

High and low resolution satellite images to monitor agricultural land

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High and low resolution satellite images to monitor agricultural land

Susanna Azzali

Report 18

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ABSTRACT

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The evaluation of feasible methods to improve the real time information on the agricultural production has been presented in detail as one aspect of the MARS (Monitoring Agro-ecological Resources by means of Remote sensing and Simulation) project in Zambia.

The use of remote sensing images together with geographical information system and implementation of numerical simulation model based on crop growth (WOFOST) have been used to develop such methods.

The combination of different indirect measurements as satellite data (LANDSAT Thematic Mapper and Multispectral Scanner, NOAA-AVHRR-NDVI), aerial photographs, meteorological data, literature information and maps has shown a synergistic effect to understand the considered agricultural scenarios. Remarkable results have been obtained to assess agricultural production by means of NOAA-AVHRR-NDVI data.

Keywords: Zambia, agriculture, LANDSAT-TM, LANDSAT-MSS, NOAA-AVHRR-NDVI, MARS, WOFOST.

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CONTENTS

PREFACE

Satellite Remote Sensing techniques offer complementary information to direct field observations to observe vegetation growth. The vantage point of satellite-borne sensors is a particularly valuable asset when large, scarcely known areas have to be dealt with.

Meteorological and earth observation with satellite images and aerial photographs, when applied in a combined manner, give a wealth of synoptic, detailed and timely information on vegetation conditions over large areas.

Experience shows that this accurate information on vegetation conditions as a whole is not sufficient to assess quantitavily growth and to forecast yield of specific crops. Meteorological, agronomic, hydrological, ecological and statistical data are required to obtain a reliable estimate of crop production. Conversely, the use of ground-based data only to work-out yearly, nation wide estimates of crop production without the support of satellite data would require massive human and financial resources.

In this report the results are presented of investigations on the development and validation of methods to improve crop assessment and yield forecasting procedures with satellite data in Zambia. Scope and restrictions of using satellite data at different spacial and temporal resolution (NOAA/AVHRR, LANDSAT Thematic Mapper and MultiSpectral Scanner) are illustrated by means of practical examples. Aerial photographs, meteorological data, literature and carthographic information are applied when necessary to support the analysis of satellite data.

This investigation is part of MARS, a demonstration project on the combined use of crop growth simulation models, earth observation and meteorological satellite data on behalf of the National Crop Forecasting and Early Warning System in Zambia.

The author wishes to thank the following persons for their contribution: Tom Bucx, who has performed the satellite and GIS data processing presented in paragraph 4.4; Jaap Huygen, who provided the results obtained by means of the crop growth simulation models WOFOST presented in paragraph 4.5; Massimo Menenti for his constructive comments on the manuscript.

SUMMARY

The objective of the MARS (Monitoring Agro-ecologycal resources by means of Remote sensing and Simulation in Zambia) project (Berkhout et al., 1988) is to assess and, when feasible, to demonstrate in practice methods to improve Crop Forecasting and Early Warning procedures in Zambia.

In this report the results are presented of investigations on the integration of different satellite data, maps and tabular data to obtain indicators of agricultural production and to map agricultural land, specific crops and arias where shifting cultivation is being practiced.

The analysis is focussed on features of agriculture in large administrative units, i.e. the entire country, provinces and districts. Whenever a better detail is required, a close-up procedure is applied. For such purpose satellite data at different resolutions have been applied in a combined manner. Different applications are presented:

- Estimation of maize cultivated area in a district by means of LANDSAT-TM images and crop phenology (crop calendar). Statistical data collected by the Central Statistical Office (CSO) in Zambia confirmed the validity of the maize area values obtained with satellite data.
- Mapping areas where shifting cultivation is being practiced. Traditional agriculture (mainly shifting cultivation) is widespread in Zambia. To quantify the extension of the area under shifting cultivation a close-up analysis of sample areas was carried out by means of aerial photographs and LANDSAT-TM images. The results show that fiels under shifting cultivation can be very well visually identified as well in the aerial photos as in the LANDSAT-TM images. Discrimination of these fields, having circular shape, from fields under commercial agricultural (rectangular shape) has been done on the basis of roundness-values as measured by means of the Quantimet Image Analysis System.
- Analysis on yearly basis of vegetation growth for the entire country, provinces and districts. It has been demonstrated that the sum of decrements of the Normalized Difference Vegetation Index (NDVI), calculated by taking as a reference the highest NDVI-value in the growing season, is a practical indicator of agricultural production. The evolution of NDVI-values throughout the growing season relates to the phenology of the dominant vegetation type, i.e. natural vegetation in most cases. This statement rests, particularly, on the experimental evidence that the NDVI increases prior to the beginning of the rainy season.

- Close-up procedure by means of LANDSAT-MSS and TM data. The NDVI data often are not sufficiently detailed. Particularly, the mean NDVI-values do not provide useful information on the sites where crops are actually being grown. An investigation on the influence of geological and soil characteristics on vegetation growth has been carried out by means of LANDSAT-TM images. It has been shown that significant information on growth conditions of specific crops can be obtained when "NDVI agricultural pixels" (pixel size 7.3 x 7.3 km) only are considered. To identify such agricultural pixels, LANDSAT-MSS data have been applied. When extensive agricultural areas are identified, this procedure gives the location of suitable NDVI pixels to obtain indicators of crop conditions.
  Useful results have been obtained correlating NDVI-values of agricultural pixels with agricultural statistics on maize production in a district.

1 INTRODUCTION

1.1 Problem definition

The monitoring of agricultural land-use in Zambia and in particular crop monitoring and harvest forecasts are based on traditional methods applying rainfall data coupled with field reports and surveys. It is very problematic and enormously expensive to obtain yearly inventories based on traditional methods of a land like Zambia, containing different types of land-use units and agro-ecological zones and having limited infrastructure. The remote sensing techniques can help to overcome such problems.

The purpose of this report is to present more in detail one important aspect of the MARS (Monitoring agro-ecological Resources with Remote sensing and Simulation in Zambia) project (Berkhout et al., 1988) which consists of the evaluation of feasible methods to improve the real time information on the agricultural production. Combination of remote sensing information, i.e. high and low spatial resolution images, with geographical information system and the implementation of numerical simulation model based on crop growth WOFOST, will be used to develop such methods, where in Chapter 3 they are explained more in detail.

The analysis will also consider a three level approach including national, regional and local levels.

This "zooming" procedure should be carried out whenever information on national level needs more details according to the user requests. Moreover, the zooming procedure may be very economical when results extracted from significant agricultural areas can be extrapolated on national level statistical figures. Inventories in small areas can include land-use classification distribution of different agricultural systems, estimation of the agricultural area and its production. Such analysis is carried out by means of high resolution satellite images e.g. LANDSAT-MSS and TM and with the help of aerial photographs.

One of the important objective of such analysis is the determination of crop yield in a system of early warning by means of satellite images. For such purpose satellite data, mainly NOAA-AVHRR Normalized Difference Vegetation Index images, will be analyzed for the entire crop year and indicators of crop production will be extracted. These indicators will be compared with other production indicators extracted i.e. from rainfall data and from mathematical models for crop growing simulation.

1.2 Brief description of agriculture in Zambia

Allocation of land for agriculture (arable and permanent crops) in Zambia has been increased in the last quarter of this century of about 0.5% reaching nowadays 6.9% (5,188,000 ha) of the total area (74 millions of hectare) of the country (FAO, 1987). Table 1 shows the changes of land-use and irrigated area which have taken place in Zambia in 24 years. Actually, no dramatic changes did occur in the arable land exploitation which increased only 8% from 1962 to 1986. The above mentioned 5 millions of arable land in 1986 refer to land under temporary crops, temporary pasture or meadows, greenhouses and land temporarily fallow or lying idle. The last category of land allocation can be very significant when fallow land resulting from shifting cultivation is included. In fact, shifting cultivation in Zambia was and is a used practice in different provinces (Mansfield, 1975; Schultz, 1976; Stroemgaard, 1984).

Table 1 Land-use and irrigated area in Zambia in the years 1962 and 1986 (FAO, 1987).

	1962 (1000 ha)	1986 (1000 ha)
Total area	75,261	75,261
Land area	74,072	74,072
Land-use: arable land	4,800	5,180
land under permanent crops	-	8
permanent meadows	33,800	35,000
forest and woodlands	34,000	29,290
other land	2,661	4,594
Irrigated area	2	20

The main yearly staple crops cultivated in Zambia are maize, sorghum, finger millet, sunflower, groundnuts and pulses. Other important crops which cultivated area increases steadily are wheat, paddy rice and soybean. Prominent crops are also cassava, cotton, tobacco, sugarcane, fruits and vegetables. Table 2 shows area and production of the main cultivated crops in Zambia in 1961 and 1987. According to the statistical figures (Table 2) of 1961 and 1987, main agricultural crops have been cultivated on 18% of the total arable land which the remaining part of the arable land (82%) was left fallow as consequence of the crop rotation technique in the traditional agricultural systems. As Table 2 shows, the agricultural production in Zambia is strictly limited to one main crop, maize, which occupies nearly the 64% (in 1987) of the crop cultivated area in Zambia.

Table 2 Cultivated area and production of the main cultivated crops in Zambia in 1961 and 1987 (FAO, 1987).

Crop	1961		1987	
	Area (1000 ha)	Production (1000 m)	Area (1000 ha)	Production (1000 m)
Maize	305	515	609	954
Wheat	1	1	5	13
Paddy rice	-	-	11	13
Sorghum	236	191	47	26
Finger millet	79	64	43	30
Groundnuts	76	64	25	14
Sunflower	-	-	60	43
Soybeans	-	-	10	15
Pulses	120	61	14	6
Cassava	46	145	63	230
Cotton (lint)	1	0.3	62	21
Tobacco	10	9	4	4

Since independence (1964) the government has allocated substantial resources to the rural sector. Producer and consumer receive large subsidies on agricultural goods. The high price paid for rice, wheat and sunflower has increased cultivated area in the '80s (Table 2). Also maize cultivated area, massively supported by the government, has drastically increased (doubled in nearly 25 years) with detriment to other crops, i.e. sorghum, which cultivated area decreased in the same period of time by about 80% (Table 2).

Production in zambian agriculture is closely related to the yearly amount and time distribution of rainfall. In fact, only 20,000 ha of arable land profit from irrigation practice (Table 1) while the unirrigated arable land (98%) remains the greatest portion of it.

Nowadays agricultural population includes the 70% of the total population in Zambia (Table 3). In 25 years the percentage of active population in agriculture has decreased; high percentage of the total population, however, is still employed in agriculture (Table 3).

Zambian 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.

Table 3 Total and agricultural population, active population in agriculture, percentage of the active agricultural population over agricultural population in Zambia in the years 1960, 1970, 1980 and 1987 (FAO, 1972, 1982, 1988).

Year	Total population (1000)	Population in agriculture (1000)	Active population in agriculture (1000)	% Active population in agriculture
1960	3219	2532	1008	78.7
1970	4295	2979	1144	69.4
1980	5766	3842	1394	66.6
1987	7139	5003	1678	70.1

The agricultural statistical figures for each province obtained by the Central Statistical Office in Zambia (Ministry of Agriculture and Water Development, 1985) include extension of cultivated area and production values of main crops. Table 4 shows an example of such figures referred to maize for two crop years. Comparing the maize cultivated area with the total area within one province, it is possible to see which province in Zambia contributes mostly to the agricultural production. Last column of Table 4 shows indeed such percentage calculated for the year 1985, where Eastern, Southern, Central and Lusaka provinces did contribute most to the zambian maize production. The percentage of cultivated maize area in the four most productive provinces (Table 4) is remarkably low, from 3 to 0.8%, compared to their territorial area.

Table 4 Total provincial area, maize cultivated area and production by province in Zambia in the years 1982 and 1985, percentage of maize cultivated area over total province area.

Province	Province total area (1000 ha)	1982 maize area (1000 ha)	Product. (1000 m)	1985 maize area (1000 ha)	Product. (1000 m)	% Agric. area in 1985
Central	11,629	101	195	119	286	1.02
Copperbelt	3,133	7	10	16	29	0.5
Eastern	6,910	196	222	206	330	3.0
Luapula	5,056	3	5	5	10	0.1
Lusaka	2,190	23	35	17	66	0.8
Northern	10,700	24	60	47	97	0.4
N.Western	12,580	4	6	5	10	0.04
Southern	8,523	85	208	134	278	1.6
Western	13,351	11	9	18	19	0.1
ZAMBIA	74,072	456	735	567	1123	0.8

Zambian agriculture is divided into three major sectors:
1) few hundred large commercial farms who produce about one-half of the total marketed agricultural production;
2) a growing number of small-scale emergent farmers and
3) plenty of traditional farmers who are scattered throughout the country, producing mainly for self consuming and selling little to the market.

More detailed information over farm types in Zambia are given in Berkhout et al., 1988 and Azzali, 1987. The most updated information over the percentage of farm types existing in Zambia are from the late '70s beginning of the '80s (Admiraal, 1981). Therefore, they are not very recent if we consider that the sector of emergent farmers is very dynamic. The agricultural allocation in the territory is related to the type of farming. Commercial farms are mainly concentrated where large infrastructure facilites (railroad, main roads, big cities) are present. Fig. 1 shows a sketch map of Zambia of the early '70s where location of commercial farms is evident.

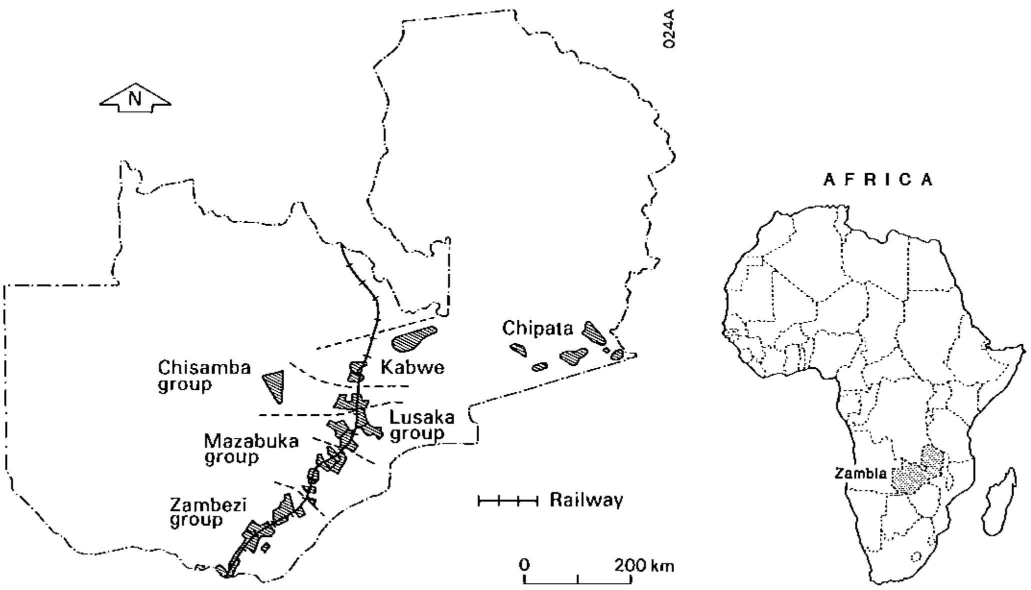

Fig. 1 Map of commercial cultivated area in Zambia.

Emergent and traditional farms are more scattered in the territory but they are, above all, situated nearby villages and roads. Traditional farming is still playing a very important role in the zambian food production. In some provinces it is still the most used agricultural system. According to different zambian ecosystems, traditional farming consists of different practices (Schultz, 1976): no updated figures are available, however, on the actual extension of traditional farmed land.

2 APPROACH

2.1 Combination of satellite information with GIS

An important aspect of this analysis is the integration of different information, i.e. satellite data, maps and tabular data, in a system able to generate comprehensive and updated maps.

Agricultural information presented in map form is a necessary tool for agricultural planning and management. To mantain updated the increasing agricultural information generated by means of remote sensing and to supply information to different users categories, the conventional data handling methods have to be supplied by modern computer assisted techniques. A Geographical Information System (GIS) is a multipurpose computer based information system for retrieval, administration, processing, integrated analysis and graphic/carthographic and statistical presentation of any kind and combination of data/information which can be defined in time and space.

The principle of GIS is to combine spatial information (i.e. thematic maps and remote sensing data) as different information layers in a grid system. Also tabular data can be linked to spatial information layers. Remotely sensed data can be used for further image processing and classification purposes for the generation of new informations layers such as land use/land cover distributions, etc. The satellite data, or the generated information layers, can be combined with digitized information i.e. topographical data to calculate crop yields. Information from scattered point measurements, i.e. rainfall data, can be interpolated and linked to the data base.

To be able to compare results from different images/satellites, these data have to be georeferenced. For example, if statistical data have to be extracted from defined administrative - units masks, of these administrative units have to be created from the existing topographical maps and merged with different satellite images. Such procedure is only possible if satellite data have been previously geometric corrected. Consequently, statistical data of crop area within assigned administrative units can be updated by interpreting satellite images.

Expecially for small areas, digitized topographic information is of great help to be able to make an accurate interpretation of the satellite images and to get accurate estimates of the hectarage of different crops. In particular different combinations of GIS and remote sensing data are described in this report:

a. Influence of soil and geological characteristics on the presence of vegetation and of crop cultivated area in a study-area.

b. Extraction of crop cultivated area from administrative units by means of LANDSAT-TM images.
c. Analysis of annual crop growth pattern in selected zambian provinces/districts.

2.2 Use of high and low resolution satellite images for agricultural assessment in Zambia

The use of satellite information covering very large areas in short time interval can help to update agricultural information at relative low costs. In this context different types of satellite images offering different pixel resolutions can be applied. To monitor large crop area on provincial or national basis the use of LANDSAT data (high resolution satellite images) has some drawbacks as massive amounts of data to be processed and stored, erratic acquisition of the scenes because LANDSAT views each area on the Earth only once every 18 days with risk of cloudiness.
For this purpose, then, the use of NOAA-AVHRR data (low resolution satellite images) are complementing the LANDSAT data and they appear to be of great use for monitoring vegetation conditions during the growing season. In particular, monitoring of the vegetation resources has been attempted by means of low resolution satellite images by using vegetation indices (Justice et al., 1985; Tucker et al., 1985; Prince, 1986; Johnson et al., 1987).

Methods using low resolution satellite data have also been developed to assess the vegetative biomass and indirectly crop yield (Taylor et al., 1985; Hansen et al., 1987; Xu Xiru et al., 1987; Guyot et al., 1988, Kennedy, 1989). Whenever the monitoring of agricultural resources requires a very great accuracy, LANDSAT or SPOT images, thanks to their pixel resolution, are not replaceable by any NOAA-AVHRR images. The agricultural land which mainly contributes to the national annual crop production of Zambia is principally concentrated in few specific areas of the nation. So, the aim of this analysis is to quantify with the help of few high resolution images the exact location of the characteristic agricultural areas and to distinguish which type/s of cultivation system is/are present. Then, by means of low resolution images in a yearly time-serie, it is possible to follow the yearly growth pattern of crops cultivated in the chosen agricultural areas.

In particular we can divide such analysis in different applications:

Use of high resolution images
The analysis on district level has to give estimates of the agricultural area and can be done by means of LANDSAT-TM images. Different types of agricultural systems contribute to crop production but the most productive one remains the intensive

agriculture. Despite the high output of intensive agriculture, it is not so often practiced in Zambia while traditional agriculture is broadly applied. The possibility to discriminate the two agricultural systems (traditional and intensive agriculture) can help to estimate if any change in the agricultural practices in Zambia is taking place and how fast is developing. For the latter purpose the analysis on local level of different types of cultivation systems by means of aerial photo products and LANDSAT-TM images will be applied.

Use of low resolution images

Analysis on yearly basis of vegetation growth pattern on regional and county basis can be done by means of NOAA-AVHRR-NOVI data.
A close-up procedure can be carried out when the NOVI information extracted for large areas are too generic.
For this purpose the following analysis can be performed:

- Influence of soil and geological characteristics on vegetation growth by means of LANDSAT-TM images.
- Interpretation of crop growth patterns by means of NOAA-NOVI time series and LANDSAT-MSS images.

The last analysis will show how different types of data i.e. satellite images at different resolutions, maps etc. enhance the interpretation of NOAA-NOVI time series for monitoring actual crop growth patterns.

3 DESCRIPTION OF PROBLEM

3.1 Crop cultivated area obtained from statistical data and satellite image classification

This application focuses on a RS-GIS study which involves the agricultural land classification by means of satellite images, within land-units used as sample-basis for the statistical elaborations in Zambia. To obtain agricultural area classification and crop discrimination the following procedure is applied:

- calculation of mean average crop calendar for the study area. It is calculated on the basis of the collected phenological observations for the reference year and it is used to assess the period during the growing season when discrimination of different types of crops can be performed. In fact combining the information of different spectral signatures of crops during their growth stages, we are able to obtain the temporal variations of such signatures. To obtain crop signatures, reflectance values in bands 3, 4 and 5 of LANDSAT-TM and the vegetation index TVI are calculated;
- use of multitemporal LANDSAT-TM scenes. Using the average crop calendar it appears that a multi-temporal acquisition of satellite images enhances crop discrimination. A multi-temporal crop classification needs a standardization of the images, which is obtained via the radiometric correction formulae calculated for LANDSAT-TM sensors.
- authomatic image interpretation. The maximum likelihood classification method is used to classify agricultural land on the satellite image. The results so achieved are expressed in agricultural area (hectare) obtained in assigned land-units smaller than one district; the agricultural area in the land-units multiplied by a calculated factor gives the total agricultural area for e.g. a district. The so-calculated agricultural area per district is compared to the corresponding figures obtained by the Central Statistical Office in Zambia. In particular, the Central Statistical Office (CSO) in Zambia elaborates the yield production figures on the basis of land-units called SEA (Standard Enumeration Area) and CSA (Census Supervisory Area) which are located in a district. For each CSA and SEA data on cultivated area, yield and marketable surplus production are collected. These data are, then, extrapolated to district level by applying boosting-factors, obtained as the ratio of the number of households in a district to the number in a SEA. Yield figures per unit area are obtained by the ratio of estimated production to area (bags/ha). Every year changes of the number of households, percentage of cropped area, etc., are applied and the basic figures for the statistical elaborations have to be up-to-date to achieve results the nearest to the reality. The calculation of the boosting factor by means of satellite images can, as alternative method, help out the updating process of such statistical data.

3.2 Analysis of cultivated area under shifting cultivation system by means of LANDSAT-TM images and aerial photos

In the most updated study (Stroemgaard, 1984) over shifting cultivation in Northern Province of Zambia, air photo interpretation was used for mapping the extension of shifting cultivation and the allocation of different land uses.
Fields under shifting cultivation can be very well spotted by means of remote sensing images thanks to their characteristic circular shape while fields under commercial agriculture are of rectangular shape.

The extension of such traditional agriculture has not been updated since more than 10 years. In such period of time some radical changes could have been occurred. In some regions of Zambia shifting cultivation is considered the most diffuse agricultural system.

Discrimination of fields under shifting cultivation from those under commercial agriculture has been attempted by means of LANDSAT-TM images and of aerial photos. An automated procedure is set up for measuring the hectarage of fields under shifting cultivation, which could be achieved following two different approaches:

i) Discrimination of fields under shifting cultivation from commercial and semi-commercial agricultural areas analyzing and comparing the spectral measurements, extracted from remote sensing data, of the two agricultural systems.
By analyzing the spectral signatures of the two different types of agriculture from the LANDSAT-TM images in different dates, we can see whether any statistical significant differences occur between the spectral signatures of fields under shifting and commercial cultivation. The signatures of the two agricultural systems, have been obtained with Normalized Difference Vegetation Index (NDVI) and with the reflectance measurements out of the seven LANDSAT-TM bands.

ii) Discrimination of the two types of agriculture on the basis of the different shapes of cultivated fields. As it has been previously mentioned, differences in shape occur between fields cultivated under shifting cultivation and those under commercial agriculture. Then, discrimination of the fields under shifting cultivation can be performed:
   - by enhancing the colour contrast between circular fields and the background by means of filtering;
   - via feature analysis performed by means of the Quantimet 970 system. The system is able to scan characteristic features and it performs object roundness analysis which is able to quantify both the number of circular fields under shifting cultivation and rectangular fields under commercial agriculture.

3.3 Monitoring vegetation growth patterns by means of NOAA-NDVI-time series

Satellite data have been combined with meteorological data to assess the growth dynamic of natural vegetation in Zambia. This study focuses on the correlation of the pattern of NDVI values extracted from NOAA-AVHRR images (7.6 km pixel resolution) with the rainfall patterns of four different agro-ecological zones. For this purpose 10-days-NOAA-NDVI images from two growing seasons (1983-84, 1984-85) are analyzed and extraction of NDVI time-series are obtained from four agro-ecological zones. The NDVI-time-series are then plotted for the study areas and compared with the cumulative rainfall profiles for the considered years and areas. Additional data such as the nature of the existent vegetation, temperature, humidity, soil water balance and LANDSAT-MSS images are also taken into account to explain growth patterns of natural vegetation, when a direct correlation between NDVI-time-series and cumulative rainfall profiles is not clear at the beginning of the growing season.

This application will concentrate on how NDVI-ARTEMIS data can be actually used to monitor the temporal variation of natural vegetation growth on country scale in different agro-ecological zones in Zambia.

3.4 Influence of soil and geological characteristics on vegetation growth

Soil and geological characteristics of an area have definitely high influence on the presence and growth of vegetation.
Soil and geological characteristics of an area can be usually represented in form of a map. Agricultural land can be also given in form of updated maps by means of satellite images.
To be able to compare results from different map sources, data base management is very important. Therefore the above mentioned maps have to be georeferenced and fed into a geographic information system.

In particular, geological and soil maps of the study area have been digitized on a georeferenced system. A colour composite product obtained by means of LANDSAT-TM image (bands 4, 5 and 3), which enhances green vegetation, has been analyzed. Comparison of the soil and geological characteristics with the presence and growth of vegetation has been subsequently done.

3.5 Interpretation of crop growth patterns by means of NOAA-NDVI-time series and LANDSAT-MSS images

The aim of this application is to find a correlation between low resolution satellite data (NOAA-AVHRR-NDVI data) and crop production. For this purpose remote sensing data have been analyzed jointly with meteorological data and simulated crop production to obtain indicators of crop production. The accuracy of these indicators is assessed with the statistical data on crop production of the Statistics Section of the Ministry of Agriculture in Zambia.

One important aspect is to test if the NDVI data, having pixel resolution of 7.6 km, are useful to assess crop production in those countries where agriculture is very scattered and/or concentrated in few places. The mean NDVI value as result of averaging several pixels within e.g. one province will certainly relate to the dominant vegetation, which in Zambia consists of forest and savannah.

To monitor the crop growth by means of low resolution remote sensing data (NOAA-AVHRR-NDVI data) it is necessary to know where agriculture is concentrated. Such information can be provided by existing land-use maps. An updated land-use map can be obtained by means of high resolution satellite images, e.g. LANDSAT-MSS. Consequently, the exact location of agricultural areas can be assessed on the high resolution satellite images and via a geographical reference grid the agricultural areas can be detected on the NOAA-AVHRR-NDVI images. Then, NDVI values are extracted for the "agricultural" pixels and used to obtain a NDVI indicator of crop production.

4 APPLICATIONS

4.1 Estimating crop cultivated area with LANDSAT-Thematic Mapper data

4.1.1 Materials

Satellite data and maps
Two LANDSAT-Thematic Mapper (TM) images (2nd quadrant of frame 170-70 on two different dates) have been analysed. The acquisition dates are respectively 29 November 1984 and 16 January 1985. The second quadrant of frame 170-70 is located in the Eastern province and it covers 80% of Katete district and part of Petauke district. In order to compare the two LANDSAT-TM images geometric and radiometric corrections were performed. The analysis of LANDSAT-TM images is performed at full image resolution.

To perform land-use classification, few ground truth data were available, obtained mostly at two farms located in Petauke district, respectively Kawere and Manda-Malowa farms. Fig. 2 shows a sketch of the Kawere farm where the land-use relates to the crop season 1984-85.

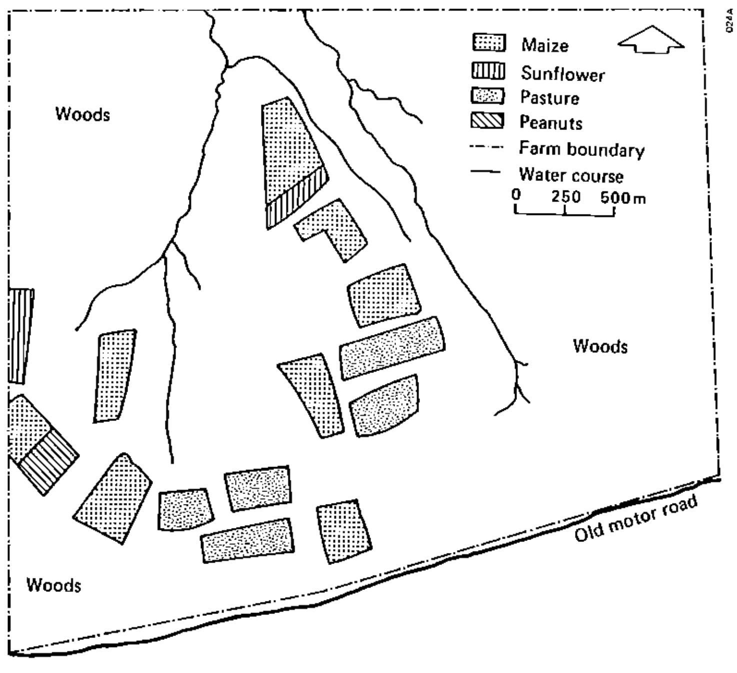

Fig. 2 Sketch of the Kawere farm 2609, Petauke district, where land-use relates to the crop season 1984-85.

One digital map has also been prepared showing the boundaries of 19 CSA in Katete district (Fig. 3).

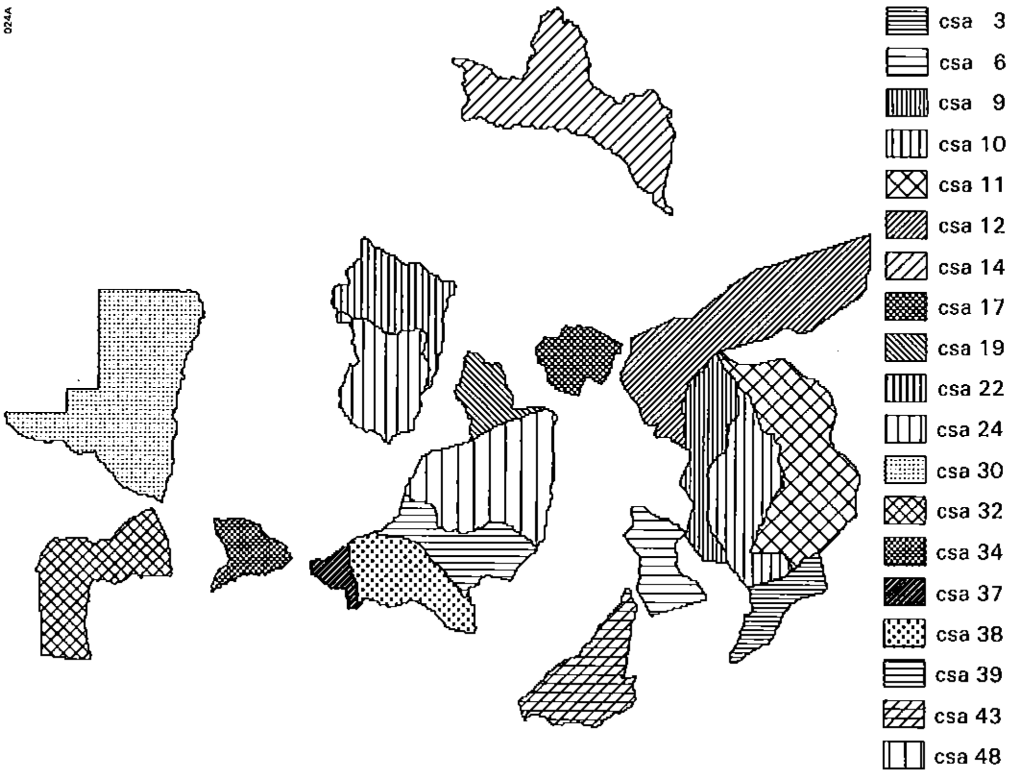

Fig. 3 Map of 19 CSA located in Katete district.

Phenological observations of crops
In order to prepare an average crop calendar for the Eastern province, phenological observations of 1984-85 crop season, obtained from the Early Warning Service in Zambia, were used. However, the collected phenological data referred to only nine main farms in the whole Eastern province. Explanation of the nature of these data is given by Berkhout et al., 1988.
Five crops were chosen as the most representative for Eastern province, respectively maize, peanuts, sunflower, cotton and soybeans. For each crop the following phenological stages were analysed: seeding, vegetative growing, flowering, yield formation, milk ripening (only for maize) and harvest.

Statistical data
Data on estimated cultivated area for each crop based on 1984-85 crop forecasting survey were collected by the Central Statistical Office in the CSA/SEA of Katete district. Table 5 summarizes the data by crop.

The same table shows also that the total cropped area for each crop in Katete district is obtained by multiplying the boosting factor at district level (5.7333) for the sum of cultivated area of each crop in 10 CSA.

Table 5 Agricultural area in several SEA located in 10 CSA. Data were collected in Katete district during the crop year 1984-1985 from the zambian Central Statistical Office; boosting factor at district level multiplied by the subtotal area for each crop gives the total cultivated area in Katete district.

CSA n.	SEA n.	Sw. potatoes area (ha)	Coffee (ha)	Tobacco (ha)	Beans (ha)	Cotton (ha)	G/nuts (ha)	Maize (ha)	Sunflw. (ha)
17	1-4				7.81	10.73	83.44	396.69	39.03
19	2						43.99	136.74	7.65
24	1-5						74.59	580.99	23.55
32	1						49.64	139.36	28.64
34	3-4			74.42			80.29	321.17	117.25
37	1-3	1.98	3.95				89.86	335.75	69.12
38	3-4						99.00	499.00	110.00
39	2-4						31.52	195.03	19.77
43	1-3				15.42		142.76	590.15	177.45
48	3-4						30.14	405.49	38.09
Subtotal cultivated area		1.98	3.95	74.42	23.23	10.73	752.23	3600.37	630.55
boosting factor at district level = 5.7333									
Total cultivated area		11	23	427	133	62	4313	20,642	3615

4.1.2 Calculation of crop calendar and crop discrimination

A crop calendar applicable to the Eastern province for the year 1984-1985 has been calculated on the basis of the collected phenological observations by means of the method developed by Menenti et al., 1986. The obtained average crop calendar (Fig. 4) is used to assess the period during the growing season when classification of different types of crops can be performed.

Combining the information between crop phenological stages and the occurrence of different spectral signatures during these stages, we are able to obtain the temporal variations of crop spectral signatures during the growing season. In particular, the reflectance measurements of bands 3, 4 and 5 of LANDSAT-TM were considered, being more sensible than the other TM bands to detect presence and development of vegetation. Moreover, the vegetation index TVI (Transformed Vegetation Index = 100*sqrt {[band 4 - band 3]/[band 4 + band 3] + 0.5} was also considered.

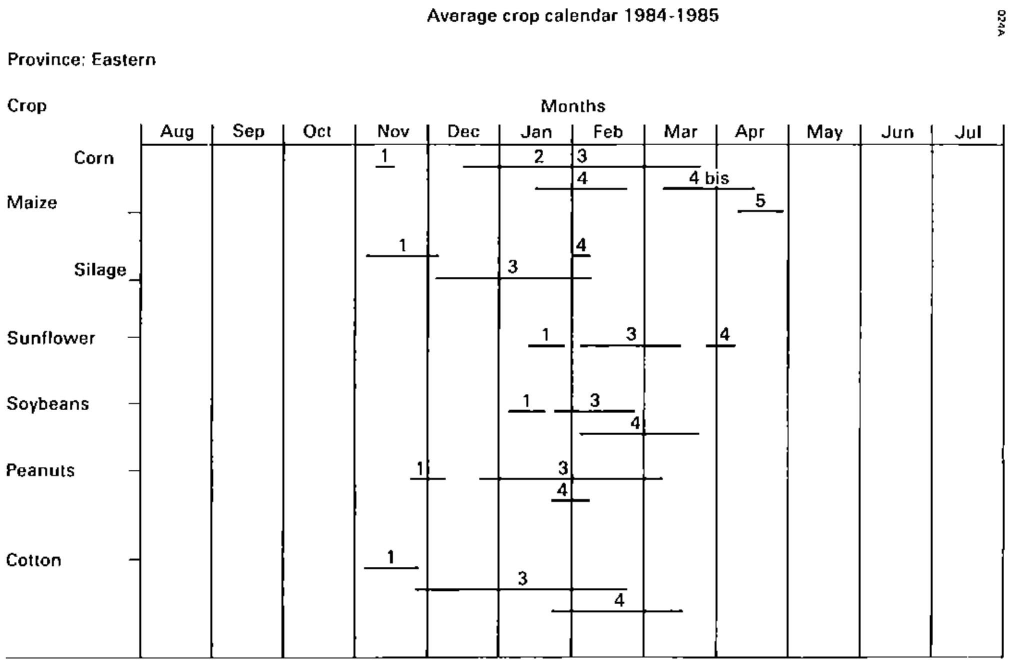

Fig. 4 Average crop calendar for Eastern province, Zambia in the growing season 1984-85; phenological stages are listed as:

1 Sowing
2 Full ground cover
3 Flowering
4 Yield formation
4bis Milk ripening (only for maize)
5 Harvest.

4.1.3 Results

In the Eastern province agriculture occupies only a small part of the territory (3.6% in 1984-1985, Ministry of Agriculture and Water Development, 1985). The rest of the territory is mainly covered by natural vegetation (evergreen forest and savanna-type ecosystem). Consequently, an exact discrimination of the cultivated area from natural vegetation is very important. Within the agricultural crops, maize is cultivated on 67 to 84% on the total cropped area (Ministry of Agriculture and Water Development, 1985) showing that maize represents the main crop in the Eastern province of Zambia.

Reflectance and vegetation index values for each type of vegetation in the two available images have been obtained for every ground control plot. The following land-use classes have been considered: natural vegetation (forest and savanna), agricultural crops and water.

The class 'agricultural crops' was further subdivided into maize, peanuts and sunflower. Considering the dates of the two available TM images and the average crop calendar of Fig. 4, the best period to discriminate maize from the other crops was the first half of January, where only peanuts and maize are at the flowering stage. The best results of land-use discrimination were achieved by applying the maximum likelihood classification method to the image of January 1985. Moreover, the best discrimination between classes was achieved using the spectral reflectance of band 5.

A multi-temporal approach has been also attempted using two images of TVI calculated with the LANDSAT-TM images of November and January. However, lack of several ground truth plots did not give satisfactory results and the classification left a large amount of pixels unclassified.

The map (Fig. 3) showing 19 CSA in Katete district was, then, superimposed on the classified image and the percentage of maize cropped area for ten CSA was calculated. Nine CSA were actually excluded from the classification statistics because either they were located outside the TM image or the ground data collection was not performed in those particular CSA in the crop year 1984-85 by the CSO.

Table 6 column 3 shows the maize cultivated area obtained for each considered CSA. Boosting factors were calculated according to the following equation:

$$Ad/At * Aat/Aacsa = Bf \quad (1)$$

where Ad : Area of the whole district
At : Area TM image
Aat : Maize cultivated area in the TM image
Aacsa: Maize cultivated area in each CSA
Bf : Boosting factor
and summarized in Table 6 column 4.

Fig. 5 shows the relationship between the agricultural area values in 10 CSA calculated via the boosting factor method applying the results of the LANDSAT-TM image classification and according to the estimes of the Central Statistics Office (CSO) of the Ministry of Agriculture in Zambia. The continuous line of Fig. 5 represents the regression line of the agricultural area estimes and it points out how the obtained estimes deviate from the aspected pattern. Only for four CSA (CSA 19, 39, 37 and 24) the estimes of agricultural area are rather satisfactory with both the applied techniques, but for the other CSA the results

Table 6 Agricultural area calculated by means of maximum likelihood classification and boosting factors in 10 CSA located in Katete district.

Location	Total area (ha)	Agricultural area (ha)	Boosting factor
Katete district	379,713		
CSA 17	3,926	164.9	106.701
CSA 19	3,495	143.4	122.699
CSA 24	8,113	393.9	44.669
CSA 32	9,943	622	28.288
CSA 34	3,253	557	31.589
CSA 37	1,503	318.2	55.296
CSA 38	7,031	266.4	66.047
CSA 39	6,671	299	58.846
CSA 43	8,026	1,106.1	15.907
CSA 48	13,141	188.1	93.541

obtained via the boosting factor method are not so encouraging. The results in Fig. 5 show that overestimations of cultivated area via the CSO techniques are widely present as well as via the LANDSAT-TM image classification (Fig. 5). It seems, then, that the boosting factor method to estime agricultural area does not work out properly and alternative methods should be further

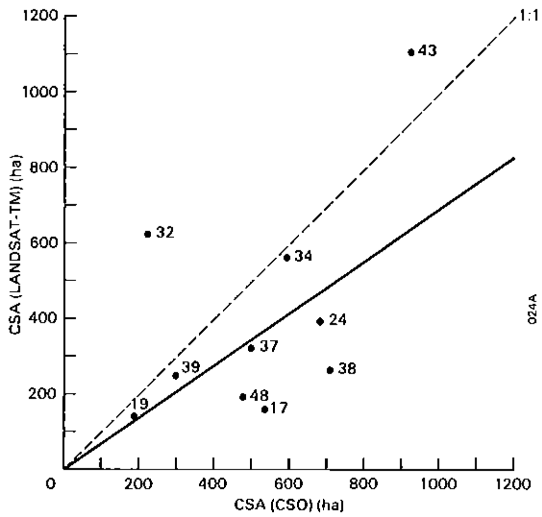

Fig. 5 Relationship of cultivated area estimes (in hectare) for 10 CSA in Katete district, Eastern province, Zambia. The estimes are obtained applying the boosting factor method from two different sources, respectively the CSO estimes and the results of the LANDSAT-TM image classification. The dotted line shows the x=y line while the continuous line represents the regression curve of the obtained estimes.

searched. For example, methods based on the area sampling frame technique (Hanuschak et al., 1979) could be a good alternative for agricultural area estimation and they could be used by CSO officers for next national Census in 1990.

Finally, the results of the LANDSAT-TM image classification show that the total maize cultivated area in Katete district was 17,595 ha while the same value given by the CSO calculation was 20,642 ha (Table 5).

4.1.4 Conclusions

Maize identification and classification performed via the maximum likelihood classification with LANDSAT-TM data has given rather good results considering the scarce ground truth available. Statistical data collected by the CSO confirmed the validity of the maize area values calculated by means of remote sensing data which results are very close (85%) to the CSO estimation (100%) of the maize cropped area. Scarcity of several ground truth plots has hampered the classification of the other types of vegetation and crops. Eventhough the procedure shows that it is essential to have a rather consistent amount of ground truth plots, the detailed crop calendar applied to the study year was of great help to identify the best time of the year when maize could be discriminated from the other crops. The achieved maize discrimination by means of the LANDSAT image can give the necessary inputs to produce maps of cultivated maize areas and to update the existent maps.

4.2 Analysis of cultivated area under shifting cultivation system by means of LANDSAT-TM images and aerial photos

4.2.1 General features of shifting cultivation in Zambia

Traditional farming system, i.e. shifting cultivation, plays an important role in food production in Zambia (Schultz, 1974). Eventhough shifting cultivation is mainly practiced in the northern part of the country, the same agricultural system is also present in the provinces characterized by commercial and semi-commercial agriculture.

The practice of shifting cultivation consists of clearing up some areas from thick vegetation by cutting and burning trees. In this way, being the vegetation the only source of fertilizer, a good crop production can be achieved in the traditional farming system using the resulting ash as fertilizer.

In Zambia shifting cultivation is called chitemene system; large and small chitemene systems are considered (Schultz, 1974). The shape of cleared area can be circular or oval, but pear-shaped fields are also present (Allan, 1965). In the large chitemene system the cleared circles have an average radius of 60-100 mt while in the small chitemene system cleared circles show a smaller radius (< 40 m), (Puzo, 1978). Only a small part of the cleared area is actually cultivated during any given year and in different areas crop cultivation is rotated either in the cleared area or new circular areas are cleared.

According to Mansfield et al. 1975 and to Schultz, 1974, the proportion between each cultivated garden and cutted woodland is 1:12-1:20 in the small ash circle (small chitemene), while in the large ash circle such proportion is 1:6-1:11 (Trapnell, 1953).

Only few articles have been written dealing with the use of remote sensing for detection of shifting cultivation (Byrne and Munday jr., 1972; Wayumba and Philipson, 1985; Stroemgaard, 1984 a, b, c). In the most updated study (Stroemgaard, 1984a) over shifting cultivation in Northern Province of Zambia, air photo interpretation was used for mapping the extension of shifting cultivation. According to Stroemgaard, 1984a, the cleared area can be 5 to 8 times bigger than the size of the cultivated part, whereas crop rotation is practiced in the cleared area for more than one year (from 2 till 8 years). From the air-photo (Stroemgaard, 1984a), it is possible to observe that diameters of fields under shifting cultivation vary between 20 to 120 m. Even after years of fallow, patches of former shifting cultivation fields are still visible in aerial photos (Stroemgaard, 1984a).

4.2.2 Materials

Location of the study area

The study area (Fig. 6) is located in two different districts namely Petauke and Katete in Eastern Province, Zambia, where the agricultural area is classified in the category of semi-commercial cultivation of Eastern Plateau according to the land-use classification of Schultz, 1974. According to this land-use classification, Eastern province is characterized by two farming systems: the Luangwa valley system and the Eastern plateau system.

The Luangwa valley system is located in the homonymous valley and mainly characterized by shifting and mounds cultivation (Schultz, 1974). The Eastern plateau farming system is characterised by semi-commercial agriculture, having large holdings, rectangular fields in a block or strip-lay out. Main cash crops there cultivated are maize and groundnuts (Schultz, 1974).

However, presence of shifting cultivation in the Eastern Plateau farming system is not mentioned.

Materials
A set of aerial pancromatic black and white photos has been purchased. They are based on a July 1980 flight (scale 1:20,000), which did cover an area to the south of Petauke (Fig. 6), on a 1974-flight over an area close to Katete (Fig. 6) and on the 1974-flights and 1988-flights over an area located 10-15 km west of Katete near the Great East Road.

Three LANDSAT-TM images (path 170, frame 70, 2nd quadrant) on three different dates respectively 29-11-1984, 16-1-1985, 9-4-1986, have been also acquired. Topographical maps on scale 1:50,000 of the study area were also used.

Table 7 gives a list of the available materials used in this analysis.

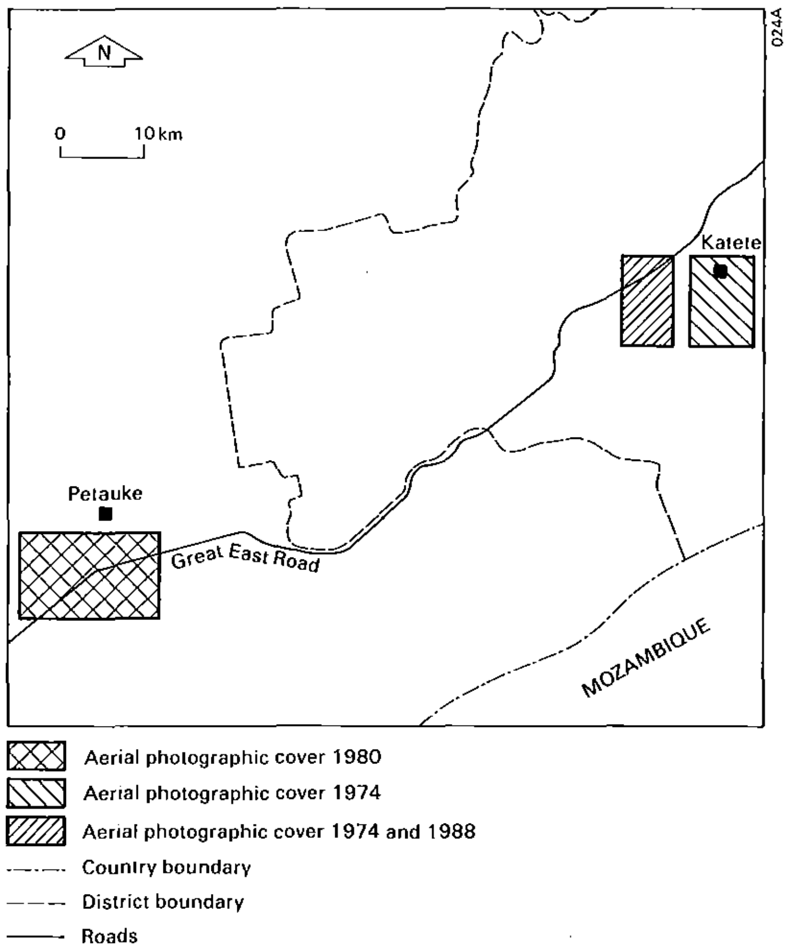

Fig. 6 Sketch map of the study area in the Eastern province, Zambia, where the location of the aerial photographic cover is indicated; scale of the aerial photographic products: 1:20,000 in 1980, 1:40,000 in 1974, 1:30,000 in 1988.

Table 7 List of available photos and satellite images.

Photos/satellite	Location	Date		Scale
Black and white aerial photos	Petauke	July	1980	1:20,000
	Katete		1974	1:40,000
	10-15 km West of		1974	1:40,000
	Katete		1988	1:30,000
LANDSAT-TM	170/70 II quadrant	29 November	1984	
		16 January	1985	
		09 April	1986	

4.2.3 Detection of shifting cultivation

4.2.3.1 Aerial photographic products

Spectral analysis
The set of analyzed photos did show that different types of agricultural systems are present in the districts of Katete and Petauke. Only in the set of photos located 10 km east from Katete City, fields characterized by circular shape were present. Such fields have a shape similar to those classified by Schultz (1976) and Stroemgaard (1984a) as chitemene system. From such photos a sub-area of both years was digitized by means of a video digitizer connected to the image processing system; afterwards the digitized images were geometrically corrected. From the visual analysis of the two geometrically corrected images it appeared that, during 14 years (from 1974 till 1988) variation in size of the circular fields has taken place. Sizes of circular fields seem to increase over the years. To enhance such variations in size, a false colour composite product was created: the 1988 image was coded with the red colour while green colour was assigned to the 1974 image.

Plate 1 shows the result of such colour composite, where the circular shape fields are coloured in red, green and yellow colours. According to the colour composite (Plate 1) circular fields coloured in yellow indicate that their location and boundaries have not been changed between 1974 and 1988. Circular fields coloured in green indicate that those fields were present only in 1974, while those coloured in red were present in 1988 only.

The shifting cultivation located in the area covered by the analyzed aerial photo products shows a comparable pattern to that of the shifting cultivation analyzed by Stroemgaard (1984a) in the Northern province of Zambia. In Plate 1, small cleared areas (small circular fields in 1974) have been included in larger cleared areas (large circular fields in 1988) according to the field rotation there applied.

Feature analysis via Quantimet system

In order to analyze more in detail the circular features located in the aerial photos, aerial photo sub-areas (from Plate 1) were extracted and analyzed by means of the Quantimet 970 system. This system allows for measurements of object roundness to be done. The area shown in Plate 1 exhibits also several other features beside the circular fields. In order to discriminate the circular fields from the other features, images without noise (other features) have been created. Particularly three overlays containing respectively the shape of circular fields in 1974 (overlay a), the shape of circular fields in 1988 (overlay b) and the shape of rectangular fields in 1988 (overlay c) were obtained. The two overlays with circular fields cover the same sub-area large 1050 ha, shown in Plate 1 as white framed area. Circular features have been selected on the basis of roundness, defined as:

$$\frac{P2}{4PA} = R \qquad (2)$$

P = perimeter of the object
A = area of the object
R = roundness

A roundness value equal to the unity identifies a circle while roundness values > 1 indicate non-circular shapes. Geometrical figures as quadrangle, trapezoid, rectangle and triangle have roundness values from 1.27 onwards. Circular fields between values of roundness from 1 to 1.27 have been selected from the overlays a and b while the rectangular field having values of roundness > 1.30 have been selected from the overlay c. The scanning technique performed by the Quantimet 970 was applied to the three overlays.

Results can be summarized as follows:
- the roundness of the rectangular fields can vary from values of 1.30 to more than 2;
- many fields, which had been erroneously included in the overlays a and b, since they gave roundness values higher than 1.27;
- quantity and size characteristics of the circular fields with roundness between 1 and 1.27 have been collected in table 8. In such table circular fields have been divided in 4 classes, according to their size. The subdivision of field diameters in four classes is done to compare the same features extracted both from aerial photos and from LANDSAT-TM images. As shown, there is a univocal relationship between the mean size of each class and the number of corresponding TM pixels.

Table 8 Number of circular objects with roundness between 1 and 1.27 in four classes defined on the basis of the principal axis in meter objects are located on aerial photos and more precisely in the white framed sub-area of Plate 1. The number of LANDSAT-TM pixels equivalent to size of the principal axis of objects in each class is given.

Specimen	Number of objects principal axis (m) < 45	45-75	75-105	105-135	Total number of objects
	N. of LANDSAT-TM pixel 1	2	3	4	
Sub-area 1974 (overlay a)	16	10	2	0	28
Sub-area 1988 (overlay b)	7	24	1	1	33

Table 8 shows that from the overlay a, the circular fields with roundness values less than 1.27 are 28 and many of them - 16 fields - have a diameter d $\leq$ 45 m. Most of the other circular fields (10) in 1974 have 45 $\leq$ d $\leq$ 75 m. In overlay (b) the total number of circular fields was 33 and most of them (24) had a diameter between 45 and 75 m. The results of table 8 confirms also the conclusions drawn on the basis of visual analysis of Plate 1, i.e. that more small fields were cultivated in 1974 than in 1988.

The circular fields in 1974 and 1988 photos belong to the small chitemene system, where cleared circles have an average diameter less than 80 m. (Puzo, 1978).

4.2.3.2 LANDSAT-TM products

Spectral analysis
The same area analyzed with the aerial photos was also examined by means of LANDSAT-TM images. The analysis of three LANDSAT-TM images involved the following procedure:

a) The LANDSAT-TM data in digital counts were converted in reflectance values in order to compare data between images taken on different dates.
b) From different fields under shifting and commercial cultivations reflectance values were extracted from the reflection TM bands (1, 2, 3, 4, 5, 7) in the three available LANDSAT-TM images and the mean reflectance value for each band was plotted in the graphs shown in Figs. 6a, b, c.
c) Reflectance values of bands 3 and 4 in each TM image were also further utilized for the calculation of the NDVI (Normalized Difference Vegetation Index) which is computed by the following formula:

$$NDVI = 100 * \frac{R4 - R3}{R4 + R3} \qquad (3)$$

The NDVI values in the satellite image of November were rather low due to the presence of haze, while in the image of April clouds and their shadows were present.

These NDVI images will be indicated as High Resolution NDVI to avoid confusion with the NDVI images obtained with the AVHRR data. The reflectance values extracted from the LANDSAT-TM image of November 1984 show that the fields attributed to shifting cultivation (circular shape fields) are without green vegetation. In fact, in November, when the rain season begins, the cultivated fields have been already ploughed and partly sown (Fig. 7a). The same growth stage can also be seen in fields (rectangular fields) where commercial agriculture is applied. Two months later, in January 1985, the reflectance measurements of the fields selected in November show that the seeded crops have been grown in both types of cultivation system (Fig. 7b). In the LANDSAT-TM image of April 1986, the reflectance mean values extracted from the same fields show that crop are still standing in the fields (Fig. 7c) in advanced stage of yellowing. Comparing the reflectance measurements of the reflection TM bands and the NDVI values between the two types of cultivation, we tried to estimate if any statistically significant difference exists between fields under shifting and commercial cultivations. For this purpose we used the method described by Menenti et al., 1986. Each type of agricultural fields (shifting and commercial cultivation) is characterized by a characteristic interval of reflectance values for each TM band and of NDVI values. Upper and lower bounds of the characteristic interval are the mean reflectance value (or mean NDVI value) + 1.5 respectively - 1.5 of its standard deviation. From the analysis of the characteristic intervals, however, no statistically significant differences were noticed between fields under shifting and commercial cultivation. Such results show that it is not possible to discriminate the two types of agriculture by means of the reflectance measurements in the six TM bands. Further analysis with the NDVI images has been carried out, however, to study better the variation of vegetation growth in different seasons and years. For such purpose, the High Resolution NDVI images of November, January and April, after being geometrically corrected, have been set in a false colour image by respectively coding red the April 1986 image, green the January 1985 image and blue the November 1984 image. The resulting colour composite NDVI image is given in Plate 2 and the following comments can be added after the visual interpretetion of plate 2:

- Dark blue and dark green patches indicate cloud presence.
- Green coloured areas indicate that NDVI values of those pixels were higher in the image of January than in the other images of November and April.
- Many red coloured areas are present with the exclusion of the middle part of Plate 2. Larger red patches are mostly located near roads. Such red areas indicate that those NDVI pixel values of April 1986 image were higher than the NDVI values of

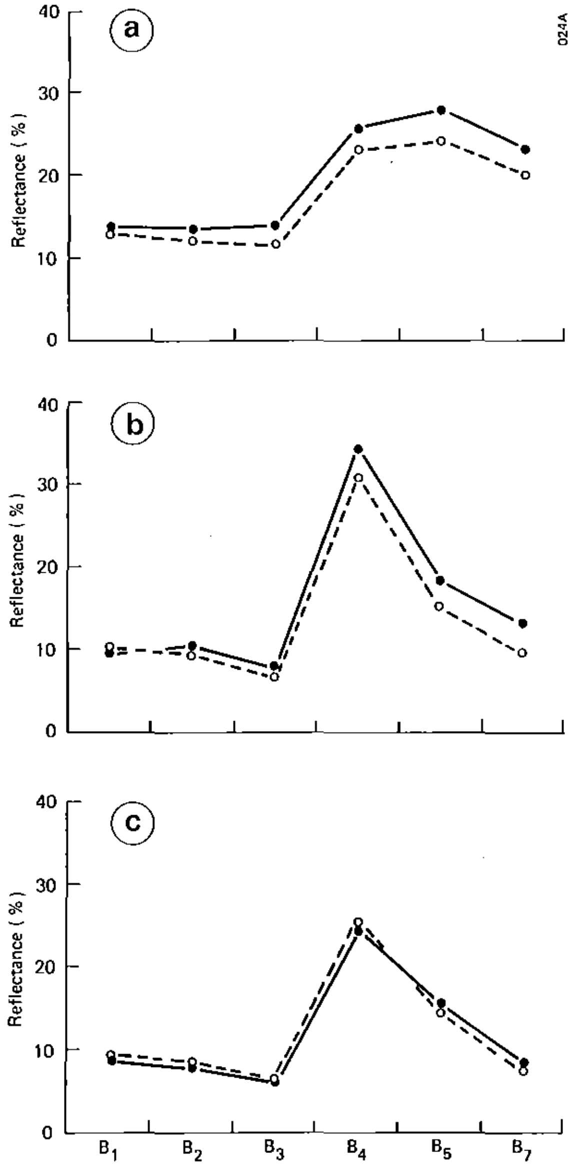

Fig. 7a, b, c Mean reflectance values extracted from cultivated fields and obtained from reflection TM bands (1, 2, 3, 4, 5, 7) in three different dates: November 29, 1984; January 16, 1985; April 9, 1986.
○ shifting cultivation
● commercial agriculture

the same pixels in the other months. It means, then, that the vegetation in those pixels of April 1986 image was greener and having larger canopy than the vegetation of the same pixels in the months of November and January.

- According to the mean reflectance values of cultivated fields (Fig. 7b and c), the expected pattern is that the NDVI values in April should be smaller than those in January, as the presence of the green coloured pixels of Plate 2 confirmed.

However, the presence of other fields where crop growth pattern is not the same as that described in Fig. 7a, b, c (red pixels in Plate 2) can be attributed both to:

1) vegetation growth pattern in the crop season 1985-86 had a later development than in the crop season 1984-85;
2) those fields were just for the first year cultivated in the crop season 1985-86.

- Light blue, violet and gray pixels in Plate 2 indicate that the NDVI values of those pixels did not change in the considered three months. Such pattern can be attributed to vegetation as evergreen forest.
- Yellow coloured pixels in Plate 2 mean that the NDVI values in the images of January and April were similar and higher than in November. Such pattern can be attributed to vegetation i.e. pasture, savanna, deciduous bush-forest.

Finally, an automatic classification method (maximum likelihood) was applied to the colour composite of Plate 2 in order to estimate the area having higher NDVI values in January (green pixels in Plate 2) and the area having higher NDVI values in

April (red pixels in Plate 2). The classification results showed that 26% of the whole area in Plate 2 is classified in the class of the vegetation having higher value of NDVI in April while only 14% were classified in the vegetation class having higher NDVI values in January. The class attributed to evergreen forest was present on the 49% of the whole Plate 2.

Shape analysis by means of the Quantimet system

The same area which was selected in the aerial photos (white framed area in Plate 1) was also analysed in the LANDSAT-TM image of 16 January 1985. Plate 3 shows a colour composite (bands 4, 5, 3, LANDSAT-TM data) of such selected area where the circular patterns of shifting cultivation are visible. Plate 3 shows the presence of shifting cultivation (circular pattern), scattered mainly in the forest and dambos, and commercial agriculture (rectangular shape), located mainly near the main roads. Analyzing closely the white framed sub-area (Plate 3) the presence of circular fields with vegetation (red colour) and without vegetation (grey-blue colour) is visible. The presence of fields without vegetation in January can be explained by later development of some crops and by areas which were left fallow in that specific year. Such differences in growing patterns and crop rotation have been also found in the results of the previous NDVI analysis. The same analysis performed for the black framed sub-area of Plate 1 via the Quantimet 970 system was also done on overlays of white framed area in Plate 3. Particularly, two overlays were prepared respectively one for the circular cultivated fields (red coloured circular fields in Plate 3) and the other for the fields not cultivated (gray-blue coloured circular fields in Plate 3). Roundness values of the fields were then selected in the range between 1 and 1.27, in order to discriminate only the circular fields (see results in par. 4.2.3.1). The results of the Quantimet analysis are summarized in Table 9.

Table 9 Number of circular objects with roundness between 1 and 1.27 in four classes defined on the basis of the principal axis in meter; objects are located on the LANDSAT-TM image and more precisely in the white framed area of Plate 3. The number of LANDSAT-TM pixels equivalent to the size of the principal axis of objects in each class is given.

Specimen	Number of objects principal axis (m)				Total number of objects
	< 45	45-75	75-105	105-135	
	N. of LANDSAT-TM pixel				
	1	2	3	4	
Fields with vegetation	1	23	7	2	33
Fields without vegetation	0	11	3	2	16

Comparing the results obtained in Tables 8 and 9, we can see that the estimation of the number of fields, where shifting cultivation is applied, in the satellite image of 1985, is very close to the results obtained in the analysis of 1988 aerial photo. In fact, the number of circular fields identified by means of the Quantimet both in the sub-area of the aerial photo 1988 and in the overlay of fields with vegetation of the TM sub-image is the same. Moreover, most of the circular fields of these overlays are classified in a diameter between 45 and 75 m.

4.2.4 Conclusions and recommendations

The possibility to detect fields under shifting cultivation has been proven by means of satellite images. Fields under shifting cultivation can be very well visually identified in the aerial photographic products as well as in the LANDSAT-TM images. Discrimination of fields under shifting cultivation (circular shape) from fields under commercial agriculture (rectangular shape) can be done on the basis of roundness as measured by means of the Quantimet System. The aerial photographic products have been used as ground-truth data and they have been of great help to understand the different patterns. It appeared that many fields, which by visual interpretation of the aerial photos belonged to the shifting cultivation system, were classified by means of the roundness analysis in the category of rectangular fields (commercial agriculture). A striking example is given by the analyzed sub-area of Plate 1 of 1988, where the circular fields detected by visual interpretation and added in the overlay b were 130. However the results of the roundness method applied to overlay b showed that only 33 fields were identified (Table 8). Consequently many fields attributed to traditional agriculture by means of visual interpretation of aerial photos, were confused (or not well discriminated) with those under commercial agriculture, when applying the roundness method. Therefore the roundness method is not able to discriminate several fields which actually belong to the traditional farming system because of their particular shape. In fact, the clearing of vegetation, which occurs regularly during the rotation of fields under shifting cultivation deforms the original shape of the single circular field including neighbouring fields together. As result of this merging, fields take a composite form i.e. pear or oval shape.

We can conclude that the roundness analysis is able to discriminate very well circular fields belonging to shifting cultivation from those ones commercially cultivated (rectangular shape), but it cannot be applied when the fields under shifting cultivation show irregular shapes. The results of the roundness analysis has confirmed that the shifting cultivation as small chitemene system is still present in the Eastern province. In particular, cultivated area under small chitemene system is often located near the fields belonging to commercial agriculture.

A second attempt to improve the achieved discrimination between the shifting cultivation and the commercial agriculture has been performed analyzing the field spectral characteristics extracted from the LANDSAT-TM images acquired at three different dates. However, the results of such analysis show that fields under the two considered agricultural systems have the same spectral characteristics in the analysed reflectance bands.

Consequently, other approaches to improve the discrimination of the chitemene system from the commercial agriculture should be more addressed to the pattern analysis of field shape, via i.e. Fourier analysis, Hough transform analysis. The Hough transform analysis is, in particular, a technique commonly used in the image analysis for detecting lines and shapes in digital imagery. To detect circular objects in a digitized picture, it requires a three-dimensional array of accumulators. Applications of the Hough transformation to detect circular features have been succesfully used in medicine (Kimme et al., 1975) and in geology (Cross, 1988).

4.3 Monitoring natural vegetation growth patterns by means of NOAA-NDVI time series

4.3.1 Materials

Satellite data

Two years, respectively 1983-84 and 1984-85 of NDVI 10 day composite images obtained with NOAA-AVHRR data (7.3 km of resolution - ARTEMIS format) have been provided by FAO (Rome). FAO together with NASA and USAID (USA) is busy to build up an archive of NOAA-AVHRR-NDVI data for Africa starting from 1980. Such archive is regularly updated. FAO receives regularly from NASA (USA) NOAA-AVHRR-Global Area Coverage (GAC) data recorded on tape. Such data are directly produced by the on-line processing system for the NOAA-AVHRR data. The sampling of LAC (1 km spatial resolution) onboard data compression reduces the pixel size to 4 km (GAC). FAO then resamples the GAC data in a set of data having 7.3 km of resolution. In addition these 7.3 km data are composed in one decade (period of 10 days) and in Normalized Vegetation Index (NDVI). Such data set is called ARTEMIS-NDVI data. Compositing is done in order to screen clouds and it is accomplished by retaining the greenest pixels (as measured by the NDVI) over the period. The ARTEMIS-NDVI data set used for this application was complete (36 decades) for year 1983-84 while for year 1984-85 only 29 images were available (Table 10). The set of these NDVI 10-day composite images covers the whole territory of Zambia. Also four LANDSAT-MSS cct's (resolution 79x56 m) have been acquired as Table 10 shows. These MSS images are located in 4 different agro-ecological zones in Zambia. Location of the chosen LANDSAT-MSS images is shown in Fig. 8.

Table 10 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-MS	172/70	31 August 1984
	172/67	31 August 1984
	172/71	8 September 1984
	170/70	25 August 1984

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 in each province, were analysed in form of 10 day records and averaged for each province by means of the isohyetal method (Linsley, 1975).

Table 11 shows the considered meteorological stations for four provinces.

Characteristics of natural vegetation
In order to correlate the NDVI time series with the growth dynamic of natural vegetation, a brief description of the characteristics of natural vegetation is here given. Natural vegetation in Zambia is mainly miombo woodland (White, 1983). According to the amount of rainfall two major miombo woodlands can be distinguished (Hough, 1986):

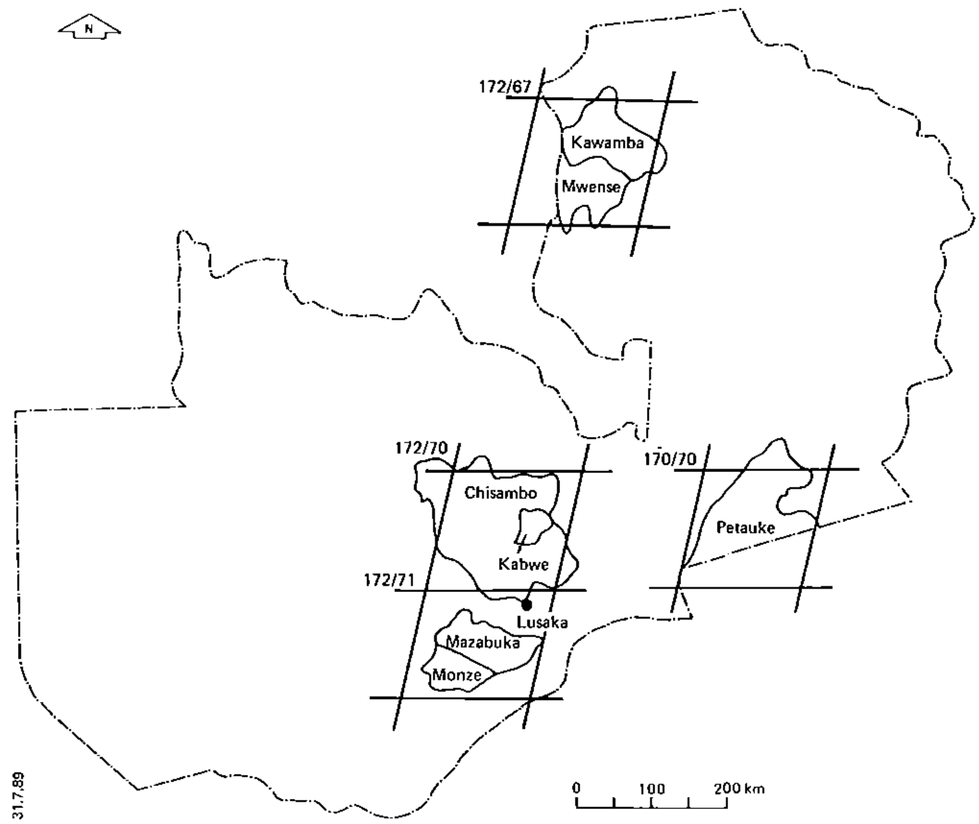

Fig. 8 Selected LANDSAT-MSS frames and Zambian districts where the pilot areas of MARS project are located (from Berkhout et al., 1988).

Table 11 List of 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

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). Most trees and shrubs lose their leaves for up to three months during the late dry season, though normally they flush before the beginning of the rain season.

Deciduous woodland is dominated by species as Brachystegia and Julbernardia (Hough, 1986), which roots can develop rather deeply in the soil intercepting water available in the dry season (Balek, 1977). Canopy height is between 10 and 30 m. Grasses are generally 0.6 to 1.2 m tall.

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, by supplying enough humidity to the root system of trees and bushes during the dry season.

It has been proven that in ecosystems similar to 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 the rain season. In fact flush of new leaves and flowering can be independent from the water supply given by rain if the groundwater storage supplies 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 can occur in Zambia in the months of September and October (Muchinda, 1985; Hutchinson, 1974).

4.3.2 Analysis of satellite and meteorological data

Calculation of time-serie profiles of NDVI data

Four provinces respectively Central, Northern, Eastern and Southern, have been closely analyzed by means of NDVI data. The four chosen provinces are representative agro-ecological zones in Zambia. National, province and district boundaries of Zambia were digitized on a map. A contour line data base included each unit as an individual segment; a graphic editor can access individual segments through a hierarchical menue and it allows the creation of masks. In particular four masks showing the Zambian province boundaries (respectively Central, Northern, Eastern and Southern) are created. Overlaying the digitized mask on the NDVI images, mean NDVI values for the four provinces are extracted for each decade. NDVI data of each 10-day composite were averaged within each province to obtain the time-serie of the mean NDVI. Fig. 9 shows NDVI time-series plots of Central, Northern, Eastern and Southern provinces for the crop season 1983-84, where the time profiles exhibit wide fluctuations.

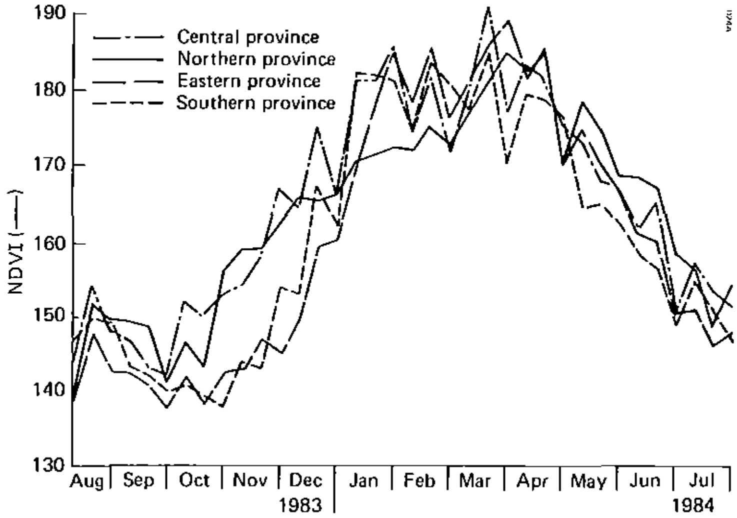

Fig. 9 NDVI time-series plots of Northern, Southern, Eastern and Central provinces for the crop season 1983-84.

To eliminate random fluctuations, the time series have been smoothed and consequently a better interpretation could be done. A cubic spline data smoother (IMSL, 1973) was applied and the results plotted in the graphs are shown in Figs. 10a, b. Four different agro-ecological zones located respectively Kawambwa, Kabwe urban, Mazabuka and Petauke districts were closely analysed by means of the four acquired LANDSAT-MSS images. For part of each MSS frame, a standard colour composite product (bands 7-5-4) was performed in order to visualize the vegetation pattern of the area.

Meteorological data analysis
Cumulative curves of the average rainfall data in four provinces have been obtained for the years 1983-84 and 1984-85 (Figs. 11a, b).

4.3.3 Results

A common result in the four provinces shows that the 1983-84 rainfall amount was lower than in 1984-85. Particularly, 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 (Fig. 11a, b).

An expected relationship between rainfall amount and NDVI values should be that at lower amounts of rainfall correspond lower NDVI values and vice versa (Tucker et al., 1985). However, analyzing the maximum values of the NDVI profiles between provinces (Figs. 10a, b), they did not show a large variation between the two years as much as it was exhibited between the values of rainfall.

Most of the variations in the NDVI time-series of Figs. 10a, b are observed at the beginning (October-November) and at the end (from April on) of the growing season. More precisely, at the end of the dry season (October) when the minimum value is reached by the NDVI curves in 1983-84 (Fig. 10a), the NDVI values for Eastern and Southern provinces were lower than the ones recorded in Central and Northern Provinces. The same trend was also

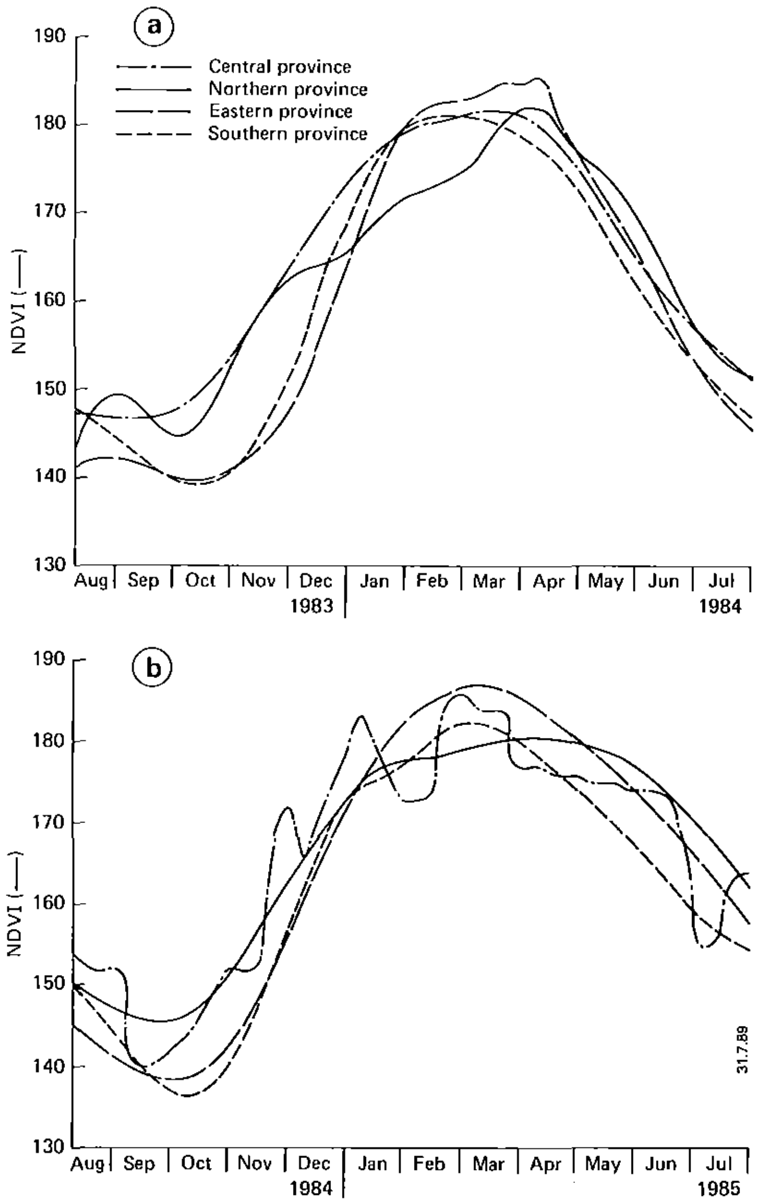

Fig. 10a, b NDVI-time-series plots after the smoothing of Central, Northern, Eastern and Southern provinces for the crop seasons 1983-84 (a) and 1984-85 (b).

recorded for the year 1984-85 (Fig. 10b) where in October the lowest NDVI values occurred also in Southern and Eastern provinces. Moreover, the minimum values reached in October 1984 (Fig. 10b) in Southern and Eastern provinces were even lower than those NDVI values recorded one year before for the same provinces (Fig. 10a).

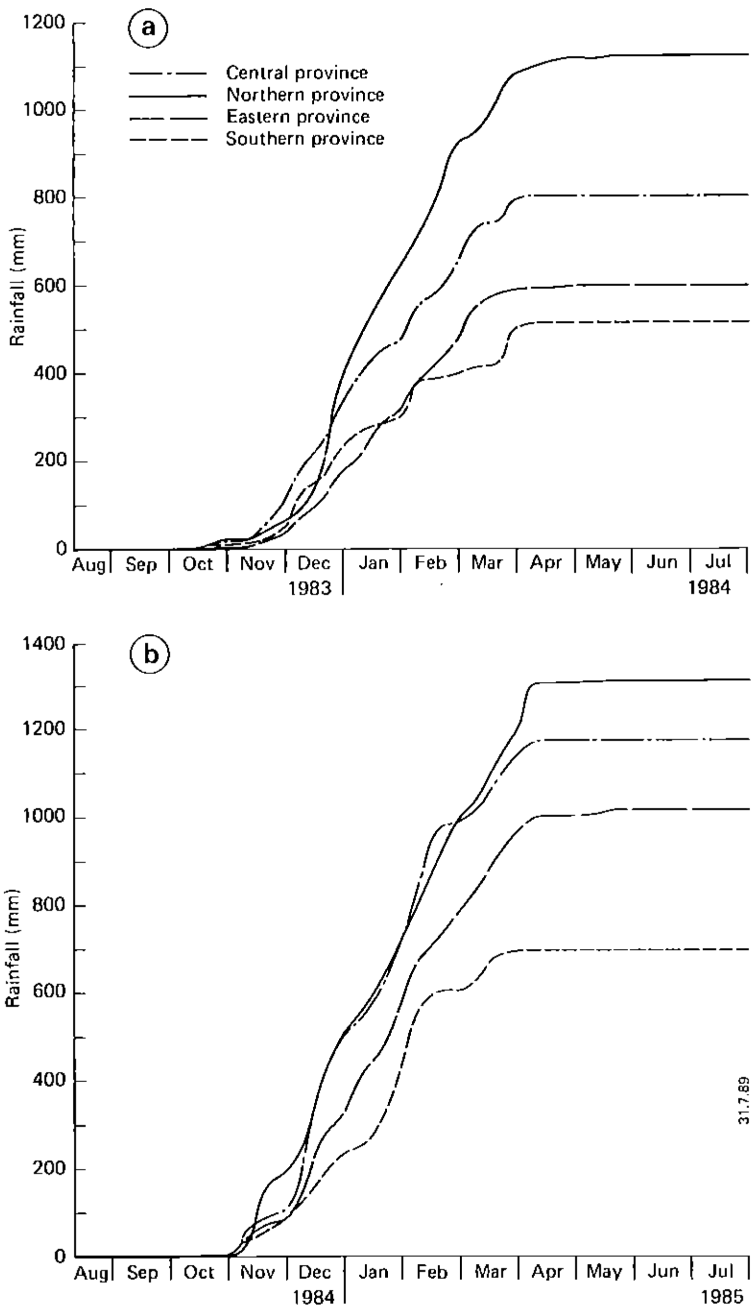

Fig. 11a, b Cumulated monthly rainfall amount for Central, Northern, Eastern and Southern provinces in the crop year 1983-84 (a) and in the crop year 1984-85 (b).

Such specific trend of NDVI values occurred in October for Southern and Eastern provinces can be explained by the nature of the vegetation growing there. According to the characteristic vegetation pattern of the considered provinces (see description in par. 4.3.1) and to the average yearly amount of rainfall (Muchinda, 1985) which is less than 1000 mm Southern and Eastern provinces are characterized by dry miombo with deciduous riparian forest. On the other hand, Central and Northern provinces, located in the area where yearly rainfall is 1000 mm or more, are characterized by a wetter miombo ecosystem with evergreen riparian forests. Consequently, the lower NDVI values can be explained by the presence of more leafless vegetation (deciduous trees) due to their particular stage at the end of the winter dormance (in October) in Southern and Eastern provinces.

The NDVI profiles at the end of the growing season (from April on) show how fast vegetation reaches senescence and one of the factors which regulates the velocity of leaf yellowing is the amount of rainfall occurred during the crop year. Observing the NDVI-time-series (Figs. 12a, b) in the sequence: 1983-84-85, the slopes of the NDVI curves from April till July 1984 are steeper than the slopes in the same time-series one year later (April-July 1985). This means that vegetation in 1984 reached senescence quicker than in 1985. These results are also confirmed by the amount of rainfall which during the growing season 1983-84 was much less (Fig. 11a) than in 1984-85 (Fig. 11b).

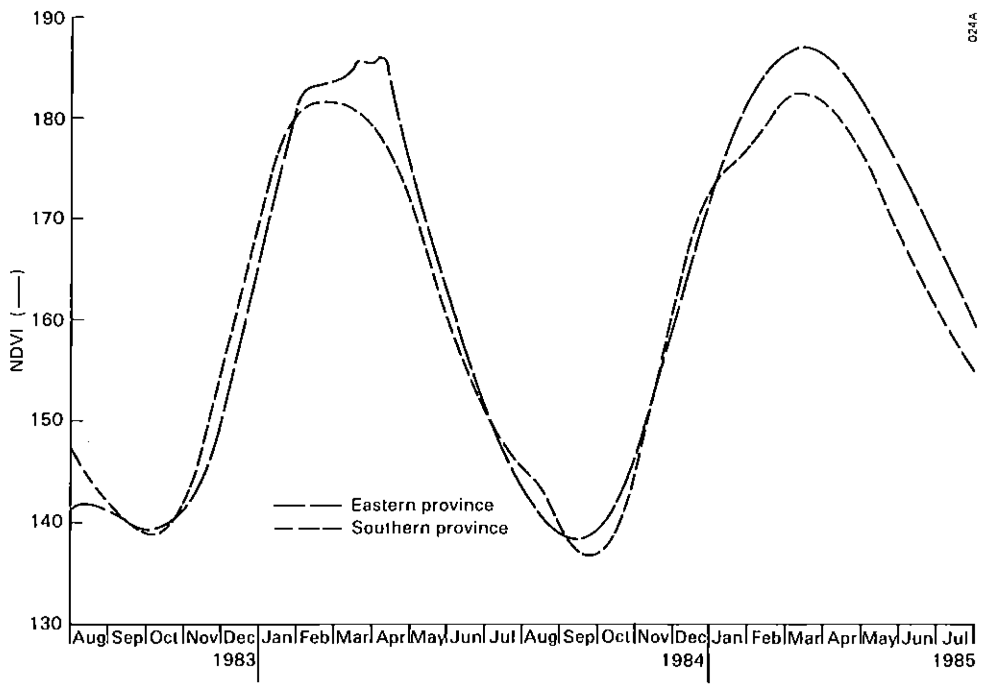

Fig. 12 NDVI-time-series plots of Eastern and Southern provinces in the crop seasons 1983-84 and 1984-85.

Correlation of start of the rain season with the beginning of the growing season

From Fig. 10a 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 the different start of the growing season in different agro-ecological zones is due to different starts of the rain season. Table 12 summarizes the start and end dates of the rain season for the four provinces. It shows, also, the dates 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 greater than 4 mm of rainfall had occurred in a decade.

Table 12 Start and end of the rain season in 1983-84 and 1984-85 for four Zambian provinces; dates when NDVI values start to increase and when maximum values of NDVI occur. Dates of mentioned NDVI values are extracted from the NDVI time-series of Fig. 10a and b relative to years 1983-84 and 1984-85 for four zambian provinces.

Province	Date increas. NVDI	Date start rainfall	Date max. NDVI	Date end rainfall
1983-1984				
Northern	21-31 October	21-31 October	11-20 April	21-30 May
Central	21-30 September	21-31 October	21-31 March	11-20 April
Eastern	21-31 October	1-10 November	11-20 April	11-20 April
Southern	1-10 November	21-31 October	11-20 March	11-20 April
1984-1985				
Northern	1-10 October	1-10 November	11-20 April	1-10 April
Central	1-10 October	11-20 November	1-10 March	11-20 April
Eastern	1-10 October	1-10 November	11-20 March	21-30 May
Southern	21-31 October	21-31 October	11-20 March	1-10 April

Considering the two analysed years, only in the Southern province (Table 12) NDVI increased just ten days later than the rain season has begun (in 1983 during the first decade of November), while for the other provinces and years the increase of NDVI values was recorded before the rain season started. In a very dry ecosystem the expected pattern should be that the increase of NDVI (increasing of green vegetation) should occur few weeks after a the rain season started, while the results shown in Table 11 do not confirm this. In fact, plenty of water is supplied to the plant root system by the ground water reservoir (Balek, 1977) and the flushing of the vegetation takes place when increase of temperature and absence of frost occurr (Hutchinson, 1974; Muchinda, 1985).

From Table 12, we can see that flushing of natural vegetation (increasing of NDVI values) starts in all cases but one, 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 canopy is reached by the vegetation during that period in the four provinces. Similar results have been obtained by Balek, 1977, on a study over the monthly evapotranspiration from grassland, woodland and transitive zone in Central African Plateau. In fact, the values of actual evapotranspiration of woodland and transitive zone (Balek, 1977) reach their maximum values 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 analyzed and the resulsts confirmed the expectations.

From MSS images available in dry season (Table 10) -end August, begin September- it was possible to identify large areas where green vegetation is located. In particular, Plate 4a, b, c, d shows a standard colour composite product of sub-areas located respectively in Kawambwa (Luapula province), Petauke (Eastern province), Kabwe urban (Central province) and Mazabuka districts (Southern province). The agro-ecological areas of Luapula province have very similar characteristics of those ones located in Northern province (Mansfield et al., 1975). In Plate 4a, b, c, d red colour evidences 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, Kabwe urban and Peatuke districts (red colour in Plates 4a, b and c).

4.3.4 Conclusions

The NDVI-time-series values extracted for the four provinces in Zambia are an appropriate indicator of the average growth pattern of the dominant vegetation type. Land-use information extracted from LANDSAT-MSS images has enhanced the interpretation of the NOAA-AVHRR-NDVI data.

Although the relationship between the start of the rain season with the beginning of the growing season is not straightforward as it would be expected, the contribution of other information as i.e. a schematization of hydrological characteristics of the country, types and growth pattern of the actual vegetation, has helped to find a better correlation between the analyzed processes. In fact, we should consider that the global pattern of zambian ecosystems is rather complex and not very homogeneous, most of the hydrological and floristic aspects cannot be simplified enough to find a direct correlation between the start of the rain season and the beginning of the growing season. Such direct relationship can probably be found in those environments where rainfall is very scarce and groundwater availability in each year is insufficient (Le Comte et al., 1988), while in the zambian ecosystems the contribution of large rivers and relatively high rainfall, feeding the groundwater table, influence constantly the water availability in the plant root zone.

4.4 Influence of soil and geological characteristics on vegetation growth

4.4.1 Materials

The study area, about 90 x 90 km (Fig. 13) large, is located in southeast of Zambia between Petauke and Katete districts. The following data have been used:
- the second quarter scene of LANDSAT-TM frame 170/70, bands 3,4 and 5, acquired on 16 January 1985;
- geological map of Zambia, scale 1:1,000,000, 1981;
- soil map of Zambia, scale 1:3,000,000, 1986;
- topographical map, scale 1:250,000, 1974;

The geological and soil map have been digitized in ARC/INFO format (a geographic information system) and converted to ERDAS format (a geographic information and satellite image processing system). Then, the two maps were geometrically corrected to a gridsize of 142.5 x 142.5 meters with the topographical map used as reference. The unaccuracy of the coordinate system of the geological and soil maps was adjusted to the coordinate system of the topographical map. To rectify the LANDSAT-TM image, ground control points both located on the satellite image and on the topo-maps were used.

4.4.2 Analysis of materials

4.4.2.1 LANDSAT Thematic Mapper product

For the LANDSAT-TM colour composite product in Plate 5 respectively band 4, 5 and 3 where chosen displayed by red, green and blue colours. In the study area the rainy season ranges from November till about end of March. Therefore the sowing-time of many crops is around November. At the moment of the TM-image at 16 January these crops were small and covered only a part of the soil (Plate 5).

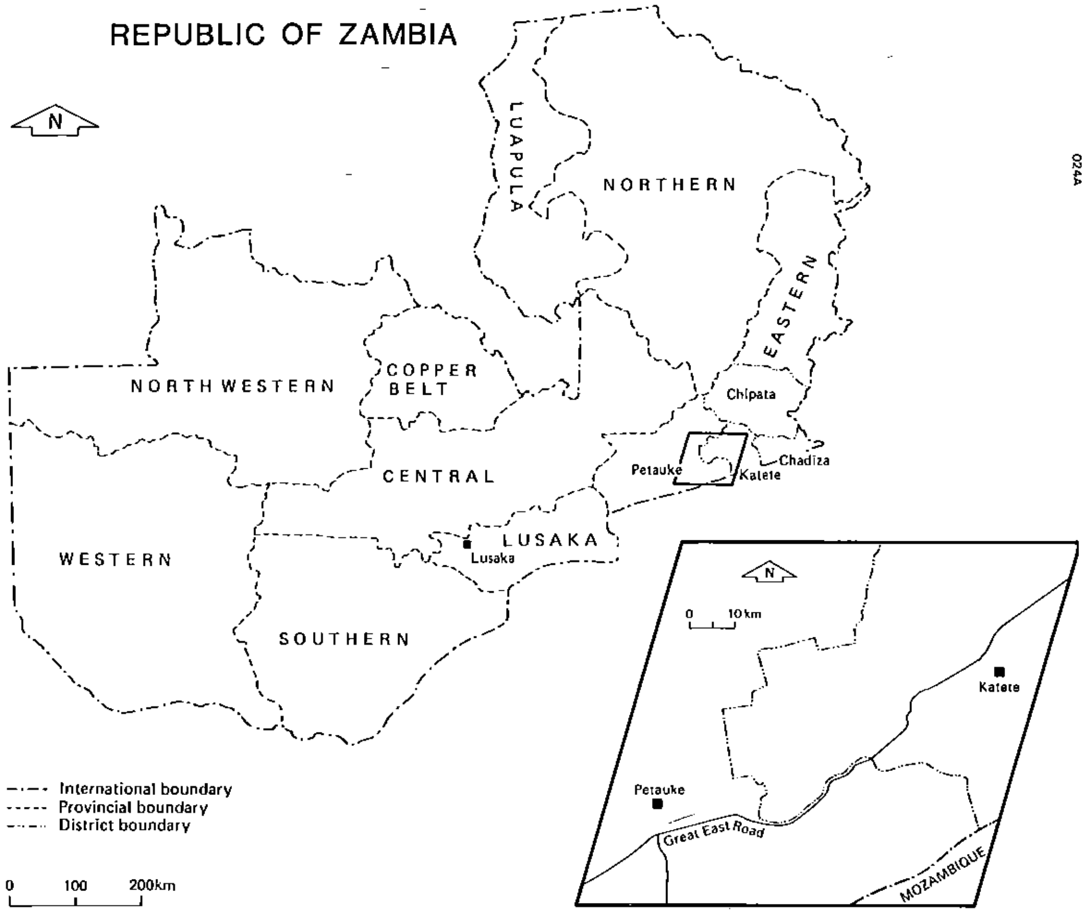

Fig. 13 Locations of study area.

Some topographic features can be recognized in the TM-image (Plate 5):

- The tse-tse boundary in the northern part, from west to east direction, comes out rather well due to the different colour (pale red) against the background colour (bright red). Such colour contrast can be explained by the applied technique of grass cutting in the tse-tse boundary. Namely to stop the migration of the tse-tse fly from one area to the other, vegetation is radically cutted down and maintained very short in a broad stripe larger than 200 m.
- Different gradations of red colour indicate the presence of different types or development of vegetation. On the hill slopes nearby Katete (on the middle-right of Plate 5) the red-brown colour indicates that the vegetation is less

developed than on the flat areas where bright red colour (well developed vegetation) is visible. Wide natural forest areas and afforestation areas are also indicated by different tonalities of red colour.
- At the bottom of Plate 5 different waterlogged areas and small lakes are visible.
- The boundary between Zambia and Mozambique, located on the bottom right of Plate 5 is very clear. It appears that in Mozambique less cleared areas are present than in Zambia.
- The white/black spots located on the top of Plate 5 denote the presence of clouds with their shadows.

4.4.2.2 Geological map

A brief description of the characteristics of the digitized geological map (Fig. 14) is here given. Geologically, Zambia lies between the Zairean and Zimbabwean cratons and therefore contains elements characteristic of geology of ancient mobile belts as well as aspects of ancient cratons. With the exception of areas underlain by Karroo sedimentary and volcanic rocks, and the poorly exposed Cretaceous clastics with Pleistocene Kalahari sediments which blanket much of the solid geology in the west, Zambia is underlain almost entirely by Precambrian rocks which account for over two thirds of the land area. The several tectono-thermal events that have affected the geological fabric of Zambia have made the geology of the country complex (Money, 1986). Two main structural-stratigraphic basins have been recognized in the study area:

The Mozambique belt
This belt, approximately 460 million years old is also a part of the Pan-African orogenic belt system, which stretches through Mozambique, Zambia and East Africa, and up into Ethiopia. In Zambia it occupies the area east of the Lwangwa Valley. It is formed by polymetamorphosed and complexly folded high grade gneisses, charnokites and granulites, cut by granitic, syenitic and basic intrusions. Series of low grade metasediments including basal conglomerate, psammites and pelites are interspersed within these rocks.

The Karroo system
The Karroo system consists of sediments and basic volcanic and hypabyssal rocks ranging in age from Carboniferous to Jurassic. It covers the down-faulted rift throughs of the Mid Zambezi, Lwangwa, Luano-Lukusashi and Kafwe Valleys and part of the Barotse Basin in western Zambia. Stratigraphically, the system is divided in Lower and Upper Karroo. The Lower Karroo consists of a basal sandstone and conglomerate formation of fluvio-glacial and glacial origin overlain by fine grained sediments of a deltaic and flood plain fluviatile formation, which also includes sandstones, carbonaceous mudstones and coal seams. The Upper

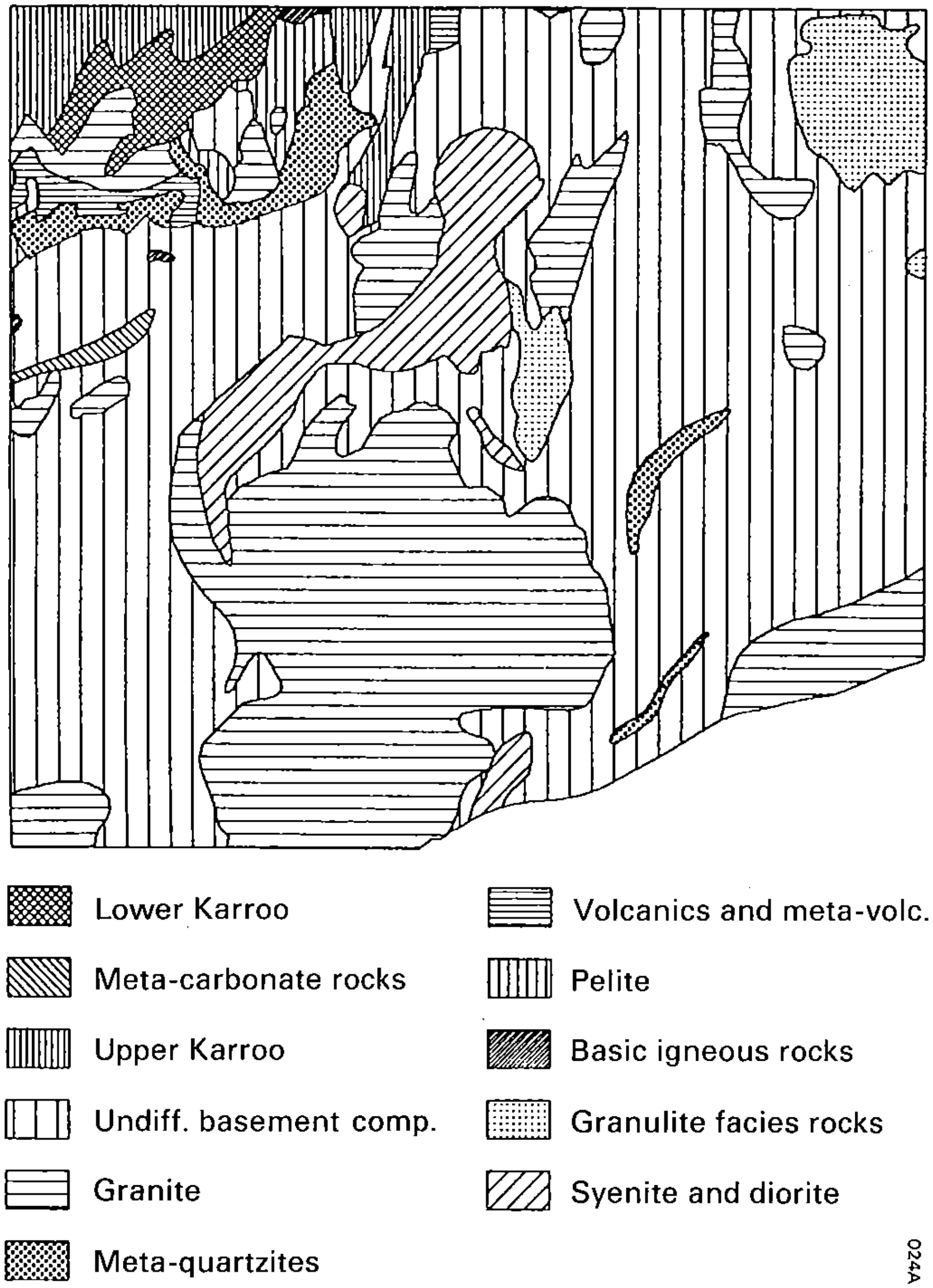

Fig. 14 Geological map of part of Petauke and Katete districts.

Karroo with a total thickness of approximately 1000 meters unconformably overlies the Lower Karroo. It consists of a series of arenaceous continental sediments, the Escarpment Grit, and a sequence of finer grained sediments, called the Interbedded Mudstones-Sandstones. The youngest member of the Upper Karroo is the Batoka Basalt Formation with pyroclastics and lava sometimes interlayered by carbonatites and kimberlites in the area of the Rufunsa and Lwangwa Valley.

4.4.2.3 Soil map

Fig. 15 shows the digitized soil map for the study area. The following sources have been combined to achieve a more complete description of the characteristics of different soil types in the study area:
- Soil maps of Zambia (1983, 1986);
- Landuse map of Zambia (Schultz, 1974);
- Brammer soil classification (1976);
- FAO-UNESCO landuse/suitability classification (1977).

Fluvisol/vertisol
In the northwest of the area belonging to the Lwangwa Valley, chromic/pellic vertisol and orthic luvisol soils are found (Fig. 15). The soils consist of a complex of sand and clay (Brammer, 1976). The characteristics of such soils can be summarized as follows:
- during the rain season the low infiltration rate of the soils caused waterlogging problems;
- alkaline particles are in large quantity while organic matter content is rather low;
- the best allocation for these soils is extensive agriculture (traditional system) cultivating cassava, maize, sorghum together with cattle-raising activity on the grass savanna.

The eutric fluvisol soil is found in the middle of the study area along the sideriver of the Lwangwa. It is very good drained soil and moderately alkaline. This good soil can hold intensive foodcropping. Semipermanent cultivation (Lwangwa System) and shifting cultivation are there present (Schultz, 1974).

Lithosol/cambisol
These shallow, rocky soils are dominant in the northern area where also much relief is present. Since the agricultural potentiality of this soil is rather low due to low CEC and water availability, the soil is used for pasture of extensive cattle-raising. The best allocation of such soil is for natural vegetation, forest and pasture (Schultz, 1974).

Luvisol/phaeozem
In some areas subsistance agriculture is practiced together with cattle-raising. These fertile clayey soils lie upon basic rock in the middle and southwest of the area, part of the Eastern

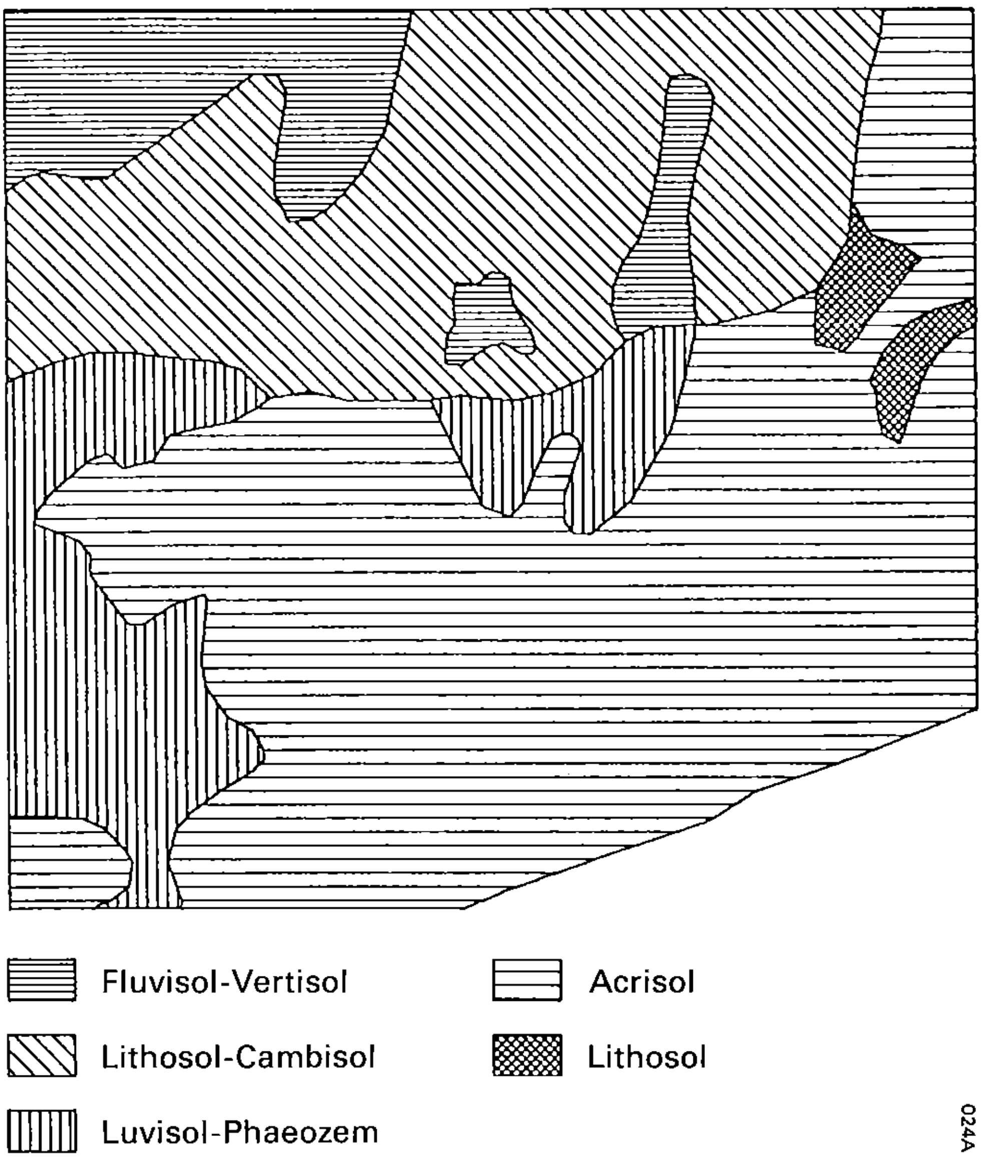

Fig. 15 Soil map of part of Petauke and Katete districts.

Plateau. The natural vegetation is tree-savanna or miombo. It is one of the best soils of the tropics, although watersupply can be a restricting factor. Such soils are very suitable for traditional and intensive agriculture, and also for pasture. The present semipermanent cultivation (Lwangwa System) in the southwest of the study area produces mainly maize, but also sorghum and millet. In the south, semicommercial cultivation (Eastern Plateau System) of maize and groundnuts and shifting cultivation are common (Schultz, 1974).

Acrisol
The acrisol is dominant in the study area. It is located especially in the middle south of Fig. 15. It is a weathered and leached clayey to loamy soil laying upon acid rock. Due to low CEC, presence of little organic matter and severe ecological conditions, the natural vegetation consists mainly of tree-savanna or miombo. Suitability for agriculture depends mainly on soil fertility and watersupply, which both are sometimes scarce. Moreover, extensive cattle-raising and traditional agriculture (cassava, beans and sorghum) are present. According to Schultz (1974) semicommercial cultivation of mainly maize, but groundnut cultivation (Eastern Plateau System) has been also developed in this area.

Lithosol
In the centrum-right part of Fig. 15 lithosol soils are present only near Katete. This shallow clay (loam) soil lies on steep slopes of acid rock. The medium or coarse texture and severe ecological conditions allow the growing of tree, savanna or miombo. On such soil intensive agriculture is not present.

4.4.3 Comparison between LANDSAT-TM colour composite product, geological and soil maps: results

The three geometrically rectified maps respectively the LANDSAT-TM colour composite product, the soil and geological maps are then visually compared. Merging the soil map (fig. 15) with the colour composite product (Plate 5), it is possible to obtain the LANDSAT-TM colour composite product for each considered soil class.

Fluvisol/vertisol
In the northwest area the presence of acid rocks -pelite and quartzite- (Fig. 14) have generated soils with low pH, influencing then the scarcity of vegetation (Plate 5 Frame A). In the rest of the fluvisol/vertisol area the natural vegetation has moderately or well developed and large savanna prairies are used probably as pasture (Plate 5). The most southeast part of the fluvisol/vertisol area shows a rather good development of vegetation and some cleared area destinated to cultivation. Such

area, which soils were not generated by acid but by neutral parent materials, shows that the higher fertility of those fluvisol/vertisol soils influences positively the presence and development of thick vegetation (Plate 5 Frame B).

Lithosol/cambisol

In the outmost northwest of the area, on the outskirt of the Lwangwa Valley, rivers and hydrographic network are clearly visible. The satellite image is acquired (mid-January) during the rain season. Still many dark pixels are present in the colour composite indicating waterlogged areas, as results of low water infiltration, one of the characteristics of those soils. Poorly or moderately development vegetation (Plate 5), caused by the presence of much relief and acid rocks, is dominant on these shallow soils. A better vegetation development can be noticed along the river sites and more on the southeast part of these soils cultivations (mainly traditional agriculture growing cassava, beans and sorghum) are noticed. Extensive cattle raising is also widespread. The remarkable bright red area (Plate 5, Frame C) in the southwest part of such soil association indicates the presence of very flourishing vegetation (thick forest) due to the high soil fertility, which can be justified by the presence of both meta-carbonate rocks as parent material and the adjacent fertile soil/association (luvisol/phaeozem).

Luvisol/phaeozem

On this soil association, classified as one of the best of the tropics, vegetation should grow very well. Mainly on the north-west part natural and thick vegetation is present while in the southern part of this association cultivated area can be seen (semi-permanent cultivation -Lwangwa system-). In the north the dark area in such soil association indicates that vegetation is not well developed caused by waterlogging problems. Similarly, the close presence of granite (Fig. 14) influences negatively vegetation growth. Observing the geological (Fig. 14) and the soil maps (Fig. 15), it is possible to remark that when the granite formation constitutes the parent material (Fig. 14) poorer soils as acrisol and lithosol/cambisol soils are generated (Fig. 15). However, in the most east luvisol/phaeozem area (Plate 5, Frame D) the soil has been generated by parent material as granite and granulite facies rocks (Fig. 14), which acid rocks have influenced the low pH of the soil with consequently presence of scarce vegetation (Plate 5, Frame D).

Acrisol

The massive presence of granite as parent material has generated a type of soil association which is not very fertile as the previous one. Acrisol is the most dominant soil in the study area (Fig. 15). It appears from Plate 5 that natural vegetation does not grow as well as in the previous soil association although agriculture is widespread applied. The presence of a very important road (Great Eastern road) which crosses the Eastern province of Zambia from west to east has influenced very much the development of agriculture in such area. However, according to the soil characteristics -low CEC and lack of organic material-, the intensive use of the soil for agriculture purpose has drastically influenced the aspect of the whole area. The depletion of the soil nutrients has hampered the regeneration of the original forest, the recover of which takes more time than if it would be located in a richer soil. In the middle of acrisol soil area few patches of forest regeneration are present.

Lithosol
The most eastern area classified as lithosol soil association occupies the Katete city hills, which are covered by vegetation to prevent erosion (Plate 5, Frame E). Then agriculture is mainly concentrated on the foothills and nearby the road (Plate 5, Frame E). Poor developed vegetation is dominant on this soil, because of the bad site on steep slopes. In some rivervalleys the ecological conditions may be good enough for small scale cultivation or extensive cattle-raising.

4.4.4 Conclusions

The results of this analysis have shown that there is a close relationship between soil and land-use characteristics of the analyzed territory in the Eastern province in Zambia. Also the geological characteristics influence the presence of certain type of vegetation. However, the geological characteristics of the area do not effect on the presence and type of vegetation as much as the soil characteristics do. Several literature sources have substitute lack of field work and they have been of great help for the land-use interpretation of the satellite data. It can be concluded that such exercise has given a better understanding about how the geology and soil characteristics affect the land-use in the districts of Petauke and Katete.

4.5 Interpretation of crop growth patterns by means of NOAA-NDVI-time-series and LANDSAT-MSS images

4.5.1 Materials

Intercorrelation between satellite images at different resolutions
The highest resolution NOAA-AVHRR images have a 1.1 km pixel size. Sampling and compression of these data generate several categories 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 7.3 km (ARTEMIS

data), which resolution does not allow to visualize features as agriculture fields. The NDVI data used in this application are the same as in the previous analysis in par. 4.3.

In order to localize agricultural areas in the NDVI pixels, LANDSAT-MSS images were used. Table 10 shows the list of the satellite images used in this application. The standard colour composite products created in par. 4.3 from bands 7-5-4 of LANDSAT-MSS images were also used here (Plate 4a, b, c, d). Moreover, in each MSS colour composite one sample area has been selected (Plate 4a, b, c, d, white framed sub-areas). In these framed sample areas (Plate 4a, b, c, d) agricultural fields can be easily seen thanks to the higher resolution of MSS pixels. In order to compare NOAA-AVHRR images with MSS images, the district boundaries respectively of Kawambwa, Kabwe urban, Mazabuka and Petauke district were digitized on a map. Then four masks were created showing the district boundaries and superimposed on the NDVI NOAA-AVHRR images (Berkhout et al., 1988). On four black and white photo products, showing the entire LANDSAT-MSS frames, boundaries of the forewritten districts were drawn. Then, a grid, each cell of which represented a NOAA pixel, was superimposed into the district masks and visual comparison between the location of district 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 it was possible to locate in Petauke district with the help of LANDSAT-TM images areas characterized by larger numbers of agricultural fields (see application in 4.1.).
From each group of agricultural pixels (Table 13) a mean NDVI value was calculated for each decade and plotted in a temporal profile using the same technique applied in par. 4.3. Figures 16a, 17a, 18a, 19a, show the time-series profiles of NDVI of the selected sub-areas in 1983-84 and 1984-85.

Rainfall data
The cumulative curves of the rainfall data recorded in the four considered districts (Table 13) are the results of the precipitation data analysis for the years 1983-84 and 1984-85 (Fig. 16b, 17b, 18b, 19b). The rainfall data of Mazabuka district were not available, therefore the data referring to the closest district, Magoye, were used.

Table 13 Location and amount of analyzed pixels of NDVI NOAA-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

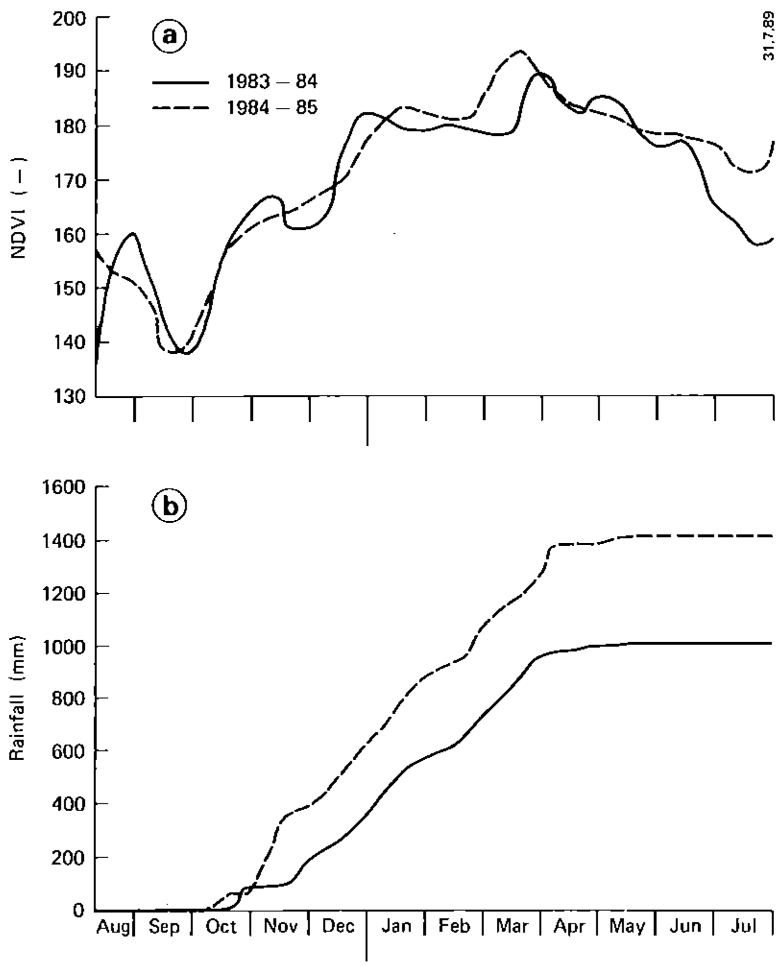

Fig. 16 a: NDVI-time-series of NDVI mean values referring to three pixels located in Kawambwa district (Luapula district, Zambia) in the crop years 1983-84 and 1984-85;
b: Cumulative decade rainfall amount recorded in the meteorological station of Kawambwa in 1983-84 and 1984-85.

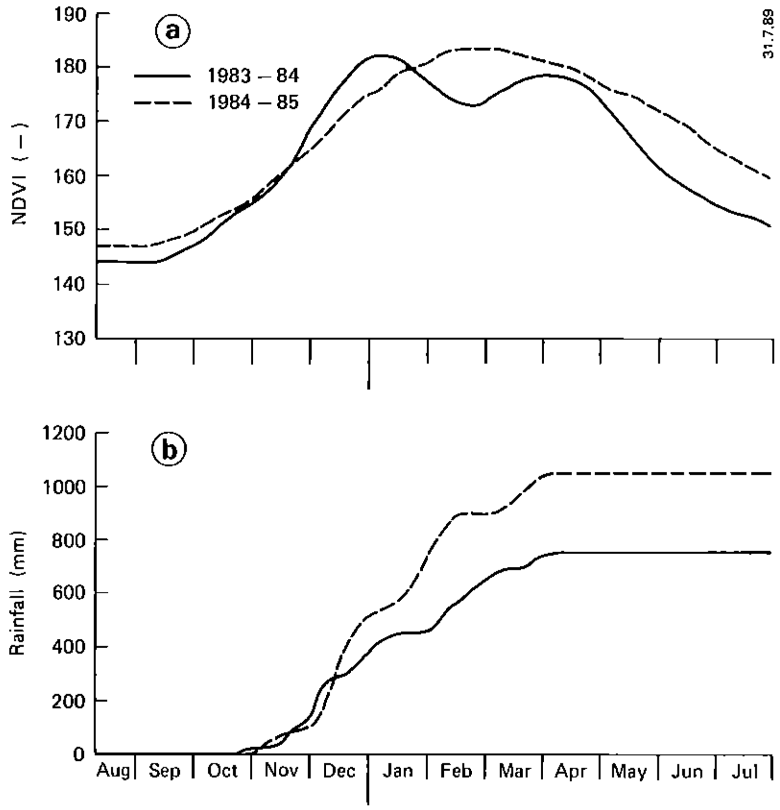

Fig. 17 a: NDVI-time-series of NDVI mean values referring to five pixels located in Kabwe urban district (Central province, Zambia) for the crop years 1983-84 and 1984-85;
b: Cumulative decade rainfall amount recorded in the meteorological station of Kabwe urban in 1983-84 and 1984-85.

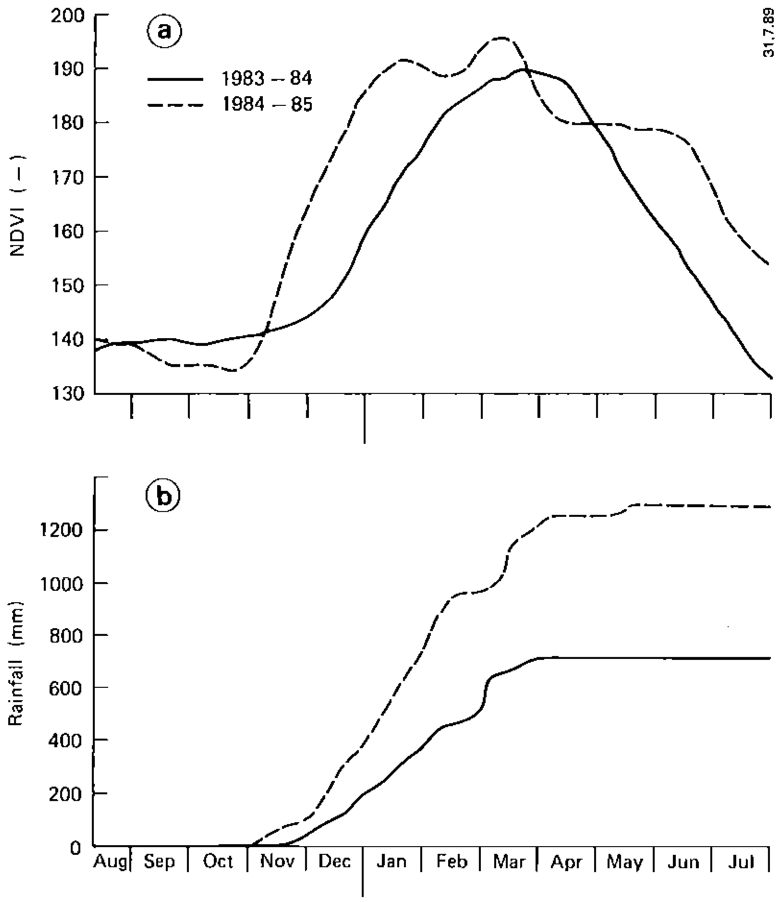

Fig. 18 a: NDVI-time-series of NDVI mean values referring to eight pixels located in Petauke district (Eastern province, Zambia) for the crop years 1983-84 and 1984-85;
b: Cumulative decade rainfall amount recorded in the meteorological station of Petauke in 1983-84 and 1984-85.

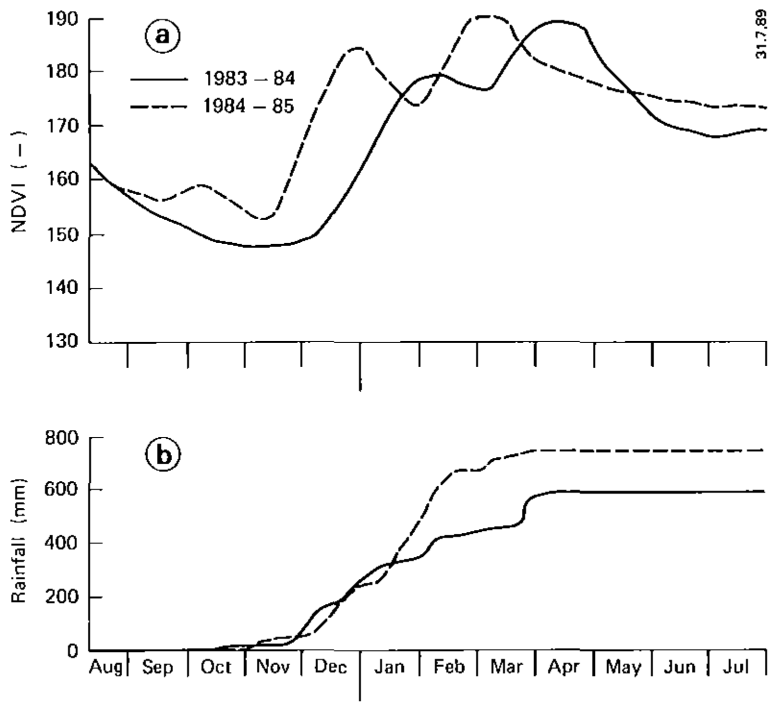

Fig. 19 a: NDVI-time-series of NDVI mean pixels located in Mazabuka district (Southern province, Zambia) for the crop years 1983-8 and 1984-85;
b: Cumulative decade rainfall amount recorded in the meteorological station of Magoye district (Southern province, Zambia) in 1983-84 and 1984-85.

Statistical data

From Central, Eastern, Southern and Luapula provinces statistical data concerning yield values (Table 14), obtained by dividing crop production by crop area, were elaborated for the crop years 1983-84 and 1984-85 (Ministry of Agriculture and Water Development, 1985). Crop production data were not available for each district. Therefore the same values extracted for the correspective provinces were used.

Table 14 Productivity per hectare of annual crop in four zambian provinces during the crop years 1983-84 and 1984-85, ratio between the crop productivities.

Provinces	Productivity (10^3 kg.ha^{-1})		Ratio 1983-84/1984-85
	1983-84	1984-85	
Central	2.01	1.98	102%
Eastern	1.25	1.46	86%
Southern	1.27	1.64	77%
Luapula	1.53	1.50	102%

Data for WOFOST model
To explain different amounts of productivity correlated to different amounts of rainfall, a numerical simulation model of crop growth, WOFOST (Van Diepen et al., 1988) which simulates agricultural production on the basis of physical and agronomic information, was applied. Model data requirements include site specific information such as the starting date of the crop growth, initial soil moisture conditions, physical properties of the soil surface, such as surface water storage capacity, natural soil fertility and more general data on climate, crop and soil characteristics. Maize, variety HYV (High Yielding Variety) cultivar MM752 has been considered and the most representative soils of the study areas have been used in the model calculation (Wolf et al., 1987). Table 15 shows the results of WOFOST model as the simulated maize production in a water-limited situation in the four considered districts. The Leaf Area Index (LAI), as one of the several output data of the WOFOST model, was provided for every decade during the simulation of the crop growth cycle. The Leaf Area Index gives a measurement of the progressive developing of crop green canopy during the growing season. LAI values can then be compared to the NDVI values.

Table 15 Simulated maize production in a water-limited production situation according to WOFOST model. The simulation is carried for two growing seasons (1983/1984 and 1984/1985) and in four Zambian districts.

Province	Production (10^3 kg.ha^{-1})	
	Year	
	1983/1984	1984/1985
Kabwe urban	9.759	10.262
Mazabuka	4.169	8.126
Petauke	10.608	10.300
Kawambwa	11.307	11.353

4.5.2 Results of the analysis of "agricultural" pixels

From the comparison between Leaf Area Index (LAI) values obtained via WOFOST model, the NDVI values and the rainfall amount on the graphs from Fig. 16 to Fig. 19, some results are summarized in Table 16. More details are given per district.

Kawambwa district sub-area
The NDVI-time-series profiles of three pixels located in Kawambwa district (Fig. 16a) show that there was no significantive difference between the two years. The results of simulated maize

Table 16 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. 16 to 19 relative to years 1983/1984 and 1984/85 for four Zambian sub-areas (Table 13).

District Sub-area	1983 - 1984			
	Date increas. NVDI	Date start rainfall	Date max. NDVI	Date end rainfall
Kawambwa	1-10 October	21-31 October	1-10 April	21-30 May
Kabwe urban	21-30 September	1-10 November	11-20 April 11-20 January	11-20 April
Petauke	21-31 October	21-30 November	21-31 March	1-10 April
Mazabuka/ Magoye	1-10 December	21-31 October	11-20 April 11-20 February	11-20 April
District Sub-area	**1984 - 1985**			
	Date increas. NVDI	Date start rainfall	Date max. NDVI	Date end rainfall
Kawambwa	21-30 September	11-20 October	12-31 March	21-30 May
Kabwe urban	21-30 September	11-20 November	11-20 March	11-20 April
Petauke	1-10 November	1-10 November	11-20 March 21-31 January	21-30 May
Mazabuka/ Magoye	21-30 November	11-20 November	11-20 March 1-10 January	1-10 April

production (Table 15) confirmed the same results achieved by the analysis of NDVI-time-series: no significative difference of maize production was recorded between the two years. This conclusion is confirmed by the crop production statistical values of Luapula province in (Table 14), showing that crop productivity in 1983-84 and 1984-85 was nearly the same. Although the sub-area was selected as most representative of agriculture, natural vegetation still influenced NDVI values, as can be seen from the relation of the beginning of rainfall with the start of the growing season. In fact, significative rainfall starts in Kawambwa much later than the growing season (Table 16).

Kabwe urban district sub-area

The NDVI-time-series of a five-pixel sub-area (Fig. 17a) show very slight differences between the two years. Maize production values (Table 15) showed that water (supplied by rainfall) was not a limiting factor of maize production, which, in both years, was rather high, as it is confirmed by the crop production statistical data in Table 14. A remarkable pattern is shown in the NDVI temporal profile of 1983-84 (Fig. 17a) where two maximum values are recorded: the first one occurred in the second decade of January while the second one at the beginning of April (Table 16). Furthermore, comparing the dates of the first maximum value of NDVI with that of the highest value of LAI, full coincidence in time is found. However, the selected pixels of the sub-area show also presence of natural vegetation which affected the NDVI value as indicated by the earlier start of the growing season compared to the beginning of the rainfall season (Table 16).

Petauke district sub-area
In the district of Petauke the amount of rainfall in 1984-85 was twice the amount fallen in 1983-84 (Fig. 18b), which seems to have affected the increase of NDVI in 1984-85 in the sub-area of 8 pixels located in Petauke district (Fig 18a). Start of the growing season (increase of NDVI), which occurred in both years before the beginning of the rain season (Table 16), shows that natural vegetation is still present in the considered sub-area. Nevertheless, the growth pattern of agricultural crops can also be detected in the NDVI time-series profile of 1984-85. In fact, looking at Fig. 18a two maximum values of NDVI temporal profile of 1984-85 are visible. The first maximum value occurs earlier, in mid-January, the second one occurs on mid-March (Table 16). Also the highest NDVI value occurred in January (Table 16). Analyzing Fig. 18a differences between the NDVI temporal profiles in the two years are rather large, which is probably due to different amounts of rainfall (Fig. 18b). Comparing the NDVI temporal profiles with the crop productivity values of Eastern province (Table 14), a good correlation was found, where at lower productivity (1.25 tons/ha) in 1983-84 the NDVI profile was lower than the profile in 1984-85 (productivity = 1.46 tons/ha). Nevertheless, simulated maize production values (Table 15) show that water amount, supplied by rainfall, was not a limiting factor (in 1983-84 total rainfall amount was 739 mm, while in 1984-85 it was 1322 mm). In addition, the results of Table 15 show that in 1984-85 the huge amount of rainfall had influenced negatively simulated maize production, which was 4% lower than that in the previous year.

From the 8-pixel sub-area a second sub-area of 3 pixels was more closely analysed to reduce the influence of natural vegetation over the agricultural area; the same results, however, were obtained as for the 8-pixel sub-area.

Mazabuka district sub-area
Rainfall amounts, respectively 589 mm in 1983-84 and 749 mm in 1984-85, recorded in Magoye meteorological station (Fig. 19b) were the lowest values as compared to the other provinces. Comparing the NDVI temporal profiles of a 4 pixel sub-area from Mazabuka district (Fig. 19a) with the total amount of rainfall (Fig. 19b), a good correlation can be found between the curves in

both years. In particular, in 1983-84 the start of rain season (> 0.4 mm per day) occurred in the third decade of October (Table 16), while the NDVI increased from the first decade of December, as consequence of very scarce rainfall in November. Such scarcity of precipitation delayed the growth season and, consequently, NDVI reached its first maximum value in the second decade of February while the second relative maximum value was reached in the second decade of April. In particular, the NDVI values have promptly increased reaching the maximum values (Fig. 19a) as reaction to the relatively large amounts of rainfall which have occurred respectively in the first decade of February (70 mm) and late March (105 mm) in 1983-84. Some contradictory results have been found comparing the LAI value obtained via WOFOST model and the NDVI values of the time-series profile of 1983-84. In fact, the highest LAI (Table 16) was reached in mid-January in 1983-84 and, comparing this LAI value with the first maximum value of NDVI (Fig. 19a) in 1983-84, a time lag of one month was observed.

However, simulation of maize production showed that in 1983-84, maize production was water limited, being 38% less than the simulated maize production in 1984-85 (Table 15). Such result can be compared with the agricultural statistics in Table 14 which shows that the Southern province had a very poor production in 1983-84 compared with 1984-85.

Analyzing the growing season 1984-85, a good correlation between NDVI temporal profile and amount of rainfall (Fig. 19a, b) can be found. In fact in 1984-85 significative rain started a week before the increase in NDVI (Table 16). Furthermore, the date of the first maximum NDVI value -December 1984/January 1985- (Fig. 19a) matches the date of the LAI maximum value (Table 16).

The second maximum value recorded in mid-March 1985 shows that the NDVI values of the chosen sub-area are also affected by some other vegetation types which reach full green cover late in the season.

A rather interesting situation has been observed in the colour composite MSS-image of Plate 4d. In particular, two sub-areas in Mazabuka district were chosen by analysing the colour composite product of Plate 4d, where was possible to identify a very large farm having green vegetation (coloured in red) and small fields not cultivated (gray-blue coloured areas). The occurrency of green vegetation in the large cultivated farm on the end of the winter season (first week of September) and in the dry season can only happen if irrigation practice has been applied there.
The green canopy there present can be generated either from winter annual crops or from evergreen plantation. Although ground truth data on the type of vegetation in the farm were not available, the existent most up-dated information (Wisse and Marchand, 1982) showed that the large farm is a state farm located around Mazabuka city and the irrigation water there

applied is supported by the Kafue Flats Irrigation Program.
The NDVI profiles recorded for two different sub-areas located in Mazabuka district (Table 13) have shown rather interesting pattern (Fig. 20).

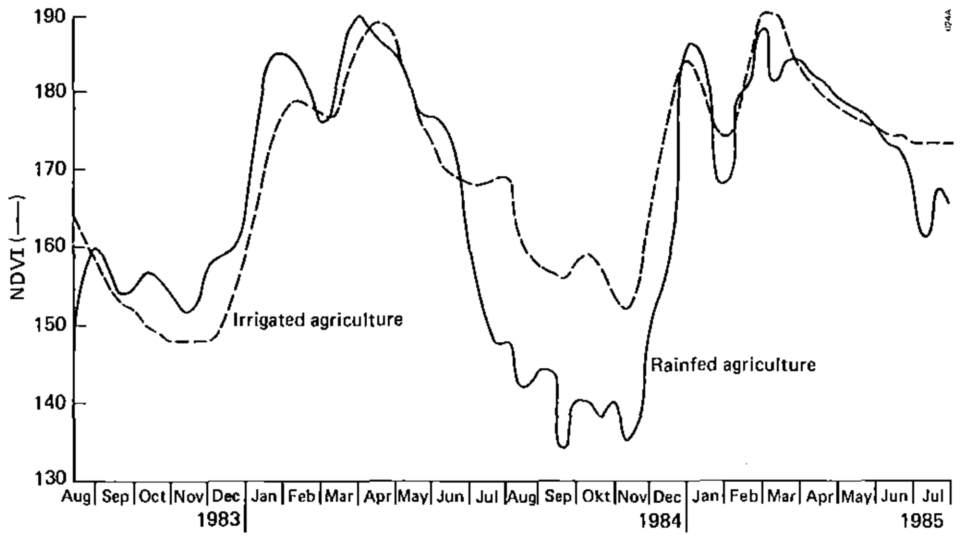

Fig. 20 NDVI-time-series of NDVI averaged values referring to four respectively five pixels located in Mazabuka district for the crop years 1983-84 and 1984-85. The four pixel-area refers to an irrigated farm while the five pixel-area refers to rainfed agricultural system.

In Fig. 19 the dashed-line curve refers to the NDVI-time-series profile of a 4 pixel sub-area including the above mentioned state-farm (which is 3 NDVI pixels large) where, during summer 1984 NDVI values were much higher (presence of green vegetation thanks to the irrigation practice) than those recorded in rainfed agriculture system (continuous-line curve in Fig. 20).

4.5.3 Calculation of indicators of crop production: discussion and conclusion

NDVI indicator

The NDVI temporal profiles of the sub-areas in the four zambian districts have shown to be correlated to the pattern of crop growth. Therefore an indicator of annual production of agricultural crops, based on AVHRR-NDVI values has been developed. More precisely, on the basis of NDVI-time-series for each crop season, the end date of vegetative growth is defined as the first decade after the last maximum value in the NDVI temporal profile. From such date till the 36th decade the NDVI cumulative decrement values were calculate for each profile and plotted.

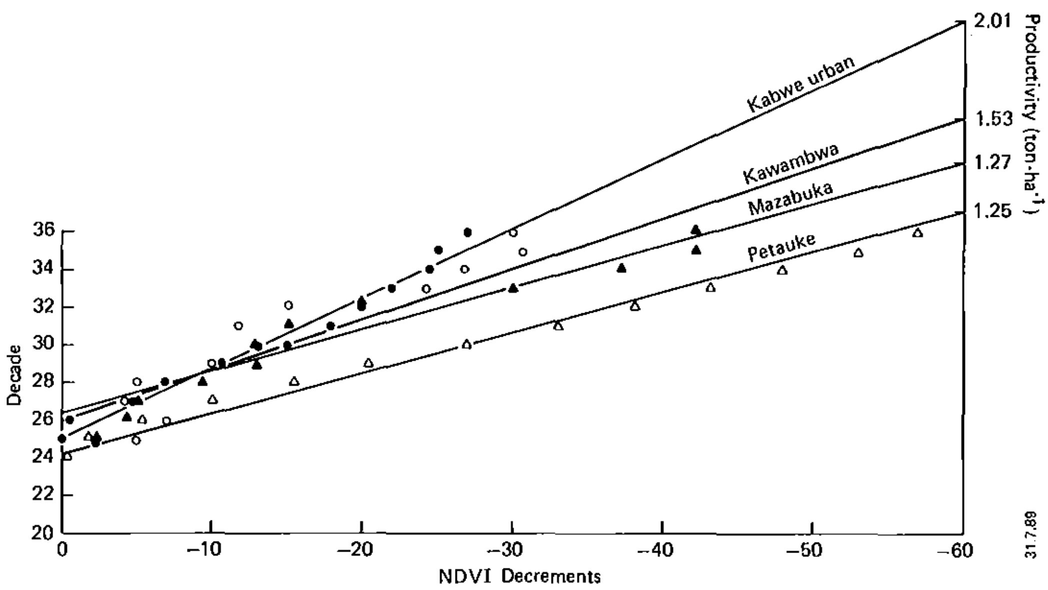

Fig. 21 Cumulative decrements of AVHRR-NDVI values extracted from selected sub-areas located respectively in Kawambwa, Kabwe urban, Petauke and Mazabuka districts, crop year 1983-84. Productivity values in tons/ha are extracted from Table 14.

The regression curves (Fig. 21) for each area in 1983-84 show a good correlation with the productivity values given in Table 14.

Comparison between NDVI, WOFOST, statistical and rainfall indicators of crop production

Comparison between the NDVI data, rainfall data, agricultural statistics and production as simulated by means of WOFOST was performed in the four agricultural sub-areas located in Kawambwa, Kabwe urban, Petauke and Mazabuka districts for the years 1983-84 and 1984-85. To compare such different data, four indicators were elaborated as follows:

1) The rain increment between the two considered years was calculated and then divided by the amount of rainfall occurred in 1984-85;
2) crop production as obtained with statistical data (Table 14) and by means of WOFOST model (Table 15) were normalized likewise;
3) cumulative decrements of NDVI values were calculated following the method described above. Then, for each province, the difference between the decrements at decade 36 was normalized.

Very interesting results were obtained for Kabwe urban and Mazabuka districts (Table 17) where the highest increment of rainfall (Kabwe urban district) corresponds to the lowest increment of production confirmed by statistical, WOFOST and NDVI indicators. On the other hand, the lowest increment of rainfall (Mazabuka district) corresponds to the highest increment of production as confirmed by the indicators of columns 3, 4, and 5 of Table 17. Consequently, such results confirm that water was a limiting production factor in the Mazabuka district between the two considered years, while in the Kabwe urban district different amounts of rainfall did not influence crop production. Moreover, from Table 17, in Mazabuka district the WOFOST production indicator shows higher values than the production indicators of columns 3 and 5. Both WOFOST and NDVI indicators (columns 4 and 5) show also a good correlation with the indicator of statistical data relative to crop production (column 3). The results in Table 17 are rather encouraging, however, the model WOFOST needs further calibration to simulate accurately crop growth patterns related to different agricultural areas. We can conclude that remarkable results have been obtained correlating the NDVI indicator of crop production extracted from "agricultural" pixels with the productivity values of maize obtained from statistical data, which results show the feasibility to assess quantitatively crop production via NOAA-AVHRR-NDVI data.

Table 17 Rainfall, statistical data, WOFOST and NDVI indicators calculated for the agricultural sub-areas (Table 13) located in Kabwe urban and Mazabuka districts in Zambia in 1983/1984/1985.

(1) Sub-area (district)	(2) Indicator rainfall [%]	(3) Indicator stat. data [%]	(4) Indicator WOFOST [%]	(5) Indicator NDVI [%]
Kabwe u.	+28.38	- 1.5	- 1.5	+ 11.1
Mazabuka	+21.36	+22.3	+48.8	+ 15.0

5 GENERAL CONCLUSIONS

The analysis carried out over extensive part of Zambia has shown that the remote sensing tools were highly suited to satisfy collection of information related to agricultural scenarios. It should be stressed that the definition of "remote sensing" as "acquisition of data about an object without any direct contact with it" has been fully applied during this research. In fact, the whole data set has been mainly collected by indirect measurements i.e. satellite data, aerial photos, literature information, maps. The whole study has revealed an interesting aspect as the use of the great amount of literature information which had substituted mostly field work data. If we compare the financial effort which could have been involved to collect the enormous amount of ground information necessary for such study, with the effort involved by information indirectly gathered, the results obtained in such global study are brilliant for two reasons.

The first reason is that such study, considering its multipurpose aspects, has shown a rather original approach in using all indirect data and trying to combine them in obtaining the final targets.

The second reason is the economic aspect involved in this research. A rather low budget has been involved in this project, which costs (100^3 U.S.$) consisted mainly in the acquisition and processing of satellite data and two years salary of a researcher. Because of the available low budget, the research was carried on giving up the collection of ground data and to stress on the indirect data, which decision has finally yielded to good results.

The analysis on a close-up scale of some specific eco-agricultural zones (i.e. districts and provinces) has been indispensable to explain the results obtained on a continental scale analysis.

Moreover, the combination of the indirect data i.e. GIS and remote sensing information have made possible a clearer and realistic interpretation of the agricultural management and yield forecasting in Zambia. Analyzing the agricultural scenario given in par. 1.2, it appears than in 25 years the zambian agriculture did not change so radically, maintaining a rather stable level of cultivated extension (Table 1). However, more variability between the same period has been remarked in the figures of the active population in agriculture (Table 3) showing a decreasing trend. Such general trend indicates that agriculture in Zambia is not expanding and its potential increment is rather hampered by factors as lack of infrastructures i.e. roads, storage facilities, etc. and as unrealistic agricultural prices than by intrinsic limitations of agricultural land. The calculation of the average crop calendar in par. 4.1 has helped the discrimination of the cultivated area from natural vegetation, showing the best date when such discrimination was possible. In fact, the multi-temporal approach (in this case the use of three LANDSAT-TM images of the same location at different dates) combined with the crop calendar informations made possible a rather good discrimination of the cultivated crops.

The multi-temporal approach was also used in par. 4.2 to discriminate the actual cultivated area from the fallow area in the shifting cultivation practice. Lack of several ground-truth data in par. 4.1 hampered both a more detailed formulation of crop calendar and a better discrimination of the other cultivated crops besides maize. The analysis in par. 4.2 revealed that chitemene system in Katete district of the Eastern province is not applied intesively only in 47 sqkm area. Such conclusion has been obtained thanks to the satellite image analysis which image has offered, in a relative large area (34,000 sqkm), a clear overview of the distribution of chitemene system in the territory, without using large amount of aerial photo products. Comparing the results obtained by the classification of the TM-image with the soil map (Fig. 15), it appears that most of the agricultural area is concentrated in the acrisol soils, which has a lower agricultural potentiality than the Luvisol-Phaeozem soil. So road infrastructure and relatively high population presence play more important role for agricultural development than high soil fertility.

The interpretation of standard colour composite used in par. 4.3 have been of great help to interprete NDVI-time-series. The last analysis in par. 4.5 has indicated that the combined use of different satellite information (i.e. high and low resolution images) with meteorological data and numerical simulation models improves monitoring of the growth of agricultural crops in Zambia. In this context the analysis of NOAA-AVHRR NDVI data (pixel size 7.3 km) in Zambia has also shown that the selection of "agricultural" pixels in the NDVI images has improved monitoring of crop growth. This means that monitoring the crop growth by means of NOAA-AVHRR-NDVI data involves an a-priori analysis of the land-use of the territory, which can be performed by means of high resolution images (LANDSAT-MSS, TM). Once the location of agricultural area is known, "agricultural" NDVI pixels, selected in such way, can be used for further calculations of indicators of crop growth.

In this research results obtained for the "agricultural" pixels (sub-areas of 200-450 sqkm) are partly representative of the agriculture condition of the province. In fact, the most limiting factor remains the pixel-size of the NDVI images (7.3 km) because even in those agricultural pixels the cropped area is often masked by natural vegetation. Then, the described analysis should be preferably carried out for selected agricultural areas by means of NOAA-AVHRR images having pixel resolution of 4.4 km

(NOAA-GAC data) or 1.1 km (NOAA-LAC data). Using higher resolution NOAA-AVHRR images it would be easier to locate in one pixel a higher percentage of cropped area.

Remarkable results have been obtained correlating the NDVI indicator of crop production extracted from "agricultural" pixels with the productivity values of maize obtained from statistical data (Fig 21), which results show the feasibility to assess quantitatively crop production via NOAA-AVHRR-NDVI data. Estimation of the line slopes in Fig. 21 can be applied as early indicator of crop yield. In fact, when the decreasing trend of NDVI values occurs in the time series profiles between March and April (Fig. 16a, 17a, 18a and 19a), a forecasted estimation of crop yield can be already calculated on the basis of such profile slopes. These type of indicators can be then further used, together with rainfall forecast data (Huygen, 1989) to improve the information collected by the Crop Forecasting and Early Warning Unit of the Ministry of Agriculture in Zambia.

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GLOSSARY OF ACRONYMS

ARC/INFO	Trademark of Environmental Systems Research Institute; Redlands, California, USA
ARTEMIS	African Real-Time Environmental Monitoring using Imaging Satellites
AVHRR	NOAA Advanced Very-High Resolution Radiometer
CFEWU	Crop Forecasting and Early Warning Unit; Lusaka, Zambia
CSA	Census Supervisory Area; Zambia
CSO	Central Statistics Office; Zambia
ERDAS	Earth Resource Data Analysis System (trademark)
FAO	Food and Agricultural Organization of the United Nations, Rome, Italy
GAC	NOAA Global Area Coverage
GIS	Geographical Information System
LAC	NOAA Local Area Coverage
LAI	Leaf Area Index
LANDSAT-MSS	LANDSAT MultiSpectral Scanner
LANDSAT-TM	LANDSAT Thematic Mapper
MARS	Monitoring Agro-ecological resources using Remote sensing and Simulation
NASA	National Aeronautics Space Administration; USA
NDVI	Normalized Difference Vegetation Index
NOAA	National Oceanic and Atmospheric Administration; USA
SEA	Standard Enumeration Area; CSO, Zambia
SPOT	Trademark of SPOT-Image
UNESCO	United Nations' Educational, Scientific and Cultural Organization
USAID	United States Agency for International Development; Washington, USA
WOFOST	Crop growth simulation model of the Centre for WOrld FOod STudies; Amsterdam-Wageningen, The Netherlands

PLATES

Plate 1 Colour coded image as product of the digitalization of two black and white aerial photos where the photo of 1988 has been coded with red colour, photo of 1974 has been coded with green colour; actual area of the image is 1350 ha; by white frame a sub-area large 1060 ha is put in evidence.

Plate 2 Colour coded image of three NDVI images; NDVI of April 1986 was coded with red colour, NDVI of January 1985 with green colour, NDVI of November 1984 with blue; sub-area of LANDSAT-TM 170/70, II quadrant.

Plate 3 Colour coded (band 4/5/3) of part of TM-image where a sub-area large 1060 ha, is framed in white; LANDSAT-TM, 170/70, II quadrant, 16 January 1985.

Plate 4 a: 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;
b: Colour coded (bands 7-5-4) MSS-image of a sub-area in Kabwe urban district, Central province, Zambia, for coding see Plate 4a; 31 August 1984, LANDSAT-MSS data;
c: Colour coded (bands 7-5-4) MSS-image of a sub-area in Petauke district, Eastern province, Zambia, for coding see Plate 4a; 25 August 1984, LANDSAT-MSS data;
d: Colour coded (bands 7-5-4) MSS-image of a sub-area in Mazabuka district, Central province, Zambia, for coding see Plate 4a; 9 September 1984, LANDSAT-MSS data.

Plate 5 Colour composite (bands 4, 5, 3) Landsat-Thematic Mapper 170/70, quadrant II, 16 January 1985, geometrical corrected, pixels resampled to 142.5 x 142.5 m. By white frame five areas respectively A, B, C, D and E are shown, which detailed description is given in the text.

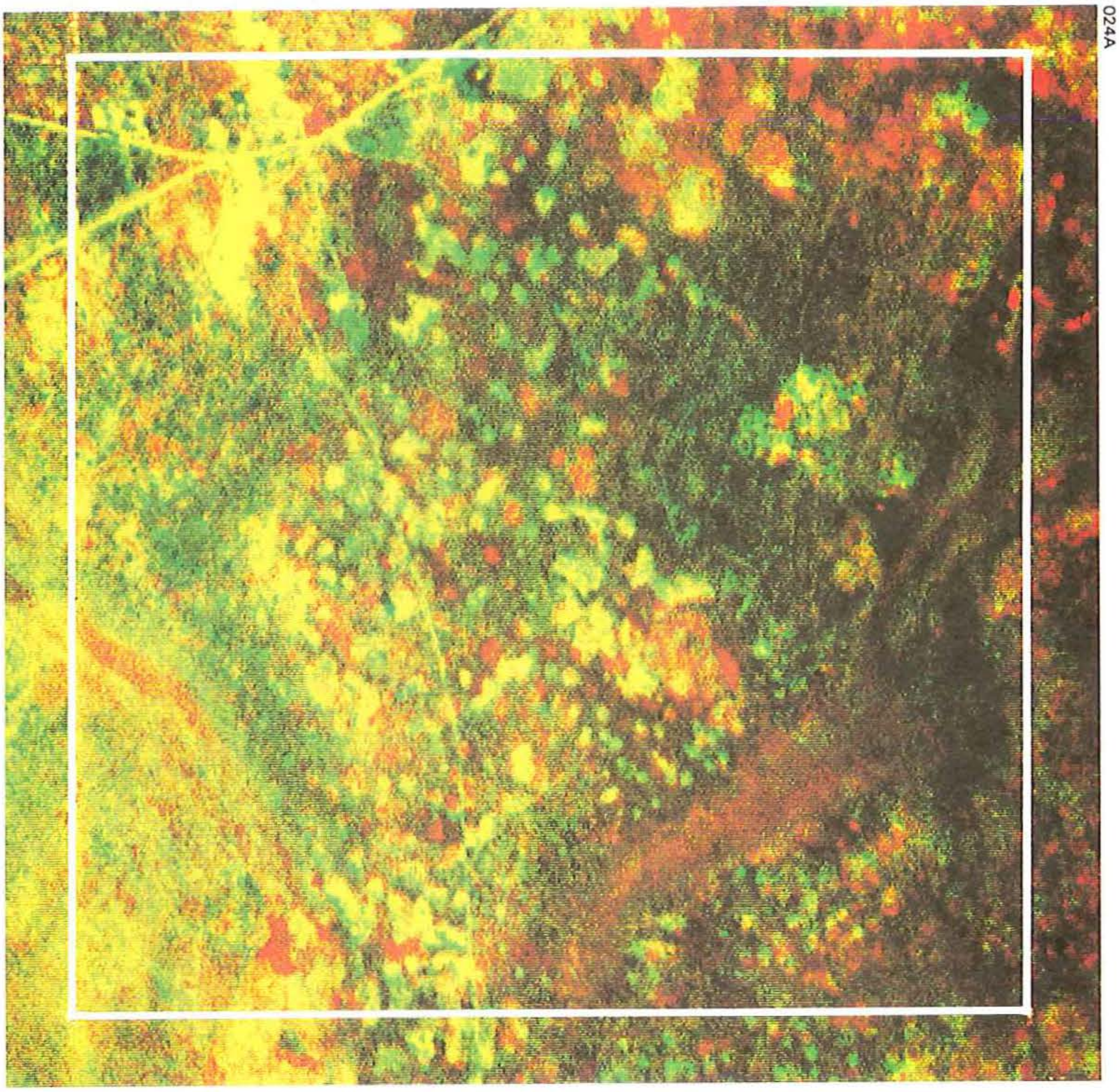

Plate 1

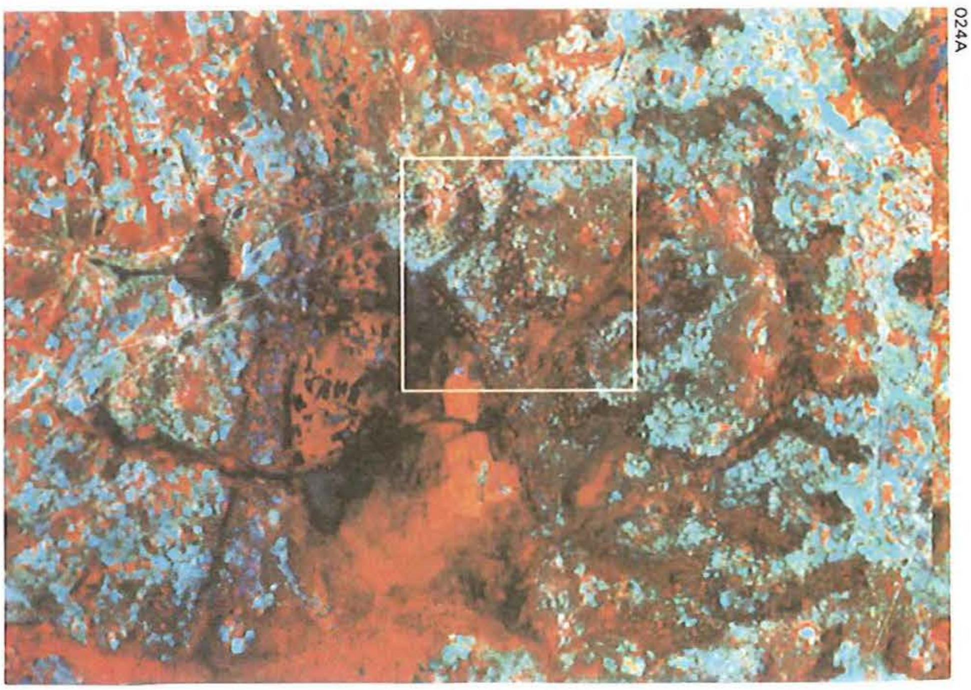

Plate 3

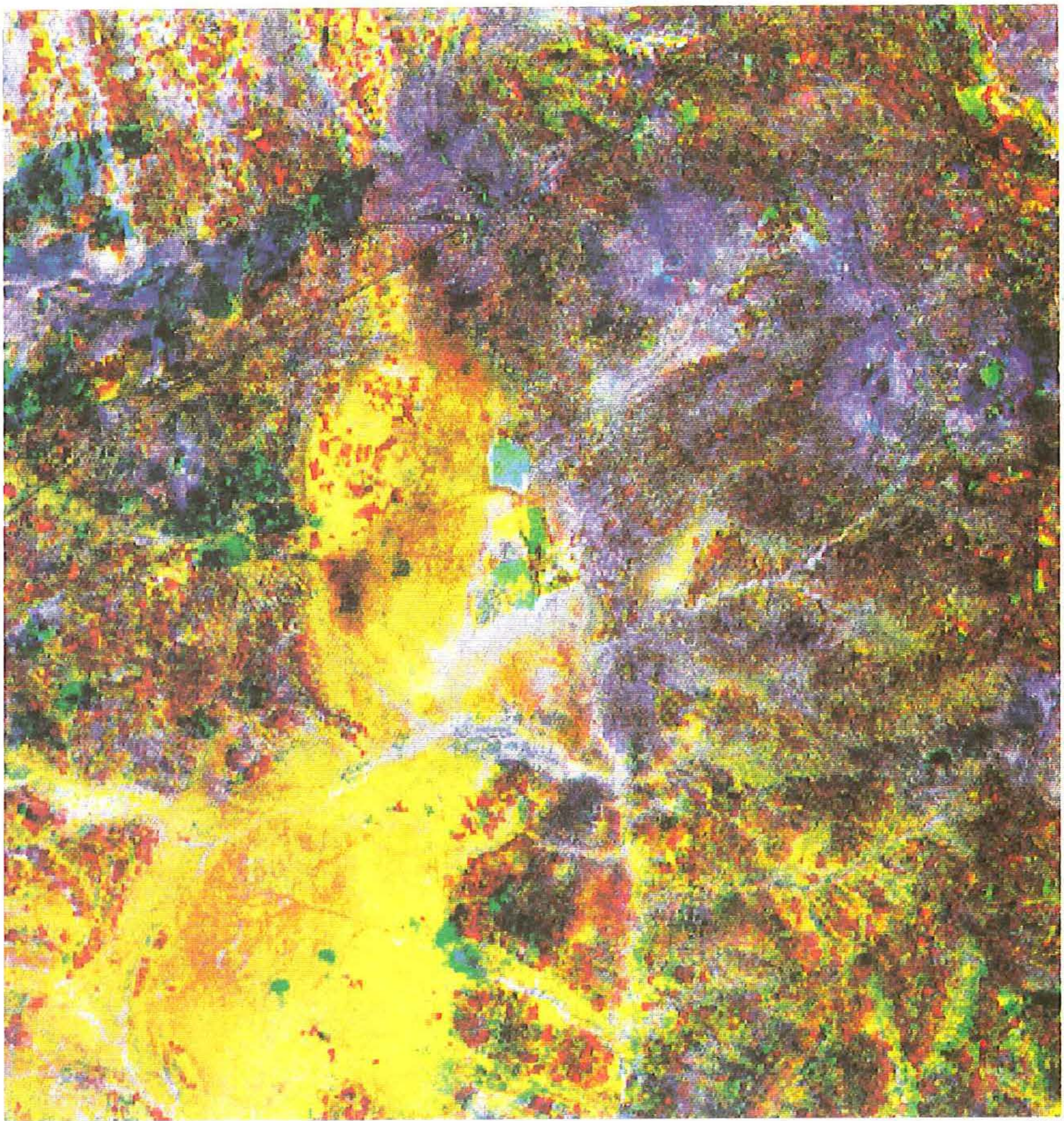
Plate 2

024A

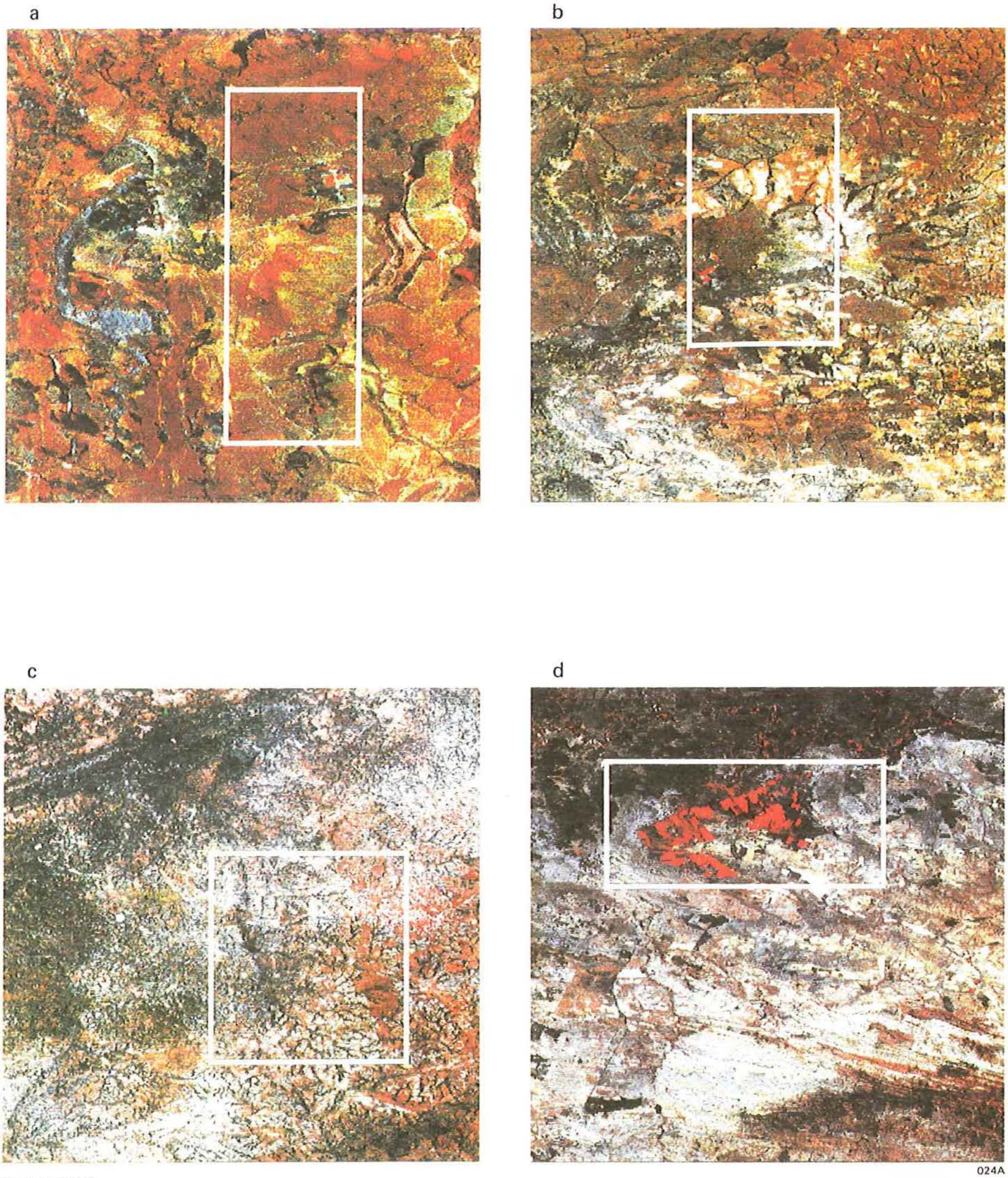

Plate 4 a,b,c,d

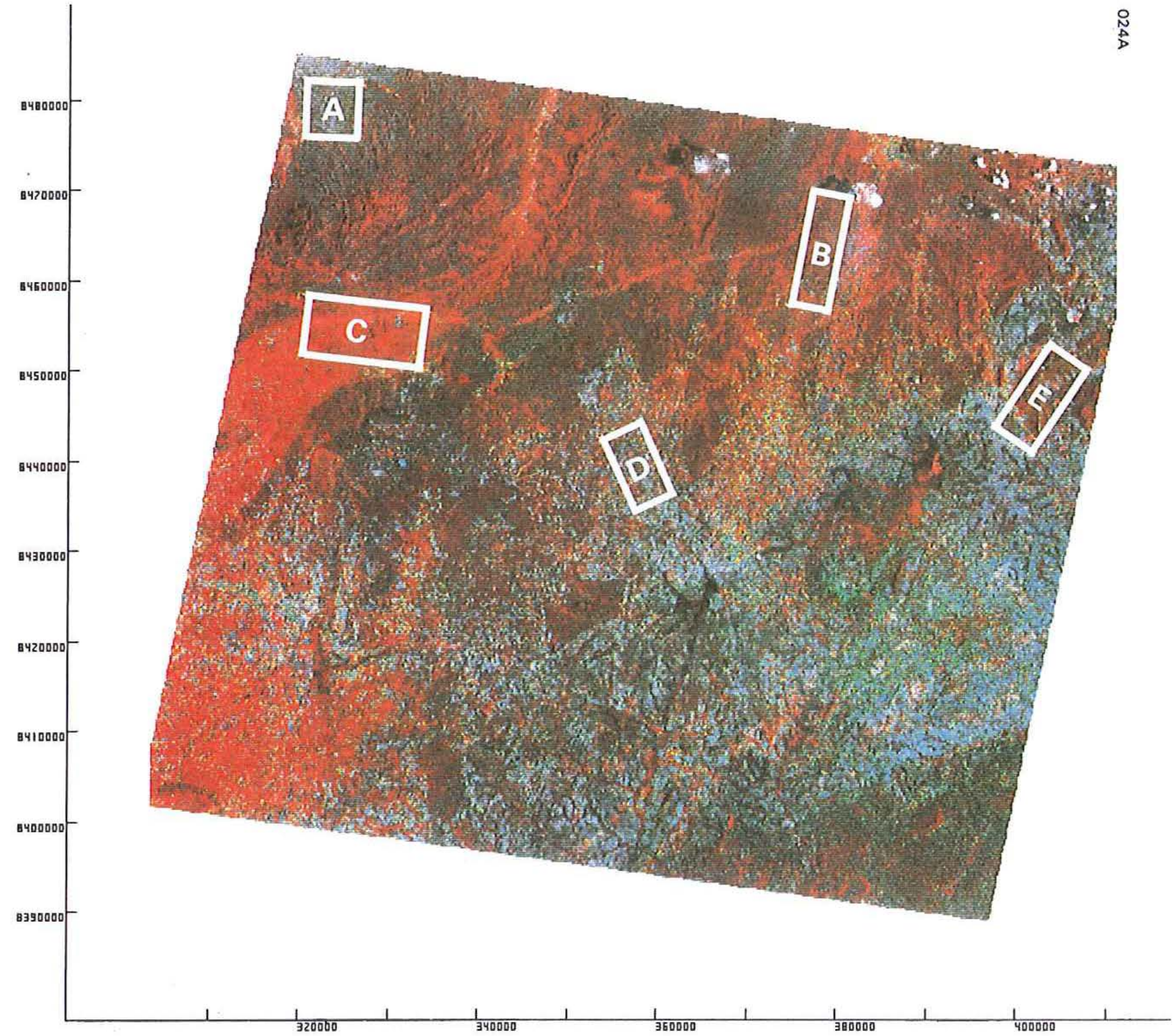
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Plate 5