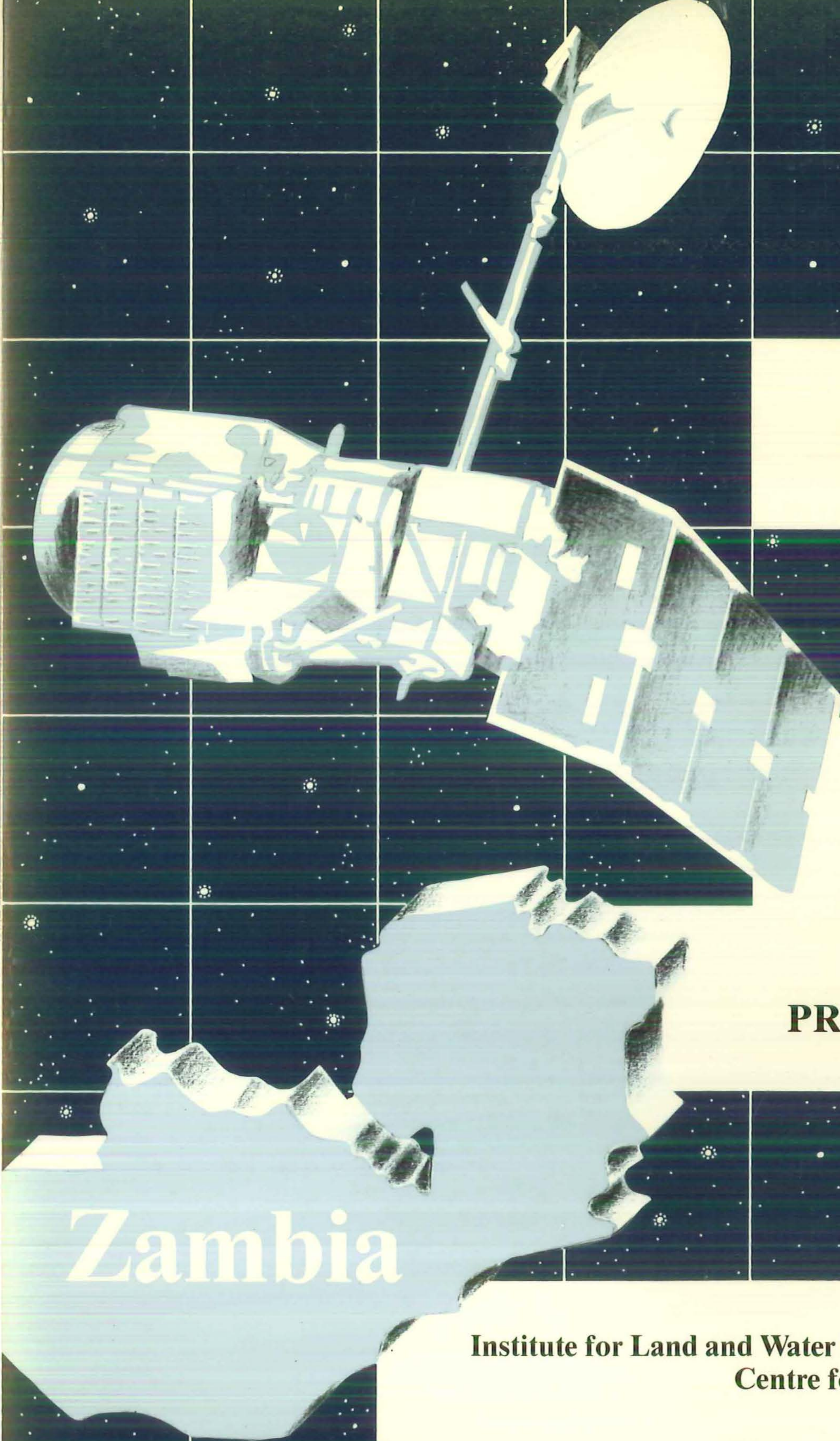

MARS

Monitoring Agro-ecological Resources with Remote sensing & Simulation

MARS DEFINITION STUDY RESULTS OF THE PREPARATORY PHASE

MAIN REPORT

Institute for Land and Water Management Research (ICW)
Centre for World Food Studies (SOW)
Amsterdam - Wageningen

MARS DEFINITION STUDY

Results of the preparatory phase

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MARS DEFINITION STUDY

Results of the preparatory phase

Main report

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PREFACE

Sub-Sahara Africa has been famine stricken for the past 15 years, due to drought, pests, and political instability. And while agricultural production stagnated, the population growth rate of this sub-continent remained among the highest in the world, resulting in declining per capita food production and food availability.

In order to remedy this situation and thus to increase food security, it is necessary to develop appropriate measures and policies. Analytical tools facilitate and support the development of such measures and policies. To use such tools appropriately, i.e. national policy models for food and agriculture, a flow of timely, accurate, and reliable information must be generated as an input to such models. It is in this respect that the primary task of a national early warning system for food security is to build such a data base. The MARS project has been initiated to contribute to this effort.

The primary objective of the MARS project is to establish a link between the data provided by meteorological satellites and the operational requirements of crop yield forecasting and monitoring at the national level. The linkages to be provided by MARS, further explained in Chapter 1, involve the use of remote sensing technology through METEOSAT, Landsat-TM or SPOT, crop growth simulation models, and weather, soil, and crop information.

The present report describes the activities of the MARS Preparatory Phase and Development Study (MARS-PPDS). The MARS-PPDS has been initiated, because it was felt by the funding agency that not sufficient information was available to take a well-founded decision.

In particular, the Netherlands Remote Sensing Board (BCRS) requested that:

- a formal cooperative agreement be established between the executing agency (SOW) and the Zambia Early Warning Unit to further develop the proposed MARS system as a support to the Crop Forecasting and Early Warning System;
- an agreement be established with the Food and Agricultural Organization of the United Nations (FAO) on further collaboration with regard to the FAO Early Warning efforts concerning SAPRO-ARTEMIS (see Chapter 1 and 5);
- that collaboration be sought with related institutes and projects in the region or elsewhere;

- an inventory be made of necessary and available data and that an effort be made to acquire such data, and finally
- an assessment be made of the application potential of MARS in a 'real world' situation; i.e. the Zambia Early Warning System. To this effect a set of research proposals have been made for execution by Netherlands based research institutes that have acquired, or are in the process of acquiring, expertise and know-how in the field of remote sensing (see also SOW-ICW, 1987).

MARS-PPDS has been financed to last 6 months starting January 1, 1987. Although most of the scheduled activities were completed on time, one key activity, namely the receipt of FAO-meteorological information, to be received by the University of Reading on magnetic tapes, was seriously delayed and caused in turn queuing problems. Reason why the present report has been delayed.

In successfully completing the present phase of MARS, we owe sincere thanks to the BCRS for having made this study possible and in particular to Dr.Ir. N.J.J. Bunnik, who has supported the MARS project with great enthousiasm and who skillfully solved and accommodated unforeseen problems.

Thanks are also due to the FAO, who agreed to share Southern African meteorological information and whose staff enthousiastically supports the MARS project activities.

Also with gratitude, mention should be made of the many preliminary and informative discussions that have been held with representatives of Meteo consult (C. Jacobs), DHV (A. van Dijk and J.B. van den Brink), NLR (H.A. van Ingen Schenau and F. van der Laan), and IAC (L.J. van Veen). Last but not least the MARS project team want to express appreciation to their SOW and ICW colleagues for their help; in particular J. van de Zande, J. Wolf, C.A. van Diepen and C. van Immerzeel.

Special mention deserve B. ten Cate (ICW) and R. Greve (ICW) who, so diligently and unrelentingly, have prepared the lay out and the typing of the report, as well as Messrs Jansen, Arnoldussen, van Ledden, Rietveld, Ariese and van Son for preparing the drawings and the photographs of the report.

er in Zambia?

CONTENTS

ABSTRACT

The main objectives of MARS-PPDS with regard to a possible application in Zambia were the definition of the proposed MARS information systems, the assessment of the proposed crop monitoring procedures and the availability of required agronomical data. The results of the assessment of the feasibility of the proposed MARS procedures can be summarized as follows.

(i) The crop growth simulation model proved to be suitable to analyze the agricultural production of a high yielding variety of maize in Zambia. The main differences in production over the country can be related to differences in the natural agro-ecological conditions on the one hand and in types of farming system on the other hand. The ratio between the yearly and the average water constrained production potential can serve as indicator for the yearly fluctuations in production due to temporary shortage or excess of water. The agronomical data required to calibrate the proposed system with the other major crop types and varieties appears to be available at the research stations in Zambia. Available at reasonable scales are the information sources describing the spatial distribution of the relevant agro-ecological variables and the land use in Zambia. The assessment of these sources indicates a reasonable to good accuracy. These data sources appear to be suitable for use in the proposed MARS-AEGIS overlay procedures.

(ii) The MARS procedure requires a proper assessment of the start of the growing season. The analysis of the available NOAA-NDVI data sets shows that - at least - the NDVI maps produced by the forthcoming ARTEMIS system can be applied to assess spatially the start of the growing season of the natural vegetation.

(iii) The assessment of the Reading rainfall estimation method indicates that in the cases of Zambia the method might be applicable. However, it will cost extra efforts to validate and calibrate the method.

(iv) The results of the assessment of the (digital) crop and land use identification procedure indicate the possibility of multi-temporal analysis of LANDSAT-TM images, acquired during the growing season.

Compared with the accuracy of the CFEWU crop monitoring results (in hectarages), the results of the MARS-PPDS exercises appear sufficient to good.

(v) The MARS system definition also required an assessment of the digital matching of maps with satellite images. The results derived with a low budget geographical information system with digital image processing possibilities (i.e. ERDAS, running on an IBM-AT) are considered to be very positive. The possible choice of an ERDAS system as the main hard- and software pivot of MARS-AEGIS appears to be quite reasonable.

The main conclusion of the assessment and system definition of MARS can be summarized as follows: the proposed MARS system is feasible in Zambia, although further calibration and validation activities are required.

1. INTRODUCTION

The concept of 'food security' in the broadest sense can be defined as an integrated plan to provide for sufficient food for the whole population in both the short and the long run, and to ensure that equal attention is paid to sustainable domestic production, consumption, processing, distribution and food reserves.

The food security concept thus provides a concise and consistent framework of the food and agricultural sector with sufficient concern for environmental degradation, the consumption pattern and the nutritional status of the public at large. For the governments to be able to take well-founded decisions with respect to food security issues, it must be provided with relevant information on which to base its decisions.

In the short run, food security can only be achieved if an adequately functioning Early Warning System is in place, especially in drought prone areas. Because actual crop production can only be estimated at the end of the harvest, governments should know well in advance the expected supply of food grains and other crops, in order to take remedial and timely measures.

Under the denomination 'Early Warning' rather different activities are grouped together, which share a conceptually similar approach towards operational, real time, crop yield forecasting. For example data on land-use, crop yield, marketable product are collected along with meteorological observations. With these data, forecasts on crop yield are obtained for well-defined administrative regions.

Although the development of such a system is rather complex, the basic factors for constructing it, namely the acquisition, processing, storing and analyzing data, the construction of a data base, etc. are of primary importance.

In the Early Warning practices, the acquisition of data appears to be one of the major bottlenecks. To meet the information requirements of these crop monitoring systems, the application of information systems using remote sensing are regarded to be available. However, the regular use of remotely sensed information, especially in regard to a tropical country as Zambia, requires an assessment of on the one hand the information sources itself and on the other the users.

The MARS project is an application-development project linking up newly available tools (e.g. Geographical Information System, Data Base Management System) and methodology (i.e. crop growth simulation model) with the routine functioning of a National Early Warning System. The MARS project will eventually deliver a tested, operational information system to match satellite information with the specific needs of the Zambian National Crop Forecasting and Early Warning System.

1.1. AN OVERVIEW OF FAO REMOTE SENSING AND EARLY WARNING ACTIVITIES IN AFRICA

The Early Warning activities of FAO can be classified at different levels (see also: FABER et al., 1987):

GLOBAL
- Global Information and Early Warning System (GIEWS) on food and agriculture
- Support Agricultural Production (SAPRO) which is based on real time data produced by the Africa Real Time Environment Monitoring using Imaging Satellites (ARTEMIS) project

REGIONAL
- Regional Early Warning System for Food in the SADCC countries
- Remote sensing component of the Early Warning Systems in Eastern and Southern Africa; SADCC and IGADD countries

NATIONAL
- Crop Forecasting and Early Warning System in Zambia
- Early Warning Unit in Tanzania
- National Early Warning Units in the other seven SADCC countries to be set up, etc.

This network may appear as a rather well structured system. A closer look at the details, however, reveals that the interlinking between these functional units is far from being satisfactory. In Fig. 1 the organization of this Early Warning Network, is presented by specifying for each functional unit:

- input data
- area covered
- geographical reference unit
- output data

From the information presented in Fig. 1 two conclusions may be drawn:

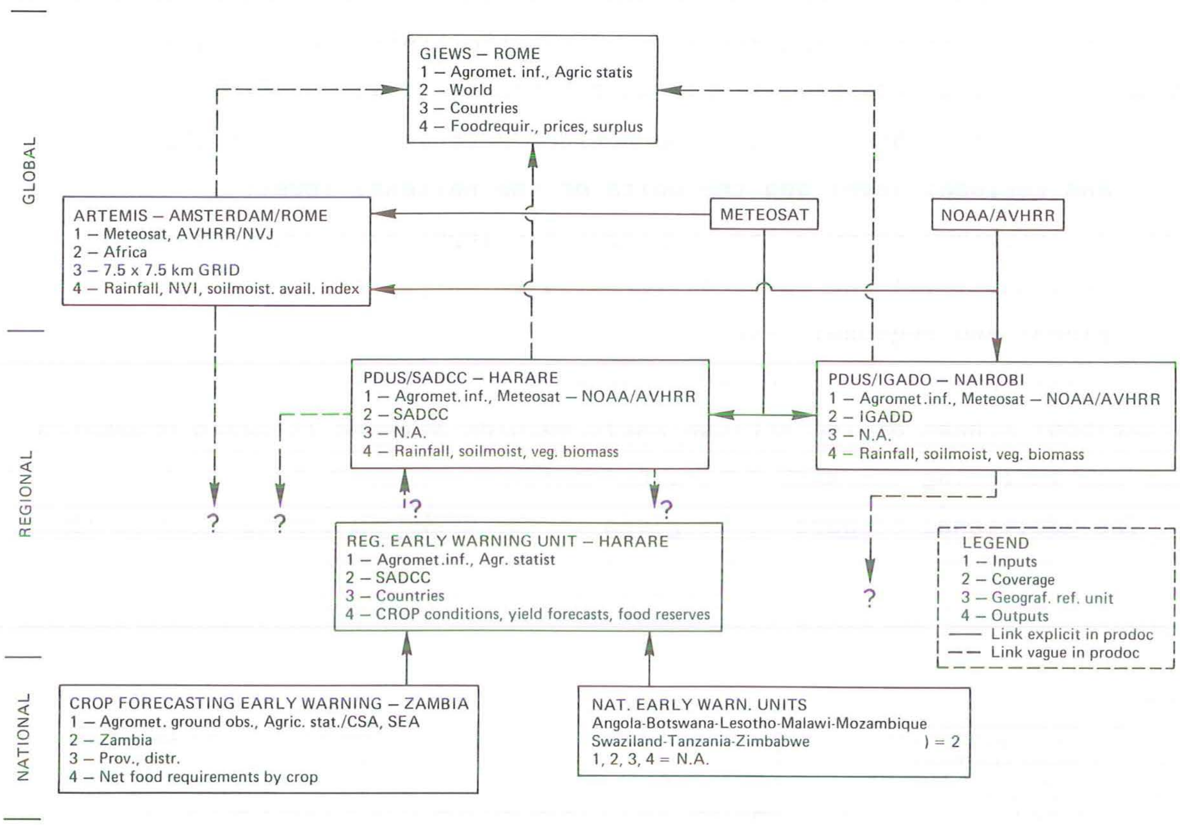


Fig. 1. Early warning network in Africa (present situation)

- the well-defined input data requirements of the Regional and National Early Warning Systems, especially as regards crop specific information, cannot be met by the output data of the remote sensing systems;
- no effort has been made to warrant the compatibility of the geographical reference units with the different functional units.

Given these conclusions, the operationalization of these systems and their application to the regional and national level is bound to fall short of the stated objectives, as the link between these levels is not provided.

The objectives of the proposed MARS project are to provide that link so as to obtain the maximum benefit possible by acquiring the relevant national level data.

1.2. THE PLACE OF MARS IN THE AFRICAN EARLY WARNING NETWORK

In Section 1.1 it has been emphasized that the African Early Warning Network, as it stands now, lacks two functional links:

(i) an interface between the geographical reference units at the global and regional level and the units of the national level;

(ii) an interface between the crop-specific input data required at the national level and the undifferentiated output data provided at the global and regional level.

The MARS÷project is intended to provide such links. In Fig. 2 the organizational scheme of the African Early Warning Network is again presented but now including the MARS functional unit.

The additional support to be given to the CFEWU in Zambia lies in the

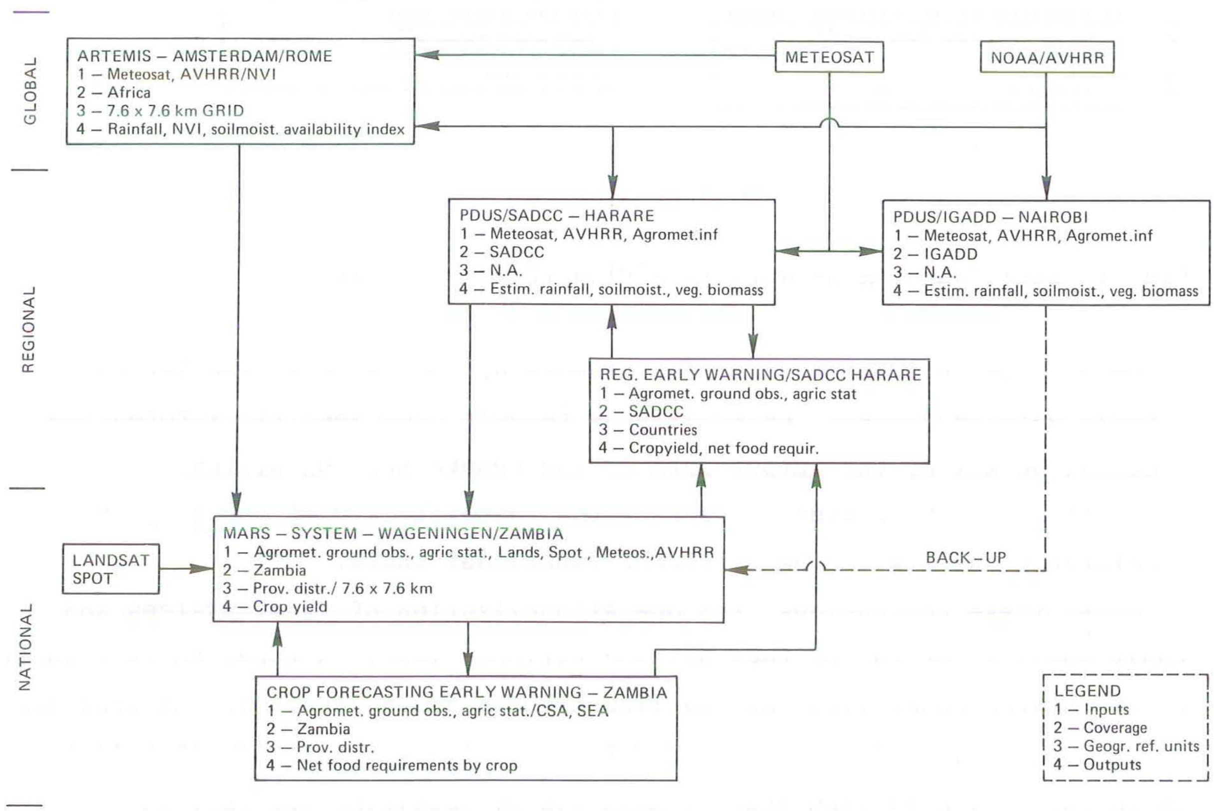


Fig. 2. Proposed Early Warning Network in Africa (based on MARS proposal)

integration of the present derived data sets provided by the participating departments of the CFEWU and the forthcoming remote sensing information sources (e.g. ARTEMIS).

The qualitative improvement provided for the regional and global levels lies in the production of MARS output data in a form compatible with the scale of these Early Warning activities and with the configuration of the systems generating the Early Warning information at the Regional and Global levels.

1.3. MARS WITHIN THE REGIONAL AND GLOBAL EARLY WARNING SYSTEMS

The proposed MARS methodology aims at the monitoring and the estimation of the yields of defined crops in defined agro-ecological zones. The methodology has been designed to be applied on a national scale, i.c. Zambia. However, the knowledge that will be acquired in the course of the MARS project, particularly during the implementation and operationalization phases, can be applied to:

- readjust, possibly redefine or calibrate the MARS methodology in order to implement the MARS-methodology in the Early Warning Units of other countries, such as the SADCC or IGADD-countries. The support of the Regional Early Warning System in both regions could be very valuable in this respect;
- training of staff of other Early Warning Units in the region in subjects such as:
  a. the application of the Early Warning methodology using e.g. the real time meteorological information derived from the SAPRO-ARTEMIS system of FAO in Rome or the future regional PDUS-stations, located in Harare and Nairobi;
  b. the application of simulation models with the purpose to monitor the actual agriculture production, to forecast the yields and - as an additional option - to analyse possibilities for agricultural development;
  c. the use of high resolution remote sensing images to identify the landuse pattern and possibly the cultivated area of specified crops;
- advise the national Early Warning Units in the design of the layout and structure of the digital data transfer facilities within the framework of the REWS in the SADCC and IGADD countries, and between the individual Early Warning Units and FAO Headquarters in Rome;

- analyse the defined products of the SAPRO-ARTEMIS system and advise the future PDUS stations of the SADCC (Harare) and IGADD (Nairobi) and possibly the FAO Remote Sensing Center in Rome to define (or possibly redefine) the output products of the stations.

1.4. THE CROP FORECASTING AND EARLY WARNING UNIT (CFEWU) IN ZAMBIA

Zambia's agricultural production, and in particular its food grain production, mainly maize, has fluctuated considerably over the past period, to a large extent due to adverse weather conditions during the growing season. For a rapidly growing population and a stagnating development of agriculture have caused Zambia to become a net importer of food grains. In order to strengthen the country's food security situation, a project has been developed to build a comprehensive Crop Forecasting and Early Warning System. Within this system various Ministries and Departments would work closely together to monitor the food situation in the country.

Within the framework of its agreement with the Government of the Kingdom of Netherlands and upon request from the Government of the Republic of Zambia, the FAO has supplied assistance for the execution of the aforementioned project titled 'Crop Forecasting and Early Warning System' (GCP/ZAM/019/NET) through funds-in-trust. This project started in June 1982 and has terminated in June 1987. This project will continue into a second phase called 'Early Warning System and Census of Agriculture' (GCP/ZAM/039/NET). The second phase is also funded by the Netherlands and executed by FAO and will last for 5 years.

The objective of the CFEWU project is to strengthen national food security through the institutionalization and development of a data and information base related to agricultural development in general, and food production, supply, and distribution in particular.

The data being gathered by the CFEWU are processed and analyzed for the monitoring of the national food situation and are also made available to the REWU in Harare for regional assessment and monitoring activities if and when requested.

The CFEWU is a unit composed of staff of the following departments:

- Planning Division (MAWD)
- Central Statistical Office (CSO)
- Department of Meteorology

The activity of the CFEWU is supported by expatriate experts, in the framework of the FAO projects GCP/ZAM/019/NET and GCP/ZAM/039/NET. In addition the CSO receives support (equipment and technical assistance) through an USAID project.

Up to date, the CFEWU has emphasized training of local staff and the development of data gathering, processing and analyses techniques. Close collaboration within the CFEWU between the various staff has, therefore, not yet been accomplished. The integration of the staff and the methods used within the CFEWU will be a first priority of the second phase of the CFEWU project (GCP/ZAM/039/NET). Each one of the three departments has developed an own method and technique in obtaining crop production forecasts. The final official estimates are set as a result of meetings held by the National Committee on Early Warning (NCEW) when the three independent estimates are compared and discussed.

It goes without saying that eventually one sound scientifically based statistical method must be used for the Crop Forecasting activities.

The early warning related activities of the three Departments can be summarized as follows:

- Planning Division (MAWD)

  Cropped area, crop conditions and yields are estimated by agricultural extension officers; there is one such officer for each Camp (comprising one or more villages). A cluster of Camps, about 2-6, are aggregated into a block. Activities within a block are supported by a Block Supervisor. The Block Supervisors transmit their data to the District Agricultural Officer (DAO), who in turn sends the aggregated figures to the Provincial Agricultural Officer (PAO). The provincial figures are reviewed during provincial meetings with the participation of a statistical officer of MAWD, Lusaka.

  The basic data are collected by extension officers. These estimates apply to poorly defined geographical units, as the boundaries of villages are variable and difficult to identify and, therefore, difficult to replicate.

- Central Statistical Office (CSO)

  Data on cropped areas, yield and marketable surplus are collected by means of direct interviews with farmers at three different periods: two in the growing season, one in the post-harvest period. Data are collected on a sample basis by complete enumeration within the selected Standard Enumeration Area (SEA). A number of SEA's are aggregated into a Census Supervisory Area (CSA). Typically 20% of CSA's are selected, with one SEA for each CSA. The boundaries of CSA's and SEA's correspond to physical

features and have been mapped at 1:250,000 (CSA) and 1:50,000 (SEA) for the entire country.
Data are extrapolated to District and CSA level by applying so-called boosting factors, obtained as the ratio of the number of households in a District or CSA, respectively to the number in a SEA. Yield figures per unit area are obtained by the ratio of estimated production to area (bags/ha).

- Department of Meteorology
  Meteorological data (a.o. rainfall, temperature, sunshine) are collected in a quasi-real time mode from some 30 stations in Zambia. Some 160 rainfall stations transmit 10 day - total rainfall figures and, in principle, also phenological observations by mail. Upon examinination of the data of the 1984-85 and the 1985-86 growing seasons, it appeared that only a small fraction of stations transmit satisfactory phenological reports. Indicative crop yield reductions are estimated by calculating the Frère-Popov water requirements satisfaction index (WRSI).
  Although the density of stations is considered to be insufficient, the data collection is thought to be sufficiently reliable.

The integration

Nationwide forecast of crop production and marketable surplus are obtained twice a year (February and April) by selecting the most reasonable figures out of the three sets submitted to the NCEW (MAWD, CSO, Meteorology). Such a method can lead to serious misjudgement, as exemplified by the outcome of the 1985-86 agricultural season. The final 1985-86 forecast for maize was 8.5 million bags of marketable produce against a requirement of 10 million bags. The expected shortfall of 1.5 million bags had to be imported. The actual post-harvest figure for the marketable produce was later determined to be 12 million bags. The resulting surplus of 3.5 million bags provided to be serious challenge to the maize storage capacity in Zambia.

The National Preparedness Plan to cope with Food Emergencies

For many years, Zambia enjoyed self-sufficiency in its basic food crop, maize and was able, on occasion, to export its surpluses. However, rapid population growth coupled with adverse agricultural production conditions, have resulted in a declining per capita production and the country becoming a net importer of maize.

With the introduction of the CFEWU in MAWD, significant improvements have been made in quantifying the extent of production shortfalls. To enable a more timely and more reliable warning to be given of such possibilities arising, there is a need to improve the monitoring of the food situation in the country.

The National Preparedness Plan (NPP) provides for the continuous monitoring of the food availability throughout the country by strengthening the CFEWU through the publication of a Monthly Crop and Food Situation Report.

The most important aspect of the NPP is that the responsibilities and lines of communication are clearly established for all individual functions in the Departments involved in the Government's food security policy for identifying and coping with food/input emergencies/shortages at national, provincial and district level.

The NPP does not replace existing procedures for meeting normal food needs of the population, but rather complements them by providing advance warning of impending shortages. The NPP thus forms an integral part of the Government's food security policy.

1.5. THE ROLE OF MARS IN THE CROP FORECASTING AND EARLY WARNING UNITS IN ZAMBIA

The objective of the Zambian Crop Forecasting and Early Warning Unit is to provide timely and accurate information on expected crop production and food supply. As described in Section 3.4 the method to acquire the necessary information is based on the procedures developed by the individual Institutions officially involved with the CFEWU.

The currently applied procedure of the CFEWU requires merging of the information generated by the Planning Division (MAWD), Central Statistical Office (CSO), and the Meteorological Department. Because of different statistical methods and survey approaches applied, problems may occur with respect to:

- the estimation of the hectarage of crops grown in Zambia, and
- the estimation of the actual crop yield per ha, especially with reference to the crop yield reduction due to unfavourable weather conditions.

The procedures proposed by the MARS project will support and ultimately improve the currently applied procedure, with respect to:

- the estimation of the actual hectarage of the total cultivable area and the total planted areas under specific crops, making use of high resolution Remote Sensing images, and

- the assessment of yields of the important crops in the distinguished agro-ecological zones in Zambia.

Also, with respect to the coarse layout of the reporting agro-meteorological observation stations, the difficulties will partly be solved with the introduction of the low resolution Remote Sensing procedures and the implementation of a crop specific simulation model. The low resolution remote sensing procedures aim at the rainfall estimation, the start of the growing season and other phenological phenomena. The simulation model will take in account the actual weather conditions, the physiological and soil characteristics and the farming practices in Zambia.

In addition to the proposed enhancement of the monitoring practices as applied by the CFEWU in Zambia, the computerization of the system will facilitate the storage of the required thematic information (e.g. soils and physiography), and all the data required on a real-time basis. In the long run, this stored information will provide a sound planning base for agricultural development and environmental management in Zambia.

2. AN OVERVIEW OF EARLY WARNING ACTIVITIES IN AGRICULTURE

During the past two decades much effort has been spent on developing methods to apply agrometeorological data, and satellite data to assess crop conditions within extensive regions. Sometimes the two classes of techniques have been applied jointly. In this chapter an overview will be presented of a number of case-studies.

The case-studies have been classified as either operational services or research/feasibility studies. The reason for this distinction is that the term 'operational' in this report means that the method is actually applied to the decision-making process, such as concerning food imports or food aid.

2.1. OPERATIONAL SERVICES

Under the restrictive definition of an operational activity as given above, no description of operational applications of satellite data to early crop yield assessment could be found in the literature. Basically all the case-studies which could be assigned to this category are based on the agro-meteorological approach to crop yield assessment, as described by FAO (1986). In Table 1 an overview is presented of these case-studies. The approach is summarized below.

A crop yield assessment method based on agro-meteorological information (FAO, 1986) was developed by FAO in 1976 (FRERE and POPOV, 1979). The method was originally designed for monitoring rainfed annual crops. At present, two different forms of the method exist: one version designed for annual crops with the exception of rainfed lowland rice and the other version exclusively for rainfed lowland rice. The method consists of the simultaneous use of climatological and agronomic information in order to assess the water consumption of the crop.

This method has the following advantages:

- it needs a minimum amount of actual data;
- it uses climatological informations which may be assembled before the 'operational' phase;

- it assesses crop conditions by successive 10 day or weekly steps during the crop season.

The FAO-method of Crop Forecasting based on agro-meteorological information applies the following model variables:

PET = Potential evapotranspiration
Kr = Crop coefficient (DOORENBOS et al., 1979)
Wr = Water required (DOORENBOS et al., 1979)
PA-WR = Available water (DOORENBOS et al., 1979)
RS = Soil moisture (DOORENBOS et al., 1979)
S or D = Excess or deficit soil moisture (DOORENBOS et al., 1979)
WRSI = Water requirements satisfaction index

The method requires the following data:

PN = Normal rainfall
PA = Actual rainfall
DA = Number of rainy days
T = Temperature sum of growing season

A short description of a few case studies as given in Table 1 is presented below.

Sahelian countries

The crop yield forecasting method (FAO, 1986) has been applied since 1976.

Senegal

The crop yield forecasting method (FAO, 1986) is being applied using a 32 year timeseries of the following variables:

- daily rainfall
- sowing dates for groundnuts
- harvesting dates for groundnuts and
- groundnut yield

Based on literature the following remarks can be made:

- no correlation was found between seasonal rainfall data and final yield for groundnuts;
- the distribution of rain over the season is more important than total precipitation;
- groundnut minimum yields (about 700 kg/ha) occur in both the driest years (400 mm/year) and the wettest (1200-1300 mm/year). In fact, if the period after fecundation is very wet, a serious loss of groundnuts may result from rotting;

Table 1. Examples of operational early crop yield assessments

Country	Type of agro-meteorological model	Satellite application	Duration	Remarks	Source
Cape Verde	FAO, 1979	-	1980-1986	the application of the method in regular use in the forewritten countries is in the first phase of the AGRYMET programme and FAO is doing the monitoring of crop yield assessment. The method is still through a calibration phase	FAO, 1986
Senegal	FAO, 1979	-	1980-1986		
Mauritania	FAO, 1979	-	1980-1986		
Mali	FAO, 1979	-	1980-1986		
Gambia	FAO, 1979	-	1980-1986		
Burkina Faso	FAO, 1979	-	1980-1986		
Niger	FAO, 1979	-	1980-1986		
Chad	FAO, 1979	-	1980-1986		
Tanzania	FAO, 1979		1980-1986	see remarks for Sahel countries	FAO, 1986
Zambia	FAO, 1979		1981-1986	see remarks for Sahel countries	FAO, 1986
Botswana	FAO, 1979		1978-1979 1982-1983	Calibration of relation between yield and I (veg. index for sorghum and maize)	FAO, 1986
Bangladesh	FAO, 1979*	-	1978	time rainfall distribution data is more important than the total amount of rainfall crop: rice Max index value = 80	FAO, 1986
Turkey	FAO, 1979	-	not specified	crop: winter wheat Max yield = 40 q/ha index = 100	FAO, 1986
Central Italy	FAO, 1979	-	1977-1979 / 1982-1983	winter wheat intercropped with vineyard and olive trees	FAO, 1986

*for rainfed rice field

- a good correlation between WRSI and yield was found;
- variations in above average yields corresponding to a WRSI equal to 100 agree with the effect of inputs as fertilizers, weeding and so on;
- yields of 0 kg/ha agree with a WRSI = 50%, which is in agreement with similar findings in Tanzania and Botswana.

Bangladesh

The crop yield forecasting method (FAO, 1986) was applied to rainfed lowland rice. In such tropical wet climate there is no drought damage. The irregularities of the monsoon season (between July and November), however, can affect crop growth. From available reports, it has been found that:

- rainfall amounts over the growing season are excessive; dry spells of two or more decades may occur, however, resulting in damage to crops;
- water availability for a crop was calculated to be equal to the sum of:
  . water available between wilting point and field capacity
  . water necessary to flood the field
  . water standing on the field;
- the rainfall distribution is more important than the total amount of rainfall. A dry spell of more than a week may reduce the yield.

Turkey

The crop yield forecasting method (FAO, 1986) was applied to winter wheat. The critical physiological stages of winter wheat in relation to an optimum yield have been found to be:

- the interval between sowing and the beginning of dormancy (end November), when plants reach the 2-3 leaves stage. In this stage sufficient water must be available;
- the beginning of growth after winter dormancy. During this stage, water should be plentiful. Winter wheat maturity was obtained at the end of June, having a WRSI-value of 80.

It should be noted however, that even if water is available for the plant at the end of winter, in many years it is not enough to satisfy the water requirement in spring for winter wheat. Also the importance of close agro-meteorological monitoring to accurately assess future yields has been underscored.

Central Italy

The crop yield forecasting method (FAO, 1986) was applied to winter wheat which was cultivated in association with vineyard and olive trees. Depending on the length of the rainy season and on total rain, the obtained WRSI for wheat may fluctuate between the values 83 and 100. The estimated wheat yield of 4000 kg/ha represents for that region an optimum yield.

Botswana

The crop yield forecasting method (FAO, 1986) was applied between 1978/79 and 1982/83. A mathematical relation has been established between WRSI and yields of sorghum in different provinces:

$$Y = 0.05(I - 48)^{1.925}$$

where I = WRSI (index)
Y = yield in %

Such a formula demonstrates that there does not exist a linear relationship between I and Y.

Note however that the value of I stayed mostly under 100, Botswana being a rather dry country (±500 mm/year). The same method was also applied to maize, for which encouraging results have been obtained.

Zambia

The crop yield forecasting method (FAO, 1986) is being applied on a national level starting from 1982 within the framework of the Zambian Early Warning System. The FAO Early Warning Project aims at strengthening the Zambian Early Warning System by:

- strengthening the agricultural statistical service;
- reliable statistical sampling;
- collection of agricultural statistics in a short period of time.

The main crops were considered: maize, sorghum, millet and groundnuts. During 1982/83, meteorological data, coming from 20-30 stations, were taken into account in the crop yield forecasting model. In 1983-84, however, 160 meteostations were involved in data acquisition. The results of the first 4 years show large fluctuations of WRSI. With respect to the applied methodology it may be concluded that:

- in the Southern Province reduction of yields is mainly caused by water stress, and
- large fluctuations of yields in 4 years of observation have been observed.

Tanzania

The crop yield forecasting method (FAO, 1986) was applied from 1980 till 1985. Eleven different agro-climatic zones have been distinguished. The description of the National Early Warning System consists of the following three subdivisions: inputs, data analysis and processing, and outputs.

Inputs

Weekly reports were given by the Rainfall and Crop Reporters (RCR), covering:

- rainfall data which were collected at 121 stations in 1980, and at 400 stations in 1984/85;
- six different crops have been analyzed: maize, sorghum, paddy rice, bulrush millet, beans, and cassava, respectively. For each crop, data concerning crop phenology, qualitative production estimation relative to previous years, and crop prices have been collected.

Monthly reports were prepared by the District Agricultural Development Officers (DADO). Such reports cover all the districts and include cropped areas, varieties grown, cycle length and yield estimations.

Data analysis

Data are analyzed by means of the following software packages:

- RAINS, which consists of 15 programs used to input, output (print, map), and manage a data base including the rainfall data together with station identification, RCRs names and addresses, etc.;
- CROP, which performs the same operations as RAINS with crop data from weekly reports;
- AGRO, which estimates crop yields using a variant of FAO Crop Specific Soil Water Balance (CSSWB) approach;
- LONGTERM, which is an analysis of long-term climatic data in order to compare with the climatic data of the current season.

The final output of these methods is the average crop yield by district given by the following equations:

$$Y_{maize} = 0.000631\ Z + 0.0225\ I_W - 1.66$$

$$Y_{sorghum} = 0.000405\ Z + 0.0246\ I_W - 1.83$$

$$Y_{wheat} = 0.000108\ Z + 0.040\ I_W - 3.97$$

$$Y_{beans} = 0.0211\ I_W - 1.14$$

where: Y = yield in metric tons/hectare

Z = average district elevation in m

I_W = weighted average index by district derived from the CSSWB

Calibration of the equations with the local data was essential.

Outputs

Several publications were issued during this project, four of which were concerned with agro-meteorological information: i.c.:

- Farming Weather Bulletin
- Consolidated Assessment of the National Staple Food Situation
- Interim Production Estimates
- National Staple Food Supply Projections (FSP).

An attempt to forecast crop yields was also made by the LACIE-project on crop monitoring by means of LANDSAT-MSS satellite images (KING, 1984). However, the infrequent satellite coverage, the small size of the fields and intercropping technique hampered the satisfactory application of LANDSAT images.

2.2. RESEARCH AND FEASIBILITY STUDIES

Many case-studies dealing with applications of satellite data to monitoring and/or assessment of vegetation conditions have been presented in literature. In Table 2 a summary is given for a number of studies. As in the previous section some details will be added for a few of them.

Sahelian countries

Monitoring biomass in relation with detection of locust breeding sites has been done by means of NOAA-AVHRR NDVI (TUCKER et al., 1985a,b) from 1980 till 1984. Such a type of data allows the monitoring of an area of 16 million km^2 at a reasonable cost. It monitors the increase or decrease of vegetation and from biomass detection an attempt of breeding area of locusts can be assessed. Ground truth observations, LANDSAT-MSS and NOAA-AVHRR data, aircraft observations were used simultaneously in the test areas. A strong correlation between the integrated NOAA-7 satellite data and actual dry biomass was found for ground samples collected over a 3-year period. Such a correlation suggests the possibility to monitor Sahelian

Table 2. Case-studies dealing with early assessment of crop conditions

Country	Type of agro-climatological model	Satellite data	Duration	Remarks	Source
China	-	NOAA NDVI	1982-1983	NDVI calculated for 9 major agricultural regions	Justice et al., 1985
China	-	NOAA NDVI GAC LANDSAT-MSS aerial photographs	1986	assess biomass changes	S.A. Morain, 1986
Botswana	-	NOAA-AVHRR GAC pixel (NDVI)	1983-1984	LANDSAT-MSS images were acquired for ground sampling identification. Regression from NDVI calculated both with MSS and AVHRR data was applied	S.D. Prince, 1986
Sahel-Sudan-Ethiopia	FAO, 1979	NOAA-AVHRR NDVI GAC and LAC data SMMR data base	1980-1988	Evaluation of drought monitoring and early warning capability by using 1983-85 drought as testcase	Anonymous, 1987
Sahelian countries		LANDSAT-MSS NOAA-AVHRR, SPOT	1980-1984	JOLIBA Project; radiometric measures on groundtruth plots; phenology and yield data of cultivated crops comparison of satellite data with radiometric measurements	A. Berg et al., 1984
USA	Meteo crop models	NOAA-AVHRR, NDVI, LANDSAT-MSS	1981-1985	Satellite calibration measurements for biomass production	G.D. Boatwright et al., 1986 C.L. Wiegand, 1984
Sahelian + Horn of Africa countries	AISC/CIAM models	NOAA-AVHRR, NDVI, LANDSAT-MSS	1985-1986	NDVI values utilized for crop yield forecasting. System ready for application	Johnson et al., 1987 Sakamoto et al., 1986
New Zealand	PET with Penman formula, water balance	NOAA-AVHRR	1981-1984	Crop: pasture. Biomass over a very large homogeneous area 1000 km^2. Collection of daily rainfall data. Not yet routinely applied	B.F. Taylor et al.,1985
Canada	Meteo crop yield models	NOAA-AVHRR	1982	Canadian wheat board needs estimates of domest. and foreign wheat production, even if promising results have been given method not yet operational	H. Glick et al., 1984

Country	Type of agro-climatological model	Satellite data	Duration	Remarks	Source
USA/Canada USSR	Meteo crop yield model	-	1976	Meteo model based on pressure-weather relationship which is analysed by a principal component analysis. Ready for application	L.T. Steyaert, 1986
Algeria	FAO, 1979	-	1971-1972 1975-1978	Correlation curve for winter wheat correlating vegetation index versus yield	Frère and Popov, 1979
Ethiopia	FAO, 1979	-	1975-1976	Correlation curve for sorghum correlating vegetation index versus yield	Frère and Popov, 1979
Togo	FAO, 1979	-	1973-1977	Correlation curve for maize correlating vegetation index versus yield	Frère and Popov, 1979
Argentina	FAO, 1979	-	not specified	Correlation curve for wheat correlating vegetation index versus yield	Frère and Popov, 1979
Tanzania	-	NOAA-AVHRR in framework LACIE project	not specified	Constraints: small size fields, intercropping, this applies to AVHRR GAC	R.B. King, 1984
Egypt	-	NOAA-AVHRR NDVI-calculation	1981	Suitable method for the global growing season response but unsuitable for inventory of a specific crop yield or specific crop acreage	Tucker et al., 1984

total herbaceous biomass production in areas where the percentage cover of woody species is less than 10%. However, methods applied in the study have yet to be applied operationally to monitor locust.

Sahelian countries, Sudan, and Ethiopia

The integration and testing of NOAA-AVHRR NDVI data with conventional agro-meteorological crop forecasting techniques deal with May 1983 - October 1986 data (ANONYMOUS, 1987). From the multitemporal NDVI database, FAO-RSC is evaluating the correlation between seasonal vegetation index profiles and soil moisture indices (FAO, 1976). NASA and FAO are implementing the global NOAA-AVHRR NDVI database for Africa 1980/87 at a spatial resolution of 7.6 km. NASA is also providing GAC data in order to help the drought monitoring and to evaluate early warning capability by using the 1983/85 drought as testcase.

A database of Nimbus Scanning Multi-channnel Microware Radiometer (SMMR) is also provided as complement of the NOAA vegetation in low biomass stations. FAO is also developing an algorithm for quantitative rangeland primary productivity estimation using the ARTEMIS-method and NOAA-AVHRR NDVI data.

Sahel and Horn of Africa countries

NOAA-AISC in association with CIAM of the University of Missouri in Columbia, Missouri, have been asked by USAID to provide operational agricultural assessments for the Sahel and Horn countries (JOHNSON et al., 1987; SAKAMOTO et al., 1986). The developed assessment system deals with different subsystems (Fig. 3), namely:

- satellite assessment models
- agroclimatic indices
- crop yield forecast

The three sub-systems merge in the so-called Geographic Information System, where the data sources are cross-checked between each other for consistency. A brief description of the three sub-systems is given.

In the agroclimatic indices sub-system, rainfall data are available on daily basis from WMO Global Telecommunication System (GTS). However, rainfall data are elaborated in the agroclimatic indices on monthly or decade basis. An appropriate threshold of indices is given by both the use of historical index data and episodic or auxiliary data. Calculations of soil moisture budget and crop indices are based on the FAO-WRSI, (FRERE et al.,

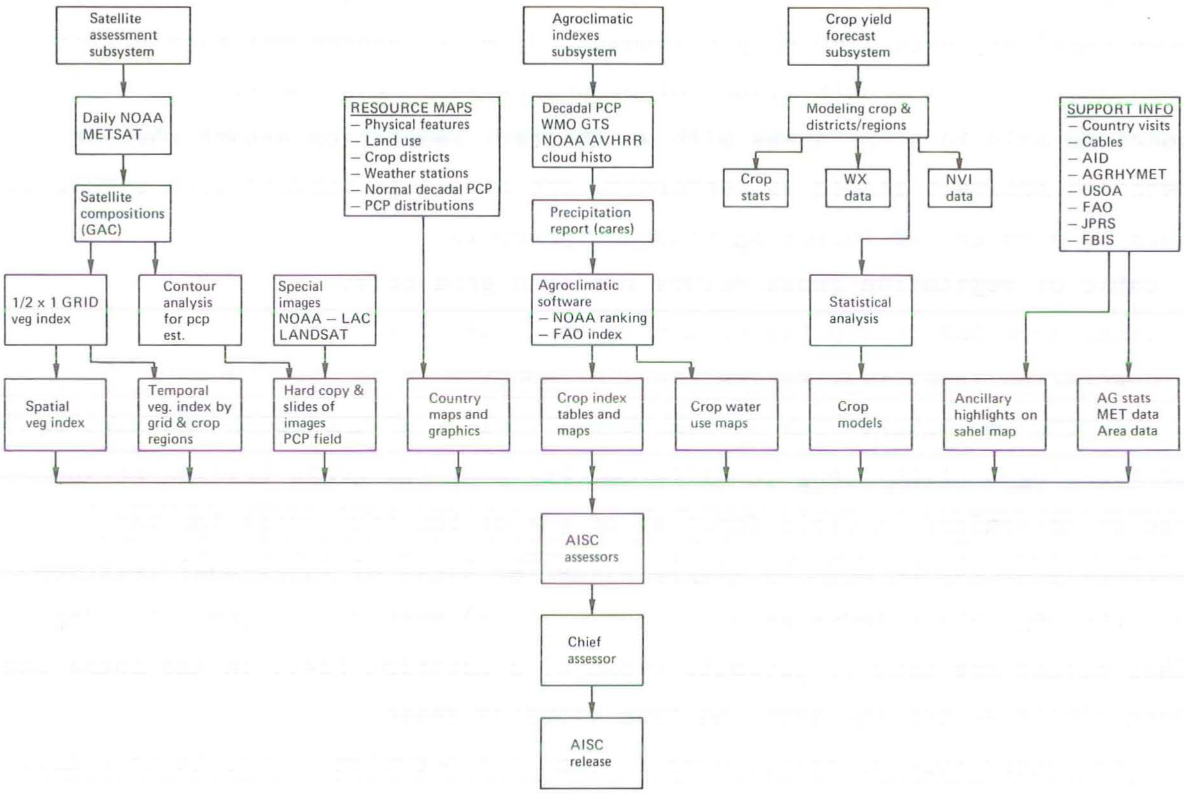


Fig. 3. Task flow chart for NOAA/NESDIS/AISC 1986 Sahel/Horn of Africa Special Assessment System (after JOHNSON et al., 1987)

1979). The so-called auxiliary data supplement knowledge on weather impact assessment, i.e. occurrence of locust infestation, floods, plant diseases.

In the satellite assessment sub-system, data coming from two different satellites are analysed. METEOSAT-images provide data on cloud types and coverage, which analysis produces cloud indices to assess the regional rainfall. Such analysis is also compared with the mean outgoing longwave radiation data. As low levels of outgoing radiation occur, the probability of rainfall occurrence is high. METEOSAT-data are also used to identify large scale patterns such as Inter-tropical Discontinuity (ITD) and Intertropical Convergence Zone (ITCZ).

The analysed NOAA-AVHRR-data consist of GAC data (4 km resolution) and PSF-data (20 km resolution). The vegetation/biomass index (NDVI) is calculated from composited data.

In the crop yield forecast sub-system, two kinds of crop yield models are used. The first model analyses NDVI data with rainfall data by regression analysis. The best interpretation of a NDVI model is achieved when auxiliary data like crop calendars, climatic characteristics of the area and critical growth slopes of crops are available. So far, such a model is able to alert areas with an abnormal vegetation growth where a detailed analysis should be performed. The satellite surveillance system is able to produce the following standard products:

- table of vegetation index values for each grid-cell;
- areal maps indicating the change in the time of NDVI;
- vegetation index time-series plots or profile.

Merging the information of time series values of NDVI with the duration of the stages of the crop in different regions, the grain filling period can be determined. A yield forecast of one of the four crops for the current year can be made by simply using the lines of functional relation and the vegetation index value at the critical week during grain filling. This method was used to estimate yield at a district level in the Sahel and Horn countries for the 1985 and 1986 cropping season.

The second type of model, used in such a sub-system, consists of classical statistical rainfall/yield modeling approach (models developed by THOMPSON, 1977) where yield is calculated from climatic variables using empirical relations derived from historical yield and weather data. Such a model provides good information on crop critical periods. Thirty days before harvest, AISC prepares quantitative crop yield forecasts. The forecasts are based on combined interpretation of NDVI/yield model, classical rainfall/crop yield statistical models and crop condition analysis respectively, based on the products of the Agroclimatic Index and Satellite Assessment Model subsystems. Verification of these results must be carried out during the coming years in order to adjust the models.

A verification of the crop production via models should be done by isolating specific crop areas and obtaining additional groundtruth data. In fact, because of the crop production data provided by national governments are roughly estimated, satellite data need to be compared with reliable data gathered in the field. In the framework of this verification the system is available to be fully utilized by the AGRHYMET Regional Centre in Niamey, Niger, which receives satellite imagery diskettes for analysis.

Egypt

Fourteen NOAA-AVHRR-images transformed in NDVI were utilized to monitor crop development through the growing season in the Nile Delta (TUCKER et al., 1984). LAC NDVI data did show the increase of biomass from early June to late October, reaching a peak on the 11th of August. The growing rate of corn, cotton, and wheat was not affected because of irrigation facilities in the area. The average field size was about 1 to 4 acres. The study demonstrated that AVHRR-data would be suitable to detect growing season response but not for crop specific inventory, which would require crop specific figures for yield and acreage.

Botswana

Rangelands were monitored by means of NOAA7-AVHRR GAC data at 3 study sites in Eastern Botswana (Prince, 1986). Each site has the size of one NOAA-AVHRR GAC pixel (4 x 4 km). Crop cover and biomass were estimated (1983-84). Air photographs were also made and used for crop interpretation. Biomass values for green herbage have a curvilinear relationship with AVHRR NDVI and values down to about 100 kg/ha can be detected. Bare soil shows a negative relationship with NDVI. The results shows that cover and even biomass of herbaceous vegetation can be resolved into at least three classes. Then, variation of NDVI related to green herbaceous cover, biomass and bare soil have to be analysed separately, using Generalized Linear Interactive Modelling (GLIM).

The predictive value of NDVI could be increased if separate calibrations were used for each date. Simple averaging of the cover and biomass is unlikely to give an accurate mean value for the GAC pixel as a whole. Then a large number of ground truth measurements would be needed for each AVHRR GAC pixel. However it should be rated that 20 plots of which size are just 5 % of the area of one GAC pixel. To overcome this bottleneck, LANDSAT-MSS images were acquired for each ground sampling date. Sample data were then compared with MSS pixel (ratio 7/5), and later mathematical regression was applied from MSS to AVHRR pixels. It may be concluded, that as a result monitoring of rangelands improved. It has to be kept in mind however, that possible sources of errors are:

- interpolation of the ground measurements to the whole field of a view of the satellite radiometer;
- estimates of net primary production taking into account the consumption by herbivores during the harvest intervals.

As general conclusion it can be said that optimal results from satellite data can be achieved if better ground truth data sets are collected.

U.S.A.

Agro-meteorological crop models have been developed in the framework of the AGRISTARS project 1981-85 (BOATWRIGHT et al.,1986; WIEGAND et al., 1986). ny the integrateb use of satellite measurements as NOAA-AVHRR and LANDSAT -MSS for biomass production and the meteorological data, an early warning assessment of yield production should be obtained. A flowchart of the models is given below.

Much data must be acquired, combined and processed in sub-routines in order to extract the data to execute the models (Fig. 4). Producing algorithms for resetting and continuing the execution of agrometeorological models is a high priority. Remotely sensed inputs are proposed to be used as feedback to the models as Fig. 5 shows.

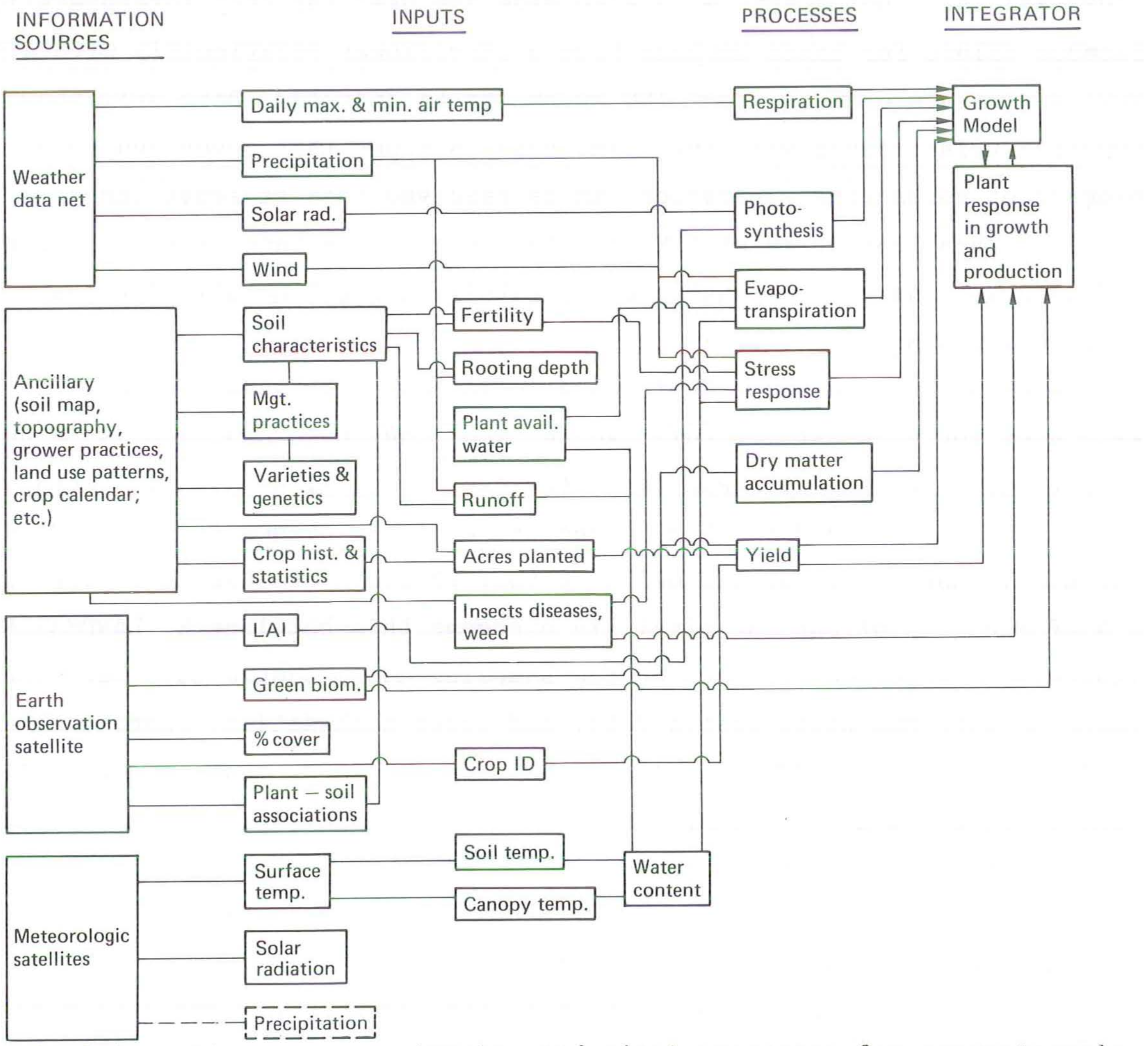


Fig. 4. Information sources, inputs, and plant processes for agrometeorological plant growth and yield models (adapted from WIEGAND et al., 1986)

Model Subroutines	Remotely Sensed Input or Check
Growth or dry matter accumulation	VI[a)] spectral surrogate of green biomass spectral profile[b)] growth rate
Photosynthesis	VI spectral surrogate of LAI for light absorption estimate Spectral estimates of IPAR
Evapotranspiration	BR or SLI[c)] albedo, surface wetness -ground cover for partitioning evaporation and transpiration Tc-Ta[d)] as related to ratio of actual to potential evapotranspiration, E/Ep
Phenology	-Spectral profile-emergence or green-up date, maximum greenness date -Tc in lieu of air temperature to pace ontogenetic events
Stress	VI -Canopy "greenness" and magnitude vs. normal; senescence rate -Tc-Ta stress severity diagnostic, or in crop water stress index (1-E/Ep)
Yield	VI near maximum canopy development or early in grain filling; spectral profile integrals

a) VI = spectral vegetation indices GR, PVI, ND, etc.
b) Spectral profile = vegetation index vs. time
c) BR, SLI = brightness and the soil line index, spectral indices dominated by soil background
d) Tc is canopy temperature; Ta is air temperature

Fig. 5. Remotely sensed inputs or feedback to agrometeorological models grouped by model subroutines (after WIEGAND et al., 1986)

It has been shown in the Wheat Belt that wheat yields relate well to spectral vegetation indices during the period of late stem extension to early grain filling. Changing of the plant canopy characteristics affects the model's photosynthesis, evapotranspiration, stress response and yield subroutine. The observation of such a change is supposed to give a correct prediction of the production in a particular area. Spectral vegetation indices are used in operational yield predictions of the Foreign Agricultural Service (FAS) of the USDA, while the same indices are still in a revising stage as inputs in agro-meteorological models. Note that the landuse pattern must be in line with the spatial resolution of the satellite.

Canada

The Canadian Wheat Board needs estimates of domestic and foreign wheat production which has pushed the preparation and use of a crop yield model. Such a model needs several meteorological data inputs as daily temperatures, precipitation and wind velocities. Crop condition and yield are strongly related to the magnitude of the peak value of the NDVI curve from NOAA-AVHRR imagery (GLICK et al., 1984). Because the radiance values from a total area is the contribution of measured values from respectively bare soil, non-agricultural area and agricultural area, the wheat yield has to be adjusted considering the percentage of uncultivated land. The correlation curve NDVI versus time in test areas has given good results which encourage to use NOAA-AVHRR data for phenological development information. Satellite data could be used to alarm the occurrence of a critical phenological period in such a way that the meteorological data used in the prediction model can be tracked more carefully. However, the described method is not yet routinely applied.

U.S.A., Canada, U.S.S.R.

Large area wheat yield models have been developed for the Great Plains (USA), Saskatchewan (Canada) and the USSR. The models are based on regression analysis of principal components of monthly sea level pressures (STEYAERT, 1976). The hypothesis is based on the study of large scale atmospheric general circulation patterns which influence sea level pressure patterns as well as "weather". So whenever anomalous sea level pressure pattern is detected, it can be correlated to wheat yield by regression type model. Even though atmospheric pressure does not influence directly the increase of wheat yield, moisture availability (or stress) influence largely the final yield. Moisture availability is also related to atmospheric pressure pattern.

Fluctuation of atmospheric pressure can support data for a large area model when other meteorological data (temperature, precipitation) are not available or not sufficiently detailed. The model is regarded to be ready for application. According to the authors, the model has given encouraging results for Canada and Soviet Union.

3. DATA COLLECTION ON BEHALF OF EARLY WARNING AND CROP FORECASTING IN ZAMBIA

3.1. PHYSIOGRAPHIC AND AGRONOMICAL DATA

The MARS methodology aims at the monitoring and the estimation of yields of defined crops in defined agro-ecological zones in Zambia. The procedure to estimate the yields is currently based on the FAO Early Warning crop-weather analysis model (WRSI), as defined by FRÈRE and POPOV (1979; FAO, 1986). The MARS methodology will apply a crop growth simulation model (see chapter 4.1; VAN KEULEN and WOLF, 1986)..The use of crop-weather models requires site specific information on weather, soils and crops (section 3.1.1). This information is a product of the agricultural research in Zambia. Section 3.1.2 describes the structure of the research in Zambia.

3.1.1. Data on weather, crop and soils

Crop specific data

To simulate growth, each crop is defined by characteristics with respect to assimilation and respiration processess, partitioning of assimilates, response to moisture stress, phenological development pattern and efficiency of nutrient utilization. The minimum required site-specific information on crops is a crop calendar defining dates of emergence, anthesis and maturity, and data on seeding rate or plant density. The yield potential is strongly dependent on crop growth duration, which in turn depends mainly on temperature. Cultivars having shorter growth cycles yield generally less because they cannot develop sufficient green leaf area, while cultivars having a longer growth cycle may develop so much vegetative material that a large part of the assimilates is needed for respiration at the expense of the production of marketable product (VAN KEULEN and WOLF, 1986).

Meteorological data

For the calculation of gross CO_2 assimilation rates, data are required on solar radiation and mean minimum temperatures (GOUDRIAAN and VAN LAAR, 1978). For calculation of the water balance required data include rainfall regime, evaporation and evapotranspiration rates. These rates are calculated with the Penman equation, using data on solar radiation, average air temperature, vapour pressure and wind speed (FRERE and POPOV, 1979).

Soil physical data

The calculation of the water-limited production is based on dynamic simulation of the soil water balance, for which the soil's infiltration, water retention and hydraulic conductivity must be known (BELMANS et al.,1983). The soils are physically defined by:

- soil profile description;
- soil moisture characteristics of every layer, notably the porosity and volumetric moisture content at field capacity and wilting point of the individual soil horizons;
- effective soil depth;
- maximum infiltration rate or other data describing runoff.

Soil chemical data

Nutrients are needed in certain quantities for optimum functioning of the plant. If their supply is limited, nutrient concentrations in the plant tissues decrease to an absolute minimum value. Under those conditions crop production is determined by the ratio of nutrient supply and minimum nutrient concentration (VAN KEULEN and VAN HEEMST, 1982). The nutrient supply depends on soil fertility and the application of fertilizers. Soil fertility is evaluated according to the so-called QUEFTS system, i.e. Quantitative Evaluation of the Fertility of Tropical Soils (GUIKING et al., 1983; JANSSEN et al., 1986; SMALING and JANSSEN, 1987; JANSSEN et al., in prep.). In this approach the most useful diagnostic chemical soil properties are pH-KCl, organic C, P-Olsen, and exchangeable K, and to a lesser degree total P, CEC and base saturation.

Landuse data

The actual agricultural production depends mainly on the applied farming practices. The actually applied and potentially applicable farming practices can be deduced from the results of sound landuse surveys, particularly if the applied classification system has been based on diagnostic criteria as land tenure, degree of commercialization, size of holding, orientation of cultivation, intensity of cultivation, implements of cultivation, maintenance of soil fertility and main crop and livestock (see SCHULTZ, 1974).

Two MARS-PPDS missions were send to Zambia a.o. to assess the availability, quality and quantity of meteorological, physiographic and agronomic data in Zambia in order to define the ultimate MARS project. The results of these missions are given in FABER et al. (1987) and VAN DIEPEN (1987).

The MARS-PPDS missions collected topographic maps and maps showing the spatial distributions of the soils, vegetation and landuse of Zambia and extensive data files on the weather. These data sets appear to be sufficiently accurate to bec included in the proposed MARS data base system. The specific data on soils appears also to be available in Zambia; the acquisition and proper interpretation of these data sets, however, will require a major effort during the next phases of the MARS project. As discussed below, this results mainly from the agricultural research organization in Zambia and the research orientation.

3.1.2. Agricultural research in Zambia

Organization

In Fig. 6 an informal organizational chart of Agricultural Research in Zambia is presented.

Mount Makulu is the Central Research Station, but important research is also done on several Provincial Research Stations. Some specialist teams as the Soil Productivity Research Team and the Adaptive Research Team have even moved from on-station research to farm level research, which is attractive at least for most donors, but the relevance, efficiency and quality of this research is very difficult to judge.

In terms of personnel input, the Commodity Research Teams (CRT), the Soil Survey Unit and the Adaptive Research Planning Teams are the most important. Among the staff with university level education are about 50 expatriates and 50 Zambian nationals. The fragmented set up by commodity, by specialty or by province seems further accentuated by separate funding of projects by a number of donor agencies (Sweden, Norway, Canada, USA, FAO, World Bank, France, Belgium, The Netherlands, Germany, United Kingdom).

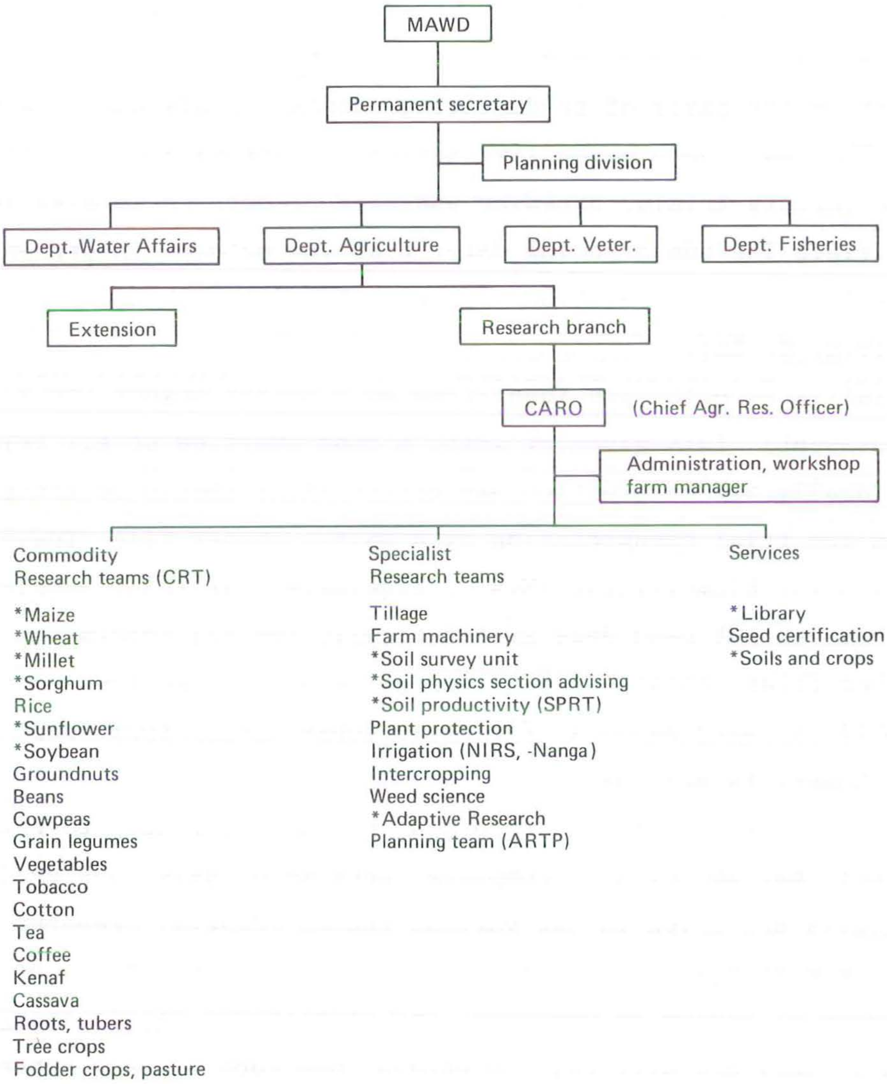


Fig. 6. Informal organizational chart of agricultural research of the Ministry of Agriculture and Water Development (MAWD)

Research orientation and results

From the relevant literature, a good picture of the research orientation and results can be obtained. This relates especially to the commodities maize, sorghum, millet, wheat, sunflower and soybean, to the work of the Soil Survey Unit and to the Adaptive Research Planning Team.

The orientation of the CRT's is to release as fast as possible highly productive new varieties to farmers. The building up of systematic knowledge is not a priority. The staffing of CRT determines also its output. Each team consists ideally of a breeder, an agronomist, a pathologist and an entomologist. Screening of varieties forms the bulk of the work. The screening is on the basis of productivity, disease resistance and drought tolerance. The tests have names like national, international, preliminary, or advanced variety trials. Breeding and seed production is also important. Agronomic trials include planting date, planting method, intercropping, time of weeding, weed competition, timing, NPKS fertilizers, and micronutrients (e.g. B, Zn).

Each trial is in principle identified by a Master Number (from 1-8000, from 1950-present). This gives at least a good overview of all trials in the past. Ideally all information and observations should be brought together in the trial documentation by a master number file. These files are kept with the biometrician (Mrs C. Engelmeyer) at Mount Makulu. However, this has not been done systematically for all trials yet. Many Master Number files contain only clippings, and cuttings from annual review reports, while on many manually filled out observation forms kept elsewhere the master number is missing.

For the trials many data are recorded, but are difficult to retrieve. Many data sets may not even be complete, because of omissions or loss. Summary results are given in the various annual reports, prepared for the annual review meetings. These reports are stapled mimeographs, of which a limited number of copies is produced, and distributed mainly among meeting participants. They are difficult to obtain. One copy of each report should be in the library. No synthesis reports are prepared on long-term trials or on a group of related trials.

The crop varieties are usually categorised as short, medium and long duration, without distinction by climatic region or by year. There is no information available on heat sums or photoperiodicity, although such information could be derived from recorded observations. A mass of information is piled up without being analysed. As some varieties are obtained from international institutes such as ICRISAT, CIMMYT, or from Zimbabwe, it is possible that more specific information on crop parameters could be obtained elsewhere.

On all agricultural research stations daily weather records are kept. For the period August 1983 - September 1986 these are available from the

Meteorological Department on diskette.

Other published weather data include:

- the monthly bulletins 'Zambian climatological summary' 1973 up to June '84 (last issue collected), 1982 is missing;
- totals of monthly and annual rainfall, up to 1980/81;
- climates of ...(by provincial town).

Interesting remarks on crop phenology in Zambia:

- sorghum and millet are thermo-insensitive and largely photoperiod-insensitive;
- maize flowered 15 days 'too late' this year (1986/87);
- soybean maturity is strongly influenced by drought.

A good case for convincing agronomic researchers of the benefits of a systems approach is the ZamCan Wheat Project. After 14 years this project is still in doubt on which cultivars to grow how, where and when. The major constraints to wheat growing are diseases, too high temperatures, drought and low soil fertility, but the importance of each of these constraints is not known.

Other institutes

At UNZA contacts were made with the Soils Section of the Faculty of Agriculture and the Agricultural Engineering Section. The University runs probably two experimental farms, but no details of the kind of research could be obtained, apart from the soil experiments: soil erosion, soil water balance, and soil physics.

At the Geological Survey Department maps and documents were collected. The orientation of the Geological Survey is uniquely towards prospecting for minerals and administration of mining concessions.

3.2. AGRICULTURAL STATISTICS

When Zambia obtained independence, in October 1964, agriculture displayed two radically different patterns. Modern commercial farming for cash and export had been developed largely by European settlers, whereas subsistence farming was the main type of agriculture for about 70 % of the African population. Detailed statistical summaries by district are given (AZZALI, 1987a).

3.2.1. Classification of farming types

Nowadays, different types of agriculture can be distinguished in Zambia according to income, technical inputs, and farm size. The different classifications of farm types are given in Appendix 1 (AZZALI, 1987a).

From the same publication we have chosen for this study the classification given by Jaeger, who classified the farming systems as follows, where the zones are according to the agro-ecological zones of Zambia (Map 1, AZZALI, 1987a).

Level 1	:	Traditional subsistence household	
size holding	:	not more than 5 ha, usually 1-2 ha as average	
production	:	consumption crops, no cash crops	
staple crops	:	zone 1	cassava, millets, sorghum (in Kasempa, Chizera and Solwezi districts)
		zone 2	cassava, maize and millet
		zone 3	maize
		zone 4	sorghum, millet and maize

Level 2	:	Small-scale emergent farmers	
size holding	:	1-10 ha	
production	:	staple and cash crops	
staple crops	:	see Level 1	
cash crops	:	zone 1	maize, rice, beans (wheat)
		zone 2	maize, rice and some cotton
		zone 3	maize, cotton (sunflower, groundnuts, wheat)
		zone 4	cotton and maize

Level 3	:	Medium scale commercial farmers	
size holding	:	10-40 ha	
staple crops	:	maize, small plots of cassava, sorghum in North Western province	
cash crops	:	zone 1	maize, rice, wheat (Copperbelt)
		zone 2	maize and rice
		zone 3	maize, sunflower, wheat, cotton and groundnuts
		zone 4	sunflower, cotton and maize

Level 4 : Large scale commercial farmers
size holding : more than 40 ha
staple crops : none
cash crops : maize, wheat, sunflower, groundnuts and cotton (mainly located in zone 3a)

CHAUDRI (1985) proposed an other farm size classification:
- commercial farmers: more than 20 ha
- emergent or small scale commercial farmers: between 5 and 20 ha
- peasants or traditional farmers: less than 5 ha

This report describes the size and type of farms (after JAEGER, 1981) for each Province and for each District. In particular, it will describe crop calendars and management techniques of cultivated crops (AZZALI, 1987a).

3.2.2. Few remarks on measurement units used to quantify crop production

Crop production figures are given in this report. Particularly, production records mainly for maize have been analysed and, when data were available, information on other crop productions has been added. Production figures apply to final produce not to biomass. Table 3 shows the correspondent values in Kg of measurement unit 'bag' used for different crops in Zambia. No information regarding the humidity percentage of the grain production is mentioned. In some other tables, also metric ton is also used as a measurement unit to express crop production.

Table 3. Measurement unit 'bag' expressed in kg for different crops

Crop	Measurement unit	
	bag	kg
Maize	1	90
Paddy rice	1	80
Sunflower	1	50
Shelled groundnuts	1	80
Soybeans	1	90

Table 4. Farm units and farm population by province and by farm level (1980)*

Level	Large-scale commercial (>40 ha)		Medium-scale commercial (10-40 ha)		Small-scale commercial (1-10 ha)		'Traditional' farming sector		Total	
Province	Farms	Pop.	Farms	Pop.	Farms	Pop.	Farms	Pop.	Farms	Pop.
Southern	320	16,000	8,000	76,000	49,000	374,000	7,500	33,900	65,720	500,000
Central	300	15,200	7,630	72,500	21,400	160,500	18,400	82,800	47,730	331,000
Lusaka	90	4,300	1,910	18,100	4,300	32,300	13,400	60,300	19,700	115,000
Copperbelt	-	-	490	4,700	2,000	14,900	17,900	80,400	20,390	100,000
Eastern	20	1,000	3,100	29,500	27,000	202,700	80,900	363,800	111,020	597,000
Western	-	-	-	-	5,450	40,800	85,400	384,200	90,850	425,000
N.Western	-	-	80	800	2,900	21,900	53,600	241,300	56,580	264,000
Luapula	-	-	50	500	2,050	15,300	73,600	331,200	75,700	347,000
Northern	-	-	90	800	7,400	55,500	111,900	503,700	119,390	560,000
Total	730	36,500	21,350	202,900	122,400	918,000	462,600	2,081,600	607,080	3,239,000

* Source: Food strategy study, 1981

3.2.3. National statistical summary

In Table 4 the distribution of farms and population by province and farm type is presented. These data clearly indicate where marketable surpluses are potentially available, e.g. Central Province and where food import requirements is stronger, e.g. Copperbelt.

3.3. CROP CONDITIONS AND CROP PHENOLOGY

Detailed crop calendars by district are given in AZZALI (1987a) so only a few general remarks will be given here.

3.3.1. Definition of phenological stages by crop

From the agronomic information collected through literature, average crop calendars have been established for each district. In these crop calendars the phenological stages have been coded and defined as follows:

1. sowing
2. full ground cover
3. flowering
4. yield formation
5. harvesting.

The occurrences of these five phenological stages is information required for the preparation of an average crop calendar. However, it was seldom possible to find the complete set of information for a specific crop and district. Consequently, only those stages and their occurrences, specifically found in the literature and concerning a crop cultivated in a specific district, were taken into account. For this reason information concerning some crop phenological stages is not uniform, as is shown in the thirty-three crop calendars prepared for this report (AZZALI, 1987a).

3.3.2. Phenology of agricultural systems

Different types of agricultural systems can be distinguished in Zambia, according to the agricultural practices, climate and technical inputs.

Map 2 (AZZALI, 1987a) gives a view of the distribution of agricultural systems, their location and extension. A full description of such systems by province has been given by AZZALI (1987a). The chitemene systems (shifting cultivation) are mainly located in Northern, Luapula, and North Western provinces and in the Serenje district of Central Province. This system occupies an area of about 200.000 km^2. However, the information on the extension of the shifting cultivation practices is referred to 1974. Further investigations should be set up in order to update the landuse map of Zambia. By matching the information on the agricultural systems given by Map 2 (AZZALI, 1987a) with the location of the agro-ecological zones of Zambia, it is possible to extract the values of the length of the crop growing period for each agricultural system. Overlaying such results on a topographical map of Zambia, values of the length of the crop growing period under rainfed agriculture can be extracted by provinces and by districts. Table 5 summarises the mean values of crop growing period for each province and for the main districts.

Table 5. Agro-ecological zones classified for provinces and districts in Zambia; length of crop growing period under rainfed agriculture

Province	District	Mean value of growing period (days)	70% of probability length of growing period (decade)
North-Western	Mwinilunga	204-212	15, start. from I/dec. November
	Solwezi	188-204	15, start. from I/dec. November
	Zambezi	180-195	15, start. from I/dec. November
	Kasempa	166-173	13, start. from II/dec. November
Western	Mongu,Kaoma	159-166	11, start. from I/dec. December
	Lukulu	166-180	12, start. from III/dec.November
	Sesheke	147-152	8, start. from I/dec. December
Southern	Monze,Mazabuka	141-147	7, start. from II/dec. December
	Kalomo,Choma	147-152	9, start. from I/dec. December
Lusaka	Lusaka	152-159	9.5, start from I/dec. December
	Luangwa	141-166	7, start. from II/dec. December
Central	Mumbwa	159-166	9, start. from I/dec. December
	Serenje	166-173	11, start. from III/dec.November
Copperbelt	Ndola rural	188-204	15, start. from II/dec. November
Eastern	Petauke,Chadiza	152-159	10, start. from I/dec. December
	Chipata	166-173	11, start. from I/dec. December
	Lundazi	166-175	11, start. from I/dec. December
Luapula	Kaputa, Kawambwa	188-221	19, start. from I/dec. November
	Mansa, Mwense	173-195	16.5, start. from I/dec. November
	Samfya	173-180	15, start. from III/dec.November
Northern	Mbala, Kasama	188-195	16, start. from III/dec.November
	Mpika, Chinsali	166-195	15, start. from III/dec.November
	Mpika (south)	141-166	11, start. from III/dec.November

3.4 QUALITY ASSESSMENT OF METEOROLOGICAL DATA

Between March 15th and April 30th an SOW-ICW mission visited Zambia. One of the goals of this visit was to collect meteorological data for a quality assessment of meteorological observations in Zambia. Data from a period covering 1974 - 1983 were obtained on hard copy. Data of the period between October 1983 and April 1986 were available on floppy disk.

In this Chapter (see also Chapter 4 in Jacobs, 1987) we will:

- check the data continuity (Section 3.4.1) and
- carry out a crude quality assessment for rainfall data and for relative humidity.

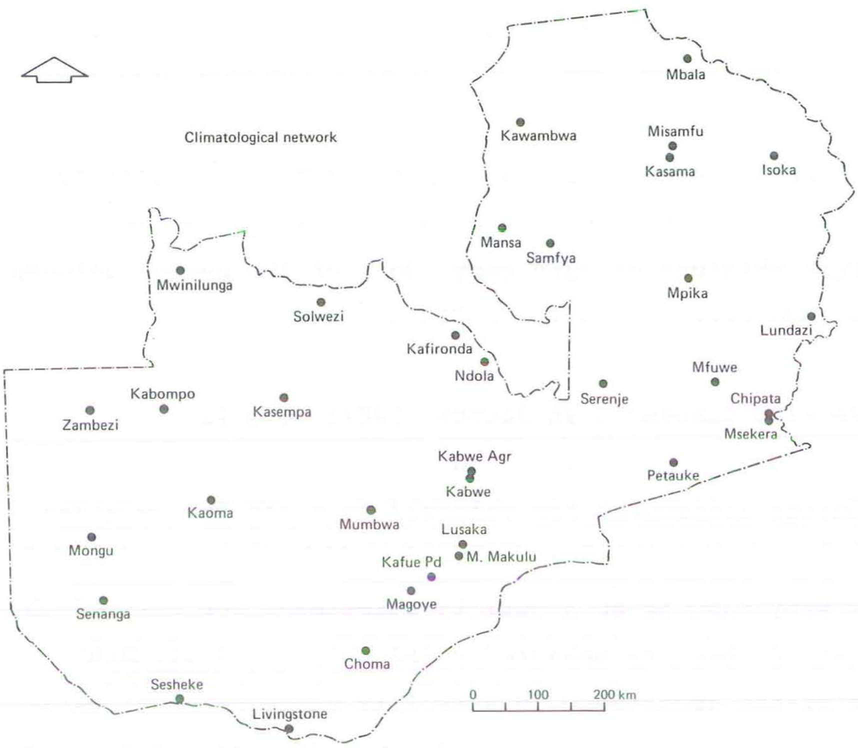
It turned out to be very hard to do a quality assessment for most of the parameters, because most of them are measured using only one instrument. Therefore, and because of the importance in satellite based rainfall estimation techniques and in agricultural applications we concentrated on rainfall data and on relative humidity data (Section 3.4.2 and 3.4.3 respectively).

3.4.1. Inventory of available data and continuity

At the moment meteorological observations in Zambia are carried out at 33 stations (the station Samfya has been closed). Location, stationnumber, name and elevation of the Meteorological Stations in the Zambian climatological network are given in Fig. 7. The stations are main Meteorological Stations reporting daily.

For this investigation, the meteorological data of the period October 1983 - April 1986 were available on floppy-disk. These data were used for an inventory of available parameters and for a crude consideration of continuity.

Over the period mentioned, listings of two months (January and September 1984) were incomplete, probably because of exceed-ing disk-capacity. Table 6 gives the number of stations for which records are complete during a given month. From July 1984 no records of station 469 (Samfya) are available anymore. About that time the station has been closed. Furthermore, 4 records of station 476 (Misamfu) are missing. The other missing records are of the following stations: 461 (Mansa), 563 (Kafironda), 571 (Serenje), 662 (Kabwe agr.), 743 (Livingstone).



Station Details

Station No	Name	Elevation meters
483	KAWAMBWA	1334
413	MBALA	1673
441	MWINILUNGA	1363
461	MANSA	1358
469	SAMFYA	1173
475	KASAMA	1384
476	MISAMFU	1538
477	MPIKA	1483
481	ISOKA	1368
531	ZAMBEZI	1878
541	KASEMPA	1234
543	KABOMPO	1875
551	SOLWEZI	1386
561	NDOLA	1378
563	KAFIRONDA	1343
571	SERENJE	1384
580	MSEKERA	1835
581	CHIPATA	1832
583	LUNDAZI	1143
585	MFUWE	578
633	MONGU	1853
641	KAOMA	1313
655	MUMBWA	1318
658	KAFUE POLDER	878
662	KABWE AGR.	1165
663	KABWE	1287
665	LUSAKA INT.	1154
667	MOUNT MAKULU	1213
673	PETAUKE	1836
731	SENANGA	1827
741	SESHEKE	851
743	LIVINGSTONE	886
751	MAGOYE	1618
753	CHOMA	1378

Fig. 7. Location, station number, name and elevation of the Meterological Stations in the Zambian climatological network.

Table 6. Number of stations for which monthly records are available during the period of 1983-1986

MONTH	J	F	M	A	M	J	J	A	S	O	N	D
Year												
1983	-	-	-	-	-	-	-	-	-	33	34	34
1984	-	34	34	34	33	32	33	33	-	33	33	33
1985	33	33	33	33	33	33	33	32	33	33	33	33
1986	33	32	32	31	-	-	-	-	-	-	-	-

- = no data available

The records of 1986 (January - April) were used to draw up an inventory of available meteorological data. The results of this inventory are given in Table 7. Data on parameters are assumed to be available when at least one monthly record of a station consisted not only of "missing values".

"Weather" phenomena (column 19 - 24) are assumed to be considered at every station. Wind gusts are assumed to be measured if at least one of the other wind parameters (column 17 - 18) is measured. The meaning of the symbols used, and the instructions for completing the records are given in Appendix 4.II and 4.III, respectively, of JACOBS (1987).

Table 7. Available meteorological data (see text)

Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
	Tx	Tm	Tg	S2	S4	S8	E1	E4	Td	Su	RR	SS	N	PP	TT	RH	FFn	FFd	F	P	T	L	H	C	Ev
Station																									
403	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
413	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
441	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
461	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0
475	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1
476	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1
477	1	1	1	1	1	0	0	0	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
481	1	1	1	1	1	1	0	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0
531	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
541	1	1	1	0	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
543	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
551	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
561*	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1
563	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
571	1	1	1	1	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0
580	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0
581	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1
583	1	1	1	1	1	1	0	0	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	1
585	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
633	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
641	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
655	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	0
659	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
662	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
663	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
665	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1
667	1	1	1	1	1	1	0	0	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
673	1	1	1	1	1	1	1	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1	1	0
731	1	1	1	1	1	1	1	1	0	1	1	1	1	0	1	0	1	1	1	1	1	1	1	1	1
741	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
743	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1
751	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1
753	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Total	33	33	33	32	32	30	22	25	30	29	33	28	33	20	33	29	27	28	33	33	33	33	33	33	26

1 = data available
0 = no data available

To obtain an impression of the daily continuity of the observations at the meteorological stations, 7 monthly records of 11 stations are checked (see Table 8). For several parameters the number of missing values are counted. Missing values are defined by:

- negative values, because of malfunctioning of an instrument or because a variable is not measured (e.g. -10);
- "0" or "9", except sometimes for the dewpoint, when a dewpoint of 0 degree Celsius seemed realistic (in comparison with the relative humidity, which was often entered as 0 when no dewpoint was available).

From Table 8 it appears that on average continuity is reasonable to excellent, for individual stations as well as for the parameters. However, the continuity of dewpoint and relative humidity data should be improved.

In the measurement of rainfall amounts some contradiction with the weather column "Precipitation" is encountered. Rather often, when an amount of rainfall is measured, a "0" (= nil) is reported in the weather code for precipitation. On the other hand when no rainfall is measured (0) the

Table 8. Average percentage of missing values (see text) in the months October 1983, March 1984, August 1984, January 1985, June 1985, November 1985, and February 1986. For explanation of symbols see Appendix 4.II in Jacobs, (1987)

Parameter	1 Tx	2 Tm	3 Tg	4 S2	5 S4	6 S8	7 El	8 E4	9 Td	10 RR	11 SS	12 N	13 TT	14 RH	15 Ev
Station															
403	0	0	5	0	0	0	-	0	6	0	2	2	0	2	13
481	1	0	5	13	45	14	-	-	4	0	-	0	14	5	-
531	0	0	0	0	0	0	29	0	13	0	2	0	14	13	1
541	0	0	0	-	-	-	0	0	0	0	-	0	0	0	3
571*	19	20	33	18	18	18	-	18	45	14	59	40	19	45	-
580	0	0	0	0	0	0	0	14	29	0	0	29	0	29	-
581	0	0	0	0	0	0	0	0	0	0	1	1	0	0	5
655	0	0	0	(73)	29	0	0	0	-	0	(74)	0	0	-	-
665	4	0	27	0	14	0	0	0	14	0	6	0	0	0	14
731	0	0	3	0	0	0	0	0	-	0	0	1	2	-	8
743	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
average 11st	2	2	7	3	11	3	3	3	11	1	8	7	5	9	6

* = records of one month completely missing
( ) = measurements probably only started recently; not counted in average for all stations
\- = no data available at the station

weather column shows a precipitation not being "0". The code for a malfunctioning of the raingauge is "-100" and is seldom reported. (see also Appendix 4.I in JACOBS (1987). The reason for such contradictions should be made clear.

3.4.2. Rainfall data

Evaluation of the quality of the rainfall data of Zambia is fraught with problems. Per station only one set of data is reported. To perform proper quality checks with respect to rainfall, precipitation should be measured using at least two independent instruments at the same station.

Because of the very localized character of showers comparison of daily rainfall data of two or more stations in a region is of hardly any use for the assessment of the quality of rainfall data. Therefore, the following procedure was applied to obtain a crude impression of the quality of the data.

Three pairs of stations were selected. The stations of a pair are located very close to each other, and have approximately the same elevation (see Table 9).

The data of two rainy seasons are used (1984/85 and 1985/86). The cumulative monthly rainfall amount (for 1 month, 2 months, etc.) is calculated for the stations and the figures for one pair of stations are plotted

Table 9. Selected pairs of stations (I, II and III) for the quality assessment of rainfall data, the elevations of the stations and the relative difference of the cumulative rainfall amount after after two rainy seasons (1984/1985 and 1985/1986)

Station	Name	Elevation (m)	% Difference
I 580	Msekera	1025	10
581	Chipata	1032	
II 662	Kabwe agr	1165	7
663	Kabwe	1207	
III 665	Lusaka	1154	4
667	M. Mukulu	1213	

against the corresponding figures of the other station. The results are shown in Fig. 8.

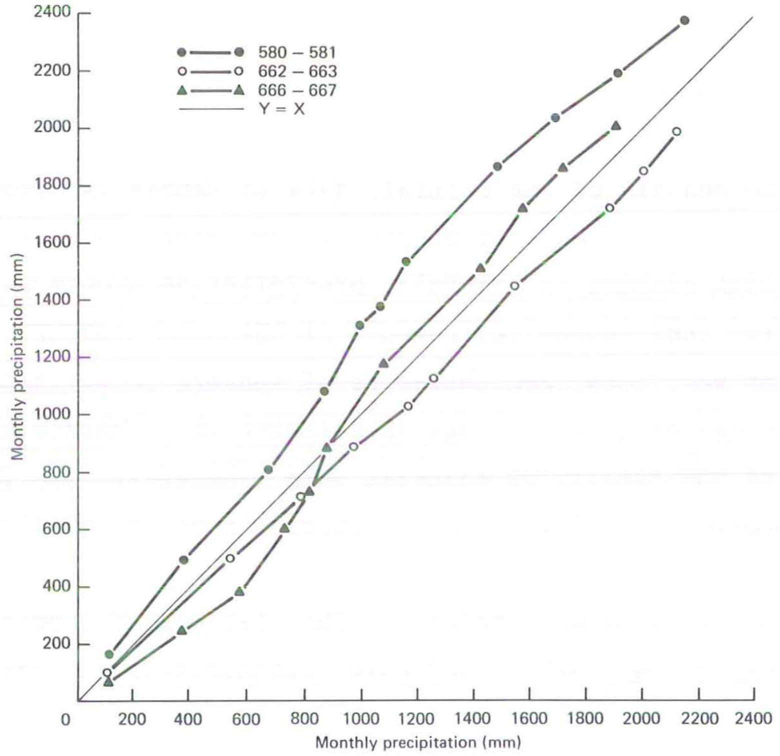


Fig. 8. Cumulative Monthly Rainfall amount (mm) of stations 580,662 and 665 plotted against cumulative monthly rainfall amount (mm) of stations 581, 663 and 667 respectively for the seasons 1984-1985 and 1985-1986

In the ideal case, the relation between the two cumulative rainfall amounts of a pair coincides with the line y=x, indicated in Fig. 8. Due to the localized character of rainfall, deviations occur, but in the case of well-performed measurements, the actual line curls around the theoretical, ideal line. This applies for stations 665 and 667. For the other pairs (580-581, 662-663) a systematic deviation occurs after one season (roughly halfway the curves), which is more or less stabilized (580-581) or slightly enhanced (662-663) in the second season. Resulting total differences at the end of the second season are shown in Table 9.

3.4.3. Relative humidity data

For 11 arbitrary stations it is tried to reproduce the reported relative humidity. Data of arbitrary days, i.e. of the 9th, the 18th and the 27th of 7 months (see Table 10) are used. When no data are available for these days, data of the days nearest to the mentioned dates are used.

Relative humidity was calculated from the saturation vapour pressure at the reported mean dewpoint (Es(Td)) (the actual water vapour pressure) and the saturation vapour pressure at the reported mean temperature (Es(TT)):

$$RH(c) = Es(Td)/Es(TT) * 100\% \qquad (1)$$

where the subscript c stands for calculated. Deviations (D) from the reported relative humidity (RH(r)) were calculated by:

$$D = RH(c) - RH(r) \ (\%) \qquad (2)$$

Table 10. Results of the quality check of Relative Humidity data (see text)

A Station	B (+)	C (-)	D (0)	E (P)	F (Mean Dev.)	G (L)	G (U)	H (5%)	I (10%)
403	13	5	3	0.048*	+2	- 9	+10	30	0
481	11	7	0	>0.1	-1	-21	+ 8	28	11
531	3	15	0	0.004*	-4	-14	+ 9	39	11
541	7	8	3	>0.1	0	- 7	+12	28	6
571	7	6	2	>0.1	0	- 8	+ 8	21	0
580	11	7	3	>0.1	+1	- 8	+ 9	25	0
581	5	14	2	0.032*	-1	- 7	+ 9	10	0
659	7	7	1	>0.1	-2	-22	+10	35	7
665	2	18	1	<0.001*	-3	- 8	+ 4	20	0
673	11	9	1	>0.1	+1	-10	+12	30	5
743	1	19	1	<0.001*	-3	- 6	+ 3	15	0

Explanation:
column A station number
column B-D: number of positive, negative and zero deviations respectively (relative humidity from Td and TT minus hygrometer value)
column E : chance of having a number of positive or negative (the least of both) deviations less than or equal to the observed number, under the assumption that the chance of a positive or negative deviation is 0.5. * means significant at the 0.05 level
column F : average deviation in % RH
column G : range of deviations: L = lowest value, U = highest value
column II-I: percentage of deviations more than 5% RH, respectively 10% RH

Numbers of positive, negative and zero deviations are counted. A sign-test was used to determine the significance of deviations from the expected distribution of positive and nega-tive values of D (expected distribution: 50% positive and 50% negative). The reported relative humidity could seldom be reproduced exactly. Therefore, mean D and the range of D are determined. Furthermore, the relative amount of deviations of more than 5% and 10% RH respectively is also calculated. The results are shown in Table 10.

The interpretation of table 3.4.3.1 is not very easy. The way in which the dewpoint is calculated or determined is not clear. Furthermore, errors can be introduced because of rounding off to the nearest decimal and because the relation between temperature and dewpoint is not linear. But the observed differences are too large to be explained simply by procedural factors and errors as mentioned above.

The WMO states that a hygrograph, in perfect condition and in an environment which is not too dry, can measure relative humidity within 3% (WMO, 1983). For Zambia it is unreasonable to expect such an accuracy because perfect hygrographs cannot be expected anywhere and in Zambia very dry conditions can occur (relative humidity well below 40%). Therefore, the limit of 5% RH is used. Deviations of more than 5% RH occur in a considerable number of cases, and even deviations of more than 20 % occur (see Table 10, column G). These deviations may lead to considerable errors in the calculation of the water vapour deficit, an important variable often used in agro-meteorological models.

CONCLUSIONS

The results of this crude overall quality check may also indicate a lack of a direct quality and error check at the stations and when data records are completed. Therefore, consequent direct quality checks might be an important improvement (personal communication, STIGTER, 1987). The above indicates that more information is needed about the situation and the methods of measurement at the meteorological stations. This probably holds for all variables measured.

The continuity of measurements and observations at the Zambian meteorological stations is reasonable to excellent, depending on station and measured variable. But the continuity of especially relative humidity and dewpoint measurements should be improved.

Some contradictions are found in the precipitation reports. The reason for these contradictions are at present not clear.

No indication of bad rainfall measurements have been found so far. Differences in cumulative rainfall amounts after two rainy seasons are acceptable. More research is needed to draw more definite conclusions about the accuracy of rainfall data.

Moisture parameters (relative humidity and dewpoint) show inconsistencies, although dewpoint is probably calculated from relative humidity and mean temperature. The reported relative humidity could often not be reproduced. The reasons for the deviations that are found cannot be explained by procedural factors, errors due to rounding and errors due to the non-linear relation between temperature and dewpoint alone. The quality of the measurements and reports of relative humidity should be improved. A direct quality check might be an important improvement of the quality of humidity data.

4. FEASIBILITY OF MARS APPROACH

4.1. NUMERICAL SIMULATION OF THE SOIL WATER BALANCE AND CROP GROWTH

4.1.1. Coupling of the simulation models WOFOST, SWATRE and QUEFTS

The WOFOST model simulates the growth of a crop from emergence to maturity on the basis of physiological processes as determined by the crop's response to environmental conditions. The major processes are CO_2 assimilation, respiration, partitioning of assimilates to various plant organs, and transpiration.

The model follows a hierarchical approach. At the highest level, solar radiation and temperature are the only environmental conditions considered. At the second level, moisture availability is introduced as a possible growth-limiting factor.

The basis for the calculation of dry-matter production is the rate of gross CO_2 assimilation of the green canopy. A part of the assimilates is used by the crop for respiratory processes to provide energy for its own maintenance. The remainder of the assimilates is available for increase in structural dry matter. The increase in total dry weight of the crop is partitioned over the plant organs: roots, leaves, stems and storage organs, whereas the partitioning is a function of phenological development stage.

Transpiration refers to the loss of water from the plant to the atmosphere through the open stomata in its leaves. The transpiration losses are replenished through water uptake by the roots from the soil. Within the optimum soil moisture range for plant growth these losses are fully compensated, and transpiration and assimilation proceed at their potential rates. Outside that range the soil can be either too dry or too wet. Both conditions lead to reduced water uptake by the roots, dessication of the plant and hence reduced growth: in a dry soil due to water shortage, in a wet soil due to oxygen shortage. Soil moisture content in the root zone follows from a quantification of the water balance based on rainfall, runoff, soil surface evaporation, transpiration, and percolation beyond the root zone.

Potential production, i.e. the maximum possible production in a given environment of a particular crop characterized by its genetic and physiological properties, will only be attained if throughout the growth cycle the moisture content in the rooting zone remains within the optimum range, the crop's nutrient requirements are met, and complete control over weeds, pests and diseases can be achieved.

To increase the accuracy of the calculations, the original waterbalance module in the WOFOST model is replaced by the SWATRE model. The model combination of WOFOST and SWATRE is called: DUET (HUYGEN, 1987).

SWATRE is a transient one-dimensional finite-difference soil water-root uptake model that applies a simple sink term and different types of conditions at the bottom of the system. One bottom boundary condition includes the flux from the saturated zone, thus offering a possibility to link it with a regional saturated groundwater model.

The model uses input data concerning daily periods. As boundary conditions at the soil surface one needs data on rainfall, potential soil evaporation and potential transpiration over 24hr. The potential transpiration and potential soil evaporation data can be given directly as inputs to the program when available, or can be calculated from a combination type of evapotranspiration equation. The soil system is divided into m compartments of equal height. The profile can be split up into layers (containing one or more compartments) having different physical properties (i.e. soil-moisture characteristic and unsaturated hydraulic conductivity).

The rooting depth on each day is given as an input and may vary with time. At the bottom of the soil compartment various boundary conditions (pressure head or flux) can be introduced.

Soil fertility is evaluated according to the so-called QUEFTS system (Quantitative Evaluation of the Fertility of Tropical Soils) (GUIKING et al., 1983; JANSSEN et al., 1986; SMALING and JANSSEN, 1987 and JANSSEN et al., in prep.). The QUEFTS system comprises a number of successive steps. First, the quantities of nitrogen, phosphorus and potassium that are potentially available for uptake by a maize crop during one growth cycle, are estimated using empirical relationships between chemical soil properties and nutrient uptake. Relationships between actual and potential uptake are used to calculate the actual nutrient uptake by maize. For this actual uptake, ranges of yields are established, using uptake-yield relationships. From the yield ranges the actual yield level without fertilizer application can be calculated.

The actual uptake of one nutrient, for example nitrogen, is only equal to the potential uptake, if the soil supply of phosphorus and potassium is sufficient. If phosphorus supply strongly limits crop yield, the nitrogen concentration in the maize crop will attain a maximum level and the actual nitrogen uptake is maximized by the P-limited crop yield multiplied with the maximum nitrogen concentration in crop tissue. The same applies for the other nutrients.

For each of the nutrients nitrogen, phosphorus and potassium the relationship between uptake and maize yield has been established, both for the situation that the nutrient is completely diluted and for the situation that the nutrient concentration is maximum. If one nutrient is mainly limiting crop production, the concentration of that nutrient is minimum and the yield-uptake ratio for that nutrient is maximum. At the same time the concentrations of the other nutrients are high and in case of a large actual uptake of these nutrients, maximum nutrient concentrations may be attained and the yield-uptake ratios become minimum. From the actual uptake of N, P, and K and the yield-N uptake, yield-P uptake, and yield-K uptake ratios at minimum and at maximum nutrient concentrations the ranges in yield can be calculated. From the three ranges in crop yield for the nutrients N, P and K the actual yield can be calculated by weighing the effect on crop yield of the availability of the three nutrients.

The response of maize to fertilizer application is also calculated with the QUEFTS system. But in this case, data on the fraction of fertilizer nutrient taken up by the crop (recovery fraction) have to be collected from fertilizer trials. The QUEFTS system uses the maximum value for the recovery fraction, which only depends on the soil- and water regime-specific losses by leaching, precipitation etc. but which is not restricted by a limiting soil supply of other nutrients.

The amount of fertilizer nutrient applied is multiplied with the recovery fraction to find the additional uptake and in the QUEFTS system this additional nutrient uptake is added to the potential uptake of the unfertilized soil. The quantities of nitrogen, phosphorus and potassium that are potentially available for uptake by fertilized maize, are calculated in this way. The successive steps are just the same as described before for the use of the QUEFTS system without fertilizer application, i.e. actual nutrient uptake is derived from the potential uptake, yields ranges are established for the actual uptake, and at last, the actual yield level for the specified fertilizer application is calculated from the yield ranges.

To appropriately estimate actual agricultural production, the natural constraints, but also the actual farming practices, and the losses due to pests and diseases, harvest, transport and storage have to be known. On a regional scale, this kind of information may be obtained with a proper land-use farming systems survey.

4.1.2. Zambia case study

To assess the described crop growth model on a national scale, a study was carried out for Zambia. A detailed description is given in WOLF et al. (1987). Below a short summary of the study is presented.

Grain yields of maize, the principal food crop, are calculated for each land unit as defined along agro-ecological criteria. Four levels of maize production are distinguished with an increasing number of constraints to crop production, i.e. the potential yield, the water-limited yield, the nutrient-limited yield and the actual yield. For this study the soil map has been digitized to allow the selection of relevant soil and climate data combinations for the dynamic simulation model, the calculation of hectarage (TOMLIN, 1983), and the geographic representation of data and results of computations.

The digitization comprises transformation of the irregularly shaped mapping units into a rectangular grid pattern by assigning to each grid cell the number of its dominant map unit. For technical reasons the cell size is a rectangle having side lengths in the proportion of 5 to 3. In this study each cell represents 150 km^2. The reproduction scale of these digitized maps is about 1:8 800 000.

For the present study on maize production only the HYV cultivar MM752 of about 150 days is used for all maize growing areas in Zambia. In areas with high temperatures its growth cycle decreases to about 120 days.

The agro-climatic zonification was derived from existing maps. The agro-climatic zone map of SCHULTZ (1974) served as a base and its classification by two components, i.e. mean annual temperature and mean annual rainfall, is used. For Zambia 9 agro-climatic zones are derived from the map of mean annual rainfall via intersection with the map of mean annual temperature. For each agro-climatic zone a representative weather station (FAO, 1984a) is selected for the calculations of the crop production.

Soil information includes the geographical distribution of soils and their chemical and physical properties. For this study the soil map was used, supplemented by more detailed information from soil surveys and soil fertility research. The basis was formed by the 1:2 500 000 scale Soil map of Zambia (BRAMMER, 1973a). It is of a rather general nature, comprising a small number of soil units, resulting in a large variability in soil characteristics within one soil unit.

In general, the type of data required for the quantitative analysis used in this study cannot be derived directly from the definitions of the soil units. In fact, such data must be obtained through careful interpretation and comparison with data from other sources. For this study the units of the soil map were regrouped on the basis of inherent soil fertility and soil moisture characteristics.

The potential and the water-limited yields of maize are calculated with a dynamic crop growth simulation model. The potential yields depend on solar radiation and temperature only, as it is assumed that the supply of water and nutrients is optimal and no losses due to weeds, pests and diseases occur. Potential yields calculated for some locations in Zambia (Table 11) are in between 10 500 and 14 000 kg ha^{-1} (grains, air dry).

In the model the soil moisture content in the root zone follows from a quantification of the water balance based on rainfall, runoff, soil evaporation, transpiration, and percolation beyond the root zone. If the soil is too dry or too wet, the crop growth is reduced and the water-limited

Table 11. Calculated potential and water-limited yields (10^3 kg ha^{-1}) dry matter in grains) of maize HYV for some selected soil[1])-climate combinations in Zambia

Station	Soil type	Available moisture fraction	Total rainfall (growing season)		Pot yield	Water-limited yield	
			Average mm	Variation		Average	
Solwezi	Red clay	12.5%	1120	12.7%	11.7	11.6	2.7%
	Loamy sand	8.0%				11.4	4.1%
	Sand	5.0%				11.0	6.2%
Kabompo	Red clay	12.5%	819	20.3%	10.2	9.8	6.0%
	Loamy sand	8.0%				9.7	7.2%
	Sand	5.0%				9.3	10.4%
Sesheke	Red clay	12.5%	557	21.9%	9.5	7.1	31.1%
	Loamy sand	8.0%				7.2	18.0%
	Sand	5.0%				6.9	14.9%

1) Rootable depth of soil is set at 50 cm

yield becomes lower than the potential yield level. This difference in yield level indicates the damage due to drought or waterlogging and the scope for yield improvement by irrigation and/or drainage.

For the agro-climatic zones in Zambia, derived from the map of mean annual rainfall via intersection with the map of mean annual temperature, representative weather stations are selected for the calculations of crop production. For each relevant soil-climate combination, i.e. land unit, derived from the agro-climatic zone map via intersection by the digitized soil map, the water-limited yield is calculated with the model (Map 1), using a series of 20 years of generated daily rainfall.

The analysis of the water-limited yield has been done for maize cultivated on well-drained upland soils only and as a consequence, water-limited production refers to drought effects only. Soils that are insufficiently drained and/or are flooded during the wet season, are not suitable for maize production and are therefore left out of this analysis. In most cases yield reductions, due to water shortage, are small, i.e. less than 10 percent below the potential yield level, and also the yield variability (Map 2) is small. Only in zones receiving less than 800 mm rainfall during crop growth, mainly the southern part of Zambia, the yield reduction due to water shortage becomes more pronounced and the average value of the water-limited yields becomes about 7000 kg ha^{-1} grains (Table 11; Map 1). In years with low rainfall lower yields may occur, if at the same time the rainfall distribution is unfavourable and the water-holding capacity of the soil is low.

For the kinds of soil that are of importance for maize production in Zambia, chemical soil data are collected that are probably representative for these soils. These data are used to calculate the potential uptake by maize of soil nitrogen, phosphorus and potassium and the corresponding yield (Table 12). These nutrient-limited yields range from about 800 kg ha^{-1} (grains, air dry) on Barotse sands in the Western province to about 1400, 2000 and 3800 kg ha^{-1} on Sandveld soils, Red brown loams and Red clays, respectively that are found mainly in the Central, Eastern and Southern provinces (Map 3). According to these calculations phosphorus is the nutrient that mainly limits the maize yields. Comparing the water-limited yields with these nutrient-limited yields the scope for yield improvement by fertilizer application appears to be large.

Table 12. Soil supply of nitrogen, phosphorus, and potassium to a maize crop, calculated from chemical soil data representative for a number of soils occurring in Zambia, the corresponding grain yields[1)] of maize HYV (in kg ha^{-1}) and the nutrient that mainly limits crop yield

Soil	Soil supply			Yield kg ha^{-1}	Limits Nutrient
	N kg ha^{-1}	P kg ha^{-1}	K kg ha^{-1}		
Red clays	119.7	9.1	63.3	3843	PK
Leached red clays	38.3	1.0	77.4	360	P
as above after liming	63.8	5.6	58.1	2384	P
Red brown loams	45.9	4.3	101.8	2047	P
Leached red brown loams	23.8	0.75	74.5	210	P
idem after liming	42.5	3.8	54.6	1655	P
Sandveld soils	30.9	3.0	104.8	1384	P
Leached Sandveld soils	15.5	0.5	75.9	60	P
idem after liming	29.8	2.6	54.2	1165	P
Barotse sands	25.5	2.1	20.3	791	P

1) Grain yields with 12% moisture and without correction for losses

In the leached soils in the Northwestern and Northern provinces the pH is so low that maize production is almost impossible. Therefore, yields are calculated both for the original pH and for a pH of 5.5 attained by liming (Table 12). In these provinces shifting cultivation is mainly practised (Map 4), i.e. part of the forest is cleared and chopped branches and trunks are collected and burnt on the cultivated area. This has the same effect as liming and it enlarges the amounts of phosphorus, potassium and other nutrients that are taken up by the maize crop. In such systems the maize yields will be higher than the nutrient-limited yields calculated for the leached soils. For more permanent cropping on the leached soils liming is required.

The availability of nutrients is shown to be the most constraining factor in Zambia, so actual grain yields of maize are mainly a function of the natural soil fertility. Actual yields in traditional subsistence farming where no fertilizer is applied, are almost always lower than the calculated nutrient-limited yields, because part of the yields is lost.

Besides subsistence farming, three more advanced levels of farming are distinguished, i.e. small-scale emergent, medium-scale commercial and large-scale commercial farming, which mainly are found in the Central, Eastern, and Southern provinces of Zambia (see also AZZALI, 1987a).

For these four management levels the amount of fertilizer nutrients applied, the level of crop protection and the resulting loss-fraction are specified. These data are used to calculate for the main soil units in Zambia the actual yields (Table 13) with and without fertilizer application at the four management levels.

On the fertile Red clays, grain yields of about 5500 kg ha^{-1} (without losses) may be attained at the highest management level, which is near the water-limited yield. This indicates that in years with low rainfall in the southern part of Zambia and only on fertile soils water shortage may limit the yield of a fertilized maize crop, but that generally the availability of nutrients determines the maize yield. Only if the timeliness of soil tillage and sowing is far from optimal, the resulting later date of crop emergence may cause losses as result of waterstress at the end of the growth cycle of maize. Such losses may be overcome if crop varieties with a shorter growth cycle are grown.

A major problem in this study posed the rather general nature of the soil map (BRAMMER, 1973a). The number of soil units distinguished is rather small, resulting in a large variability in soil characteristics within one soil unit. This has caused the accuracy of the results of this study to be less than satisfactory. The new, more detailed version of the soil map of Zambia (VELDKAMP, 1983) was not yet available at the time of this study.

The same approach for studying the limitations to maize production can also be applied to other crops, as the methodology is universally applicable.

4.2. LANDUSE MAPPING BY MEANS OF HIGH RESOLUTION SATELLITE DATA IN ZAMBIA

4.2.1. Availability of LANDSAT-TM and SPOT-images in Zambia

A list of available and suitable (from 0 to 20 % cloud cover) TM and SPOT images was prepared for four TM-frames (Table 14). The four chosen TM frames include the main commercial agricultural areas of Zambia.

The search for TM and SPOT suitable images was made through respectively the EOSAT-TM image catalogue from January 1984 to February 1987 and through the SPOT image catalogue from January 1986 to April 1987.

Table 13. Grain yields[1)] of maize HYV at four management levels, without and with four levels of fertilizer application, calculated for selected soils occurring in Zambia and corrected for losses during harvest and for reductions caused by pests, diseases and weeds

Soil	Management level[2)]						
	I	II		III		IV	
	Yield[3)] unfert.	Yield		Yield		Yield	
		unfert.	fert.	unfert.	fert.	unfert.	fert.
Red clays	2356	3074	3476	3459	4350	3651	5234
Leached red clays	221	288	714	324	1258	342	1991
Idem after liming	1461	1907	2341	2146	3108	2265	3958
Red brown loams	1255	1638	2130	1842	2927	1945	3839
Leached red brown loams	130	168	585	189	1113	200	1829
Idem after liming	1015	1324	1776	1490	2492	1572	3321
Sandveld soils	848	1107	1498	1246	2084	1315	2765
Leached Sandveld soils	37	48	341	54	702	57	1227
Idem after liming	714	932	1266	1049	1786	1107	2398
Barotse sands	485	633	930	712	1368	751	1897

1) Grain yields with 12% moisture

2) Management level I (=traditional subsistence households): yield losses estimated at 0.30, local maize variety, no fertilizer application. Management level II (= small-scale emergent farmers): yield losses estimated at 0.20, high yielding maize variety, fertilizer application of 43(N) - 20(P_2O_5) - 10(K_2O). Management level III (= medium-scale commercial farmers): yield losses estimated at 0.10, high yielding maize variety, fertilizer application of 86(N) - 40(P_2O_5) - 20(K_2O). Management level IV (= large-scale commercial farmers): yield losses estimated at 0.05, high yielding maize variety, fertilizer application of 135(N) - 70(P_2O_5) - 35(K_2O)

3) Yield of local varieties that have a lower grain-stover ratio. This results in a lower yield-nutrient uptake ratio (see Table 7, SOW, 1987) and a lower yield

Table 14. Available and suitable TM and SPOT images; the indicated SPOT-frames cover each TM frame in the left-hand column

TM		Date available	Date available	SPOT		Date available	Date available
path	frame		during crop season	row	column		during crop season
170	70	21-5-84/22-6-84/9-8-84	21-5-84/29-11-84/16-1-85	132	379	11-7-86	
		28-10-84/29-11-84/16-1-85	9-4-86	132	378	11-7-86	
		9-4-86/31-8-86/2-10-86		133	379	27-8-86	
				133	379	27-8-86	
				134	378	27-8-86	
				134	379	27-8-86	
172	67	20-6-84/22-7-84	25-5-86	126	371	26-7-86	
		25-5-86/28-7-86		126	370	26-7-86	
				126	369	26-7-86	
				127	371	25-6-86	
				127	370	25-6-86	
				127	369	25-6-86	
				128	371	25-6-86	
				128	370	25-6-86	
				128	369	25-6-86	
173	72	24-4-84/25-5-84	24-4-84/25-5-84/14-4-86	122	386	10-7-86/5-8-86/26-9-86	
		1-10-84/18-11-84	30-4-86/25-5-86	122	385	10-7-86/5-8-86/26-9-86	
		14-4-86/30-4-86		122	384	10-7-86/5-8-86	
		25-5-86		122	383	10-7-86/5-8-86	
				123	386	31-7-86/26-8-86	
				123	385		
				123	384	26-8-86	
				123	383		
				124	386	31-7-86/26-8-86	
				124	385	31-7-86/26-8-86	
				124	384	26-8-86	
				124	383	26-8-86	
				125	386	26-7-86	
				125	385	26-7-86	
				125	384	26-7-86	
				125	383	26-7-86	
172	71	20-6-84/22-7-84	7-4-86/25-5-86	125	383	26-7-86	
		7-4-86/25-5-86		125	382	26-7-86	
				125	381	26-7-86	
				125	380	26-7-86	
				126	383	26-7-86	
				126	382	26-7-86	
				126	381	26-7-86	
				126	380	26-7-86	
				127	383	21-7-86/16-8-86	
				127	382	21-7-86/16-8-86	
				127	381	16-8-86	
				127	380	4-5-86/25-6-86/21-7-86	4-5-86
				128	383	21-7-86/16-8-86	
				128	382	21-7-86/16-8-86	
				128	381	16-8-86	
				128	380	4-5-86/25-6-86	4-5-86

LANDSAT TM

Delivery of TM image within three weeks from acquisition date is guaranteed by EOSAT under the following conditions: The first requirement is to contact EOSAT Customer Services at the EROS Data Center well in advance of the desired acquisitions to learn when Landsat 5 will be over the areas of interest. From these overpass dates, special acquisitions can then be ordered at least three weeks in advance of target dates. Assuming the possibilities of cloud cover on a target date, multiple attempts can be scheduled through the growing season with the understanding that the first acceptable scene for a given path/row point will terminate the standing acquisition request for that scene. There is no charge for special acquisitions other than a surcharge for a guarantee of 30 % or less cloud cover ($ 275), if requested.

When a successful scene acquisition takes place, EOSAT can place a special priority on processing and shipping CCT's. It is assumed that the requesting institute will bear the costs of any special shipment arrangements, which may include the cost of shipping CCT's by express mail from the Goddard Space Flight Center in Greenbelt, Maryland, where TM image processing takes place, to the EROS Data Center, where final product duplication and distribution occur. Under certain circumstances, customer-paid priority shipments can originate from Maryland. No other fees are currently assessed on priority digital product orders.

SPOT

The delivery of SPOT image-CCT within 3-4 weeks from the acquisition has been guaranteed by SPOT-Image.

4.2.2. Quality assessment of available phenological observations

The phenological observations of the 1984-85 crop season and collected on behalf of the Early Warning project in Zambia have been evaluated. For the entire Katete district only the phenological data of 5 stations out of 9 were available, furthermore such data were not complete. Table 15 gives the overview of the phenological observations available for the year 1984-85 in

Table 15. Phenological observations of crops cultivated in Katete district in 1984-85 crop season; for explanatory of crop coding see text

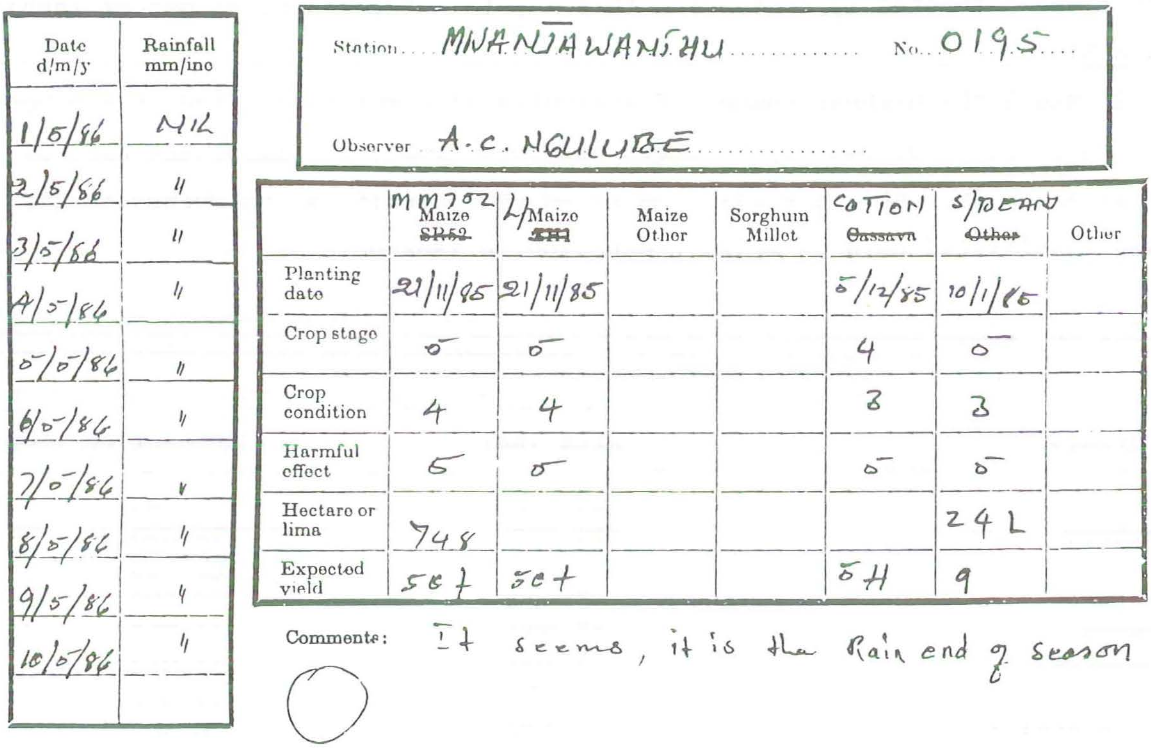
Crop		Decade 1984-1985	Phenological stage	Planting date
A1436		1-10/20-10	ploughing	
A1520	hybrid	11-11/19-11	seeding	19-11
A1520	local	11-11/19-11	seeding	15-11
A1436	hybrid	11-11/20-11	seeding	not specified exactly
A1520	hybrid	21-11/28-11	1	
A1520	local	21-11/28-11	1	
A1436	hybrid	21-11/30-11	no emergency yet	because no rain
A1436	hybrid	1-12/10-12	emergency	
A1520	hyb.+loc.	11-12/18-12	2	
A1436	hybrid	11-12/20-12	heavy weeds	
A1436	hybrid	21-12/31-12	3	
A1436		1-1/10-1		silage maize planted
A1520	hyb.+loc.	21-1/27-1	3	
A1520	hyb.+loc.	1-2/ 6-2	3	
A1642		1-2/10-2	3	5-12/13-12
A39	hybrid	1-2/10-2	tassel	5-12
A39	local	1-2/10-2	milky	10-11
A1642		11-2/20-2	3	
A39	hybrid	11-2/20-3	milky	
A39	local	11-2/20-3	milky	
A195	hybrid	19-2/28-2	2	12-11
A195	local	19-2/28-2	2	12-11
A1642		21-2/28-2	3	
A1642		1-3/ 9-3	4	
A195	hybrid	1-3/10-3	2	
A195	local	1-3/10-3	2	
A1642		11-3/31-3	4	
A1520		11-3/18-3	4	
A195	hybrid	21-3/30-3	2	
A195	local	21-3/30-3	2	
A1436		21-3/30-3	silage maize	harvested
A1642		1-4/10-4	4	
A195	hyb.+loc.	1-4/ 9-4	4	
A1642		21-4/30-4	5	
A1642		1-5/10-5	5	
B1520		1-12/8-12	seeding	7-12
B1520		1-12/8-12	1	
B1520		21-12/28-12	2	
B1520		1-2/ 6-2	3	
B1642		1-2/10-2	3	22-12
B39		1-2/10-2	with pods	10-12
B1642		11-2/20-2	3	
B39		11-2/20-3	flowering	
B195		19-2/28-2	2	20-11
B1642		21-2/28-2	3	
B195		1-3/10-3	2	
B1642		1-3/ 9-3	3	
B1642		11-3/31-3	4	

Crop	Decade 1984-1985	Phenological stage	Planting date
B1642	1-4/10-4	4	
B1642	21-4/30-4	5	
B1642	1-5/10-5	5	
C1520	1-1/ 7-1	seeding	2-1
C1520	21-1/27-1	2	
C39	1-2/10-2	flowering	16-1
C1520	11-2/16-2	3	
C39	11-2/20-3	flowering	
C195	1-3/10-3	2	
C195	21-3/30-3	3	
C195	1-4/ 9-4	3	
D1520	1-10/ 9-11	seeding	8-11
D1520	11-11/19-11	1	
D1520	21-11/28-11	2	
D1520	21-1 /27-1	3	
D1520	1-2 / 6-2	3	
D39	11-2 /20-3	balls	november
E1520	1-1 / 7-1	seeding	2-1
E1520	21-1 /27-1	2	
E1642	1-2 /10-2	3	26-12
E1520	11-2 /16-2	3	
E1642	11-2 /20-2	3	
E1642	21-2 /28-2	3	
E1642	1-3 / 9-3	3	
E1642	11-3 /31-3	3	
E1642	1-4 /10-4	4	
E1642	21-4 /30-4	5	
E1642	1-5 /10-5	5	

A = maize; B = groundnuts; C = sunflower; D = cotton; E = soybeans.
1 = vegetative; 2 = flowering; 3 = yield formation; 4 = ripening;
5 = harvest.

Katete district. Capital letters from A to E indicate respectively maize, groundnuts, sunflower, cotton and soybeans. The subscript of each capital letter indicates the station code, as established by the Meteorology Department of Zambia. Numbers from 1 to 5 in the phenological stage column of Table 15 indicate the phenological stage according to the definitions given by DOORENBOS AND KASSAM (1979).

A short explanation, describing the method of data collection, is given. People which have followed a training course on crop phenology assessment collect the phenological observation from the fields and write the data on postcards which are send every decade to the Department of Meteorology. An example of such card is presented in Figure 9. The whole data set represents input data for the meteorological model used in the Early Warning project to forecast crop production. A more accurate and widespread data collection should be obtained by the Department of Meteorology to achieve better results in crop yield forecasting.



Date d/m/y	Rainfall mm/ino
1/5/86	NIL
2/5/86	"
3/5/86	"
4/5/86	"
5/5/86	"
6/5/86	"
7/5/86	"
8/5/86	"
9/5/86	"
10/5/86	"

Station MWANJAWANTHU No. 0195

Observer A.C. NGULUBE

	MM752 Maize ~~SR52~~	L/Maize ~~SH1~~	Maize Other	Sorghum Millet	COTTON ~~Cassava~~	S/BEAN ~~Other~~	Other
Planting date	21/11/85	21/11/85			5/12/85	10/1/86	
Crop stage	5	5			4	5	
Crop condition	4	4			3	3	
Harmful effect	5	5			5	5	
Hectare or lima	748					24L	
Expected yield	50+	50+			5H	9	

Comments: It seems, it is the Rain end of season

Fig. 9. Prepaid post-card utilized for the collection of weekly rainfall and phenological information in Zambia

To increase the accuracy and achieve better results it may be suggested that:

- department of Meteorology should reply often to the cards indicating how to improve data collection;
- experts should go few times in the year to give training and to control the work;
- improve the crop phenology assessment through the use of pictorial representation of the main phenological stages of crops. The figures of growth stages shown in the FAO publiciation by DOORENBOS AND KASSAM, 1979 could be very effective.

4.2.3. Identification of important agricultural areas in Zambia

The Ministry of Agriculture in Zambia has provided a map (scale 1:1,500,000) of the location of each agricultural camp present in the territory till June 1975. From such a map the number of agricultural camps in each district was extracted by overlaying this map to a topographical map of Zambia (Map 5).

In Map 5 the highest number of agricultural camps is located in Southern province (139) followed by Northern province (103). The important agricultural areas in Zambia are also indicated in Table 16, which refers to the MAWD statistical data on maize production in 1982-83.

Table 16. Maize production in Zambia referring to crop season 1982-83; data source: MAWD statistical service

Province	Area (ha)	Production (ton)
Central	147,000	297,090
Eastern	221,000	278,640
Southern	80,000	162,720
Northern	35,700	76,500
Lusaka	25,000	44,550
Copperbelt	7,700	14,310
Western	12,100	11,880
North-Western	4,800	8,550
Luapula	3,400	5,670

Map 5. Agricultural camps in Zambia

4.2.4. Integrating satellite image analysis with the agricultural statistics collected by the Central Statistical Office

Data on crop hectarage, yield and marketable surplus are collected by means of direct interviews with farmers at three different periods; two in the growing season, one in the post-harvest period. Data are collected on a sample basis by complete enumeration within the selected Standard Enumeration Area (SEA). A number of SEA's are aggregated in a Census Supervisory Area (CSA). Typically 20% of CSA's are selected, with one SEA for each CSA. The boundaries of CSA's and SEA's correspond to physical features and have been mapped at 1:250,000 (CSA) and 1:50,000 (SEA) for the entire country.

Data are extrapolated to District and CSA level by applying so-called boosting factors, obtained as the ratio of the number of households in a District or CSA, respectively to the number in a SEA. Yield figures per unit area are obtained by the ratio of estimated production to acreage (bags/ha).

At times, complete enumeration could not be achieved in the selected SEA's. Extrapolation of land-use figures on the basis of households number, anyhow, can often give mis-estimations at the District and Province levels. The purpose of the integration, described in detail in DHV (1987b), is to assess the potential of Landsat-TM data to obtain the boosting factors as the ratio of agricultural land at the District level to agricultural land in a particular CSA/SEA.

The following activities have been performed, using an ERDAS Image Processing System:

- digitizing of the boundaries of a district, some CSA's within the district and some SEA's within the CSA's;
- digitizing of the geographic information such as the main roads, the main rivers, and the main settlements;
- geometric correction of a satellite image covering the district, the CSA's and the SEA's so that the satellite image matches the digitized CSA, SEA and the geographic boundaries;
- output on CCT in 512x512 pixel format of the corrected satellite image, the digitized CSA's, SEA's and geographic information;
- a report that describes the methodology, an evaluation of the methodology used and the accuracies involved.

Conclusion

It is very well possible to match high resolution satellite images to reference units of the Central Statistical Office of Zambia with the desired accuracy using an ERDAS Image Processing System.

The combination of satellite image processing with geographic information manipulation enhances efficient storage, retrieval, manipulation, analysis and display of large volumes of spatial data according to user-defined specifications. It is for instance possible to classify the satellite image according to landuse and to calculate the percentage landuse for each CSA or SEA. Auxiliary information like population density, animal units per hectare can be integrated and all kinds of combinations such as landuse per population density and carrying capacity maps can be derived. Also fields can be identified on the satellite image and in combination with the overlay of the roads the average distance between the roads and the fields can be calculated.

The GIS has a continuing need for timely, accurate update of the various spatial data elements. Remote sensing could assist to provide some of this data.

4.2.5. Analysis of NDVI data of Zambia in relation with agricultural statistics

NOAA-AVHRR (7.6 km resolution) data on Zambia have been provided by the FAO (Rome). These data are available as NDVI 10-day composite images, 36 for the whole crop year 1983-84. Four provinces respectively Eastern, Southern, Central and Northern are closely analysed by means of NDVI data. The four chosen provinces represent the most important agricultural areas 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; the graphic editor is able to 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, Southern, Eastern and Northern provinces) are created.

Photo 1 shows an example of such mask where national and provincial boundaries have been digitized. Overlaying the digitized mask on the NDVI images, mean NDVI values for the four provinces are extracted for each decade.

Photo 2 shows the colour coded NDVI values in Central province during the decade 20 to 30 March 1984, the colours have been assigned as follows: NDVI between 128 and 140 red; NDVI 141-153, magenta; NDVI 154-165, yellow; NDVI 166-178, blue; NDVI 179-191, dark green; NDVI 192-204, light green. Photos 3,4 and 5 show colour-coded NDVI values referring to the whole country in three different decades: 20-30 November 1983, 1-10 January 1984, 20-30 March 1984. For colour assignment see description given for photo 2. A profile or time-series plot of NDVI has been calculated by decade for each province and plotted (Fig. 10). The spatial sequence of the start of the growing season is evident (Fig. 10). The growing season started in the sequence: Northern, Central, Eastern, Southern province.

There seems to be no easy way to relate the differences between these NDVI plots to differences in agricultural production. The growing season 1984-85 can be taken as a reference for maximum production, since it has been a bumper harvest year for all of Zambia. In Fig. 10 the ratio of total production in the growing season 1983-1984 to 1984-1985 has been included to show that in the Southern Province, agricultural production in 1983-84 fell dramatically short of the maximum attainable level. In the other Provinces, much smaller reductions were recorded. The difference in the NDVI-evolution, however, was rather similar in the Eastern and Southern Provinces.

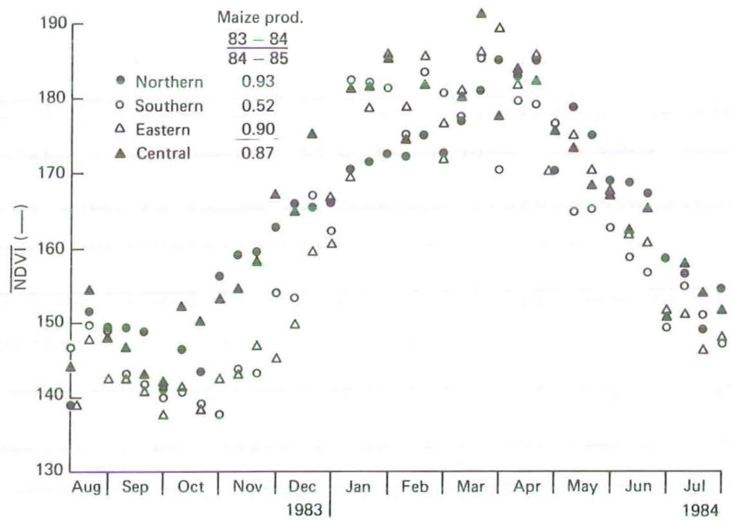


Fig. 10. NDVI time-series plots of Northern, Southern, Eastern and Central provinces for the crop season 1983-84; ratio of maize production in 1983-84 to 1984-85 calculated for the same four provinces

4.2.6. Analysis of LANDSAT-TM images of Zambia

Three LANDSAT-TM CCT's (2nd quadrant of frame 170-70 on 3 different dates) have been analysed. The acquisition dates are respectively 29-11-84, 16-1-85, 9-4-86. The 2nd quadrant of frame 170-70 is located in the Eastern province and it covers 80% of Katete district and part of Petauke district.

From the LANDSAT-TM image of 29-11-84 different sub-areas were extracted and colour coded images were calculated, using the reflectance values of bands 4/3/2.

Photo 6 shows a colour coded (bands 4/3/2) TM-image part of Petauke district, where woods and natural vegetation are coded with red colour while agricultural fields, at the time ready for planting, are light gray.

The formulas used to convert the digital count values in reflectance values for TM bands 2, 3 and 4 are:

Reflectance in band 2 = 0.24 * DN2 - 0.58

Reflectance in band 3 = 0.19 * DN3 - 0.29

Reflectance in band 4 = 0.29 * DN4 - 0.54

Where DNi = digital counts values in band i.

The second quadrant of LANDSAT-TM image 170-70 acquired on 16-1-85 was analysed (see Paragraph 4.2.4 and DHV, 1987), and furthermore utilized to map landuse.

The analysis of LANDSAT-TM image performed has resulted in a rectified-compressed TM image. The compression has been obtained by selecting one pixel out of 7 and one line out of 7. Three digital maps have also been prepared. Such maps can be used as masks and superimposed on the rectified TM image. The first map shows the boundaries of 19 CSA, the second map 7 CSA, while the third map shows the boundaries of Katete district, main roads, main rivers, main settlements and forests. To perform a landuse classification, rather limited ground truth data were available (a farm located in Petauke district). The farm landuse distribution is shown in Fig. 12, applying to the 1984-85 cropping season. Training sets were chosen to define the following classes: maize, peanuts, pasture, wood, water, flood 1 and flood 2, where the last two classes refer to land which is heavily flooded during the rainy season. Classification has been performed on a LANDSAT-TM sub-image of 300 lines x 300 pixels. The result of such a classification is shown in Fig. 11 (= Fig. 4.2.6.2., opposite page 70).

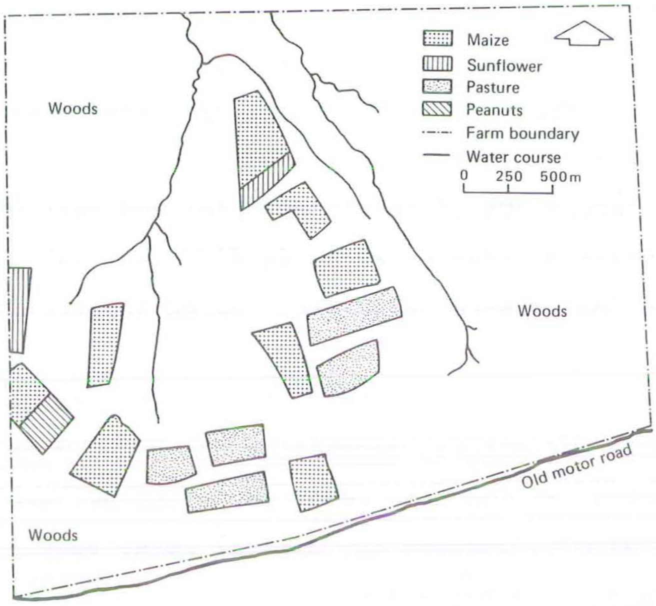


Fig. 12. Sketch of Kawere farm 2609, Petauke district, where landuse is referred to the crop season 1984-85

The use of either the compressed image or of the original one influences heavily the cost of automatic classification because of different amounts of pixels in the two images. Because of lower costs end of the limited acuring of the 1:250000 maps, the compressed TM image is used for the land use classification, which can be combined with the three digital maps mentioned before. Signatures of natural vegetation, water and agricultural fields respectively have been selected and applied to classify the compressed image. The digital map showing 19 CSA in Katete district is, then, superimposed on the classified TM image and the percentage of agricultural area for 12 CSA is calculated. Seven CSA are excluded from the classification statistics, because they are located outside the TM image.

Table 17, column 3 shows the agricultural area obtained for each considered CSA. Boosting factors for the CSA's were calculated according to the following equation:

$$\frac{A_d}{A_T} \frac{A_{AT}}{A_{CSA}} = B_f$$

where:

A_d : Area of whole district

A_T : Area compressed TM image

A_{AT} : Agricultural area in the compressed TM image

A_{CSA} : Agricultural area in each CSA

B_f : Boosting factor

and summarised in Table 17, column 4.

A large fraction of the agricultural area is located in the Southern part of the TM-image as confirmed by the high density distribution of agricultural camps located in the Southern part of Katete district. Also the 12 selected CSA are located in the high density distribution area of agricultural camps, as it is shown by the high percentage of agricultural area classified in the CSA. By multiplying each CSA agricultural area times the boosting factor, summing the individual areas and dividing by the number of areas yield the average agricultural area in the Katete district for the year 1984-85.

The average area is calculated to be 36,871 ha. The value given by MAWD was 51,369 ha.

A further analysis of LANDSAT-TM images of Zambia involved merging of 41 black and white photographic products (TM band 4) covering the total territory of Zambia. The elaboration of these photographic products is widely

Table 17. Total, agricultural area extension and boosting factors in 12 CSA located in Katete district

	Total area (ha)	Agricultural area factor (ha)	Boosting (ha)
Katete district	379,713	-	-
CSA 32	9936	2722	13.5
CSA 34	3248	1894	19.5
CSA 30	20672	3256	11.3
CSA 24	8108	2400	15.4
CSA 22	7952	951	38.8
CSA 37	1508	1087	33.9
CSA 38	7020	3116	11.8
CSA 39	6660	2289	16.1
CSA 48	13124	3586	10.3
CSA 19	3508	1465	25.2
CSA 17	3916	1134	32.5
CSA 43	7996	5353	6.9

explained (AZZALI, 1987b). The result of such elaboration is a base map to be used for the preparation of the landuse map to support MARS follow-up phases.

4.2.7. Selection of pilot areas for MARS-development phase

The most important commercial agricultural areas in Zambia are located in Central, Southern and Eastern provinces. Also in part of Northern and Lupula provinces efforts are underway to build up an intensive and commercial type of agriculture. Map 5, which shows the number and the location of agricultural camps indicates the provinces and districts in which agriculture is most advanced.

In particular, in the Southern province each district with the exclusion of Livingstone and Namwala, shows a high number of agricultural camps, particularly in Gwembe. In Central province, Chisamba district has the highest number of agricultural camps. In the Eastern province the distribution of agricultural camps is rather uniform. In Luapula province, Mansa, Mwense and Kawambwa districts show an intensive distribution of agricultural camps while in Northern province they are mainly located in Mbala, Isoka and Kasama districts.

To select the pilot areas for MARS-development phase, both the distribution of agricultural camps and the availability of LANDSAT-TM images have been taken into account.

In particular the most cost-effective selection is to choose a district having a large number of agricultural camps and located in one LANDSAT-TM frame. Accordingly, Chisamba district in Central province is chosen as one of the pilot areas for the MARS project. Chisamba district has 33 agricultural camps and is located for 90% of its area in LANDSAT-TM 172/70 frame.

In the Southern province the most efficient selection is the choice of Monze and Mazabuka districts which with an average number of agricultural camps, are located in just one LANDSAT-TM frame: 172/71. Even though Gwembe district has the highest number of agricultural camps (34), it is located in 3 different LANDSAT-TM frames. In addition, a second choice could be the selection of Kalomo district which has a higher number of agricultural camps than Monze or Mazabuka. However such a district is located partly

(70% of its total area) in one LANDSAT-TM frame 172/73 while the other 30% of its area is in 2 other LANDSAT-TM frames. In Eastern province Petauke district is chosen considering its number of agricultural camps (18). The LANDSAT-TM frame 170/70, however, contains 80-85% of the whole district. Addition of LANDSAT-TM frame 170/69 will cover the whole area of Petauke district. In Luapula province two different selections of pilot areas are possible. Many of agricultural camps are located in Kawambwa and Mwense districts, moreover the two districts are for the 95% located in one LANDSAT-TM frame (172/67). The other selection could be Mansa district which has the highest number of agricultural camps in Luapula and Northern provinces and, also, one LANDSAT-TM frame (172/68) is enough to cover the 95% of the whole district.

In the Northern province location, extension and shape of the district boundaries are such that no less than 2 to 3 LANDSAT-TM frames are required to cover any district. Fig. 13 summarizes the choice of the pilot areas for MARS-development phase showing the selected LANDSAT-TM frames and districts.

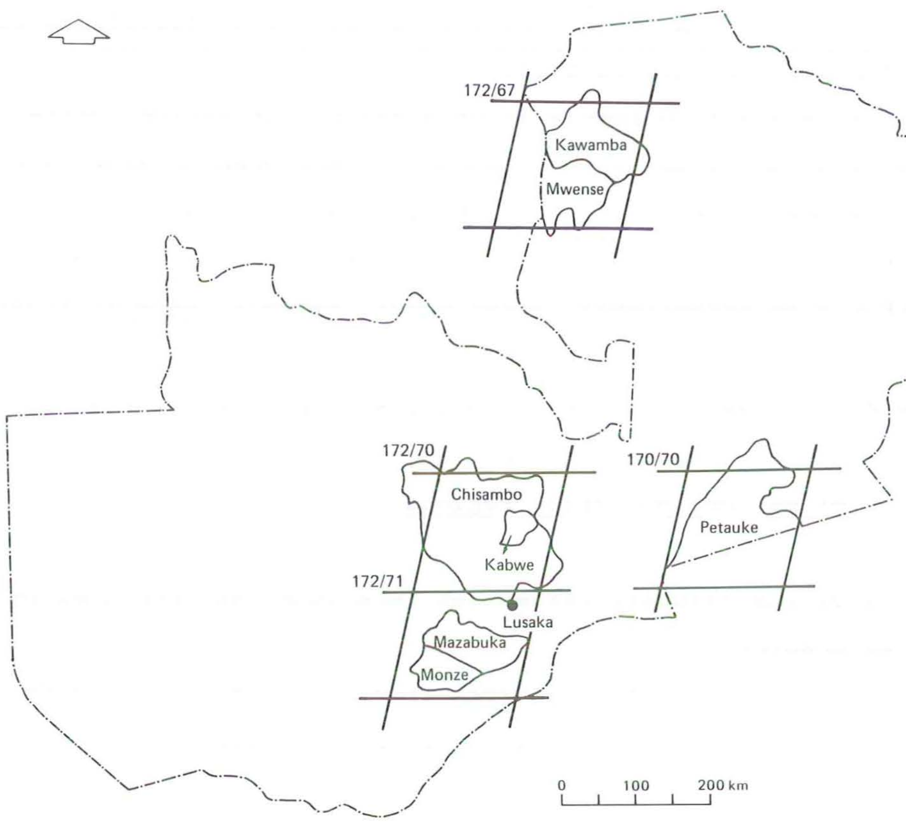


Fig. 13. Selected LANDSAT-TM frames and Zambian districts where the pilot areas of MARS-development phase are located

4.3. QUALITY ANALYSIS OF ARTEMIS RAINFALL ESTIMATIONS

4.3.1. Synoptic climatology of Zambia in relation with rainfall estimation techniques based on METEOSAT data

Although a detailed report has been given by JACOBS (1987), the main conclusions are summarized below.

Climatic conditions

On the average, more than 95% of the annual rainfall is confined to the rainy season (October - April). About 90% of the rainfall in Zambia is related to the Inter Tropical Convergence Zone (ITCZ) and the Zaire Air Boundary (ZAB). About 10% of the rain is attached to lows and troughs connected with Easterly and Westerly waves.

Minor contributions to the annual rainfall amount come from low stratiform clouds during Guti Conditions, and occasionally rainfall is attached to tropical cyclones. The contribution of Guti conditions is mainly outside the season and can be neglected. The probability of a significant contribution from tropical cyclones is small.

Most of the rainfall in Zambia is produced by convective systems and is highly localized, but some of the rainfall is produced by layered mid-level clouds (Nimbostratus), especially in the vicinity of the ITCZ. The contribution of this stratiform rain to the total amount of rain is not exactly known and should be established. Total annual rainfall amounts increase in a SE - NW direction. Anomalies are mainly due to orographic effects.

The rainfall in Zambia is highly variable. Short-term variability is larger than long-term variability. Furthermore, variability appears to be larger for drier periods and drier regions.

Applicability of the Rainfall Estimation Technique, as developed by University of Reading

The climate of Zambia is very different from the climate of the Sahel zone. The application of the method to estimate rainfall from Cold Cloud Duration (CCD) as measured by the METEOSAT-system, proposed by the University of Reading (UK) (MILFORD, DUGDALE, 1984; DUGDALE, MILFORD, 1985; CHADWICK et al., 1986; DUGDALE et al., 1986; FLITCROFT et al., 1986) cannot be applied directly in Zambia without considerable problems.

A satellite-based rainfall estimation technique in Zambia should contain:

- a cloud classification to identify rainbearing clouds;
- a delineation of the rainfall area within the rainbearing clouds;
- a classification of airmasses and/or a measurement of the moisture content of the air;
- the establishment of threshold values depending on the characteristics of the air;
- the incorporation of cloud dynamics.

Spatial Resolution and Temporal Resolution

The temporal scale and the spatial scale of the rainbearing systems in Zambia is very different from the scales related to the squall systems of the Sahel. Dimensions of the convective systems range from a few kilometers to a few tens of kilometers. The temporal scale has typically an order of magnitude of a few hours (1-2 hours).

Because of the limited spatial resolution of the METEOSAT-system (7.6 km), problems might occur in the detection of small convective systems. As these small systems may contribute significantly to the total rainfall amount, this might lead to difficulties in the rainfall-estimation technique with the METEOSAT-system. Moreover, the temporal scale of a substantial part of the rainbearing systems in Zambia might have the same order of magnitude as the time resolution of the METEOSAT-system and might also lead to detection problems.

Much more detailed information is needed about the size distribution and the distribution of the lifetimes of (thunder)-showers in Zambia to derive a suitable temporal - and spatial resolution and to estimate errors due to resolution problems.

Use of TIR and VIS Channels; Cloud Classification

The best way to achieve a cloud classification is through the combined use of the TIR and the VIS channels. Some 35 - 45% of the rainfall in Zambia falls at night. Thus, in a majority of cases the Thermal Infra Red band (TIR) can be used in combination with the Visible channel (VIS). The impossibility to use the VIS channel at night introduces errors.

Problems might occur at night when only the TIR can be used. Often cumuliform clouds transform into stratiform clouds at night and this transformation may not be detectable with the use of TIR alone. Furthermore, it is difficult to distiguish cirriform clouds from cumulonimbus - and Nimbostratus clouds on the basis of TIR alone. Much more research is needed to draw more definite conclusions because in literature some contradictions appear.

Delineation of the Rainfall Area

The classification of clouds might be well combined with the delineation of raining areas through the method proposed by LILJAS (1981, 1982, 1984). This method seems to be very promising, but some further research is needed to make the method suitable for the situation in Zambia.

Threshold Values

Threshold values must be adapted for Zambia. Moisture is an important factor in rainfall rate - height relations, and thus for the establishment of threshold values. This is important for the use of a rainfall estimation technique in Zambia, because different airmasses, having their main differences in moisture content, converge over Zambia. Moisture content might be accounted for by: the use of several sets of threshold values; or by the use of correction factors, after a stratification-procedure.

The moisture content of the upper troposphere can be measured with the Water-Vapour channel (6.3 μm) ((TURPEINEN et al., 1986). Other factors important to the establishment of threshold values are time of the season and latitude (distance from the ITCZ).

Cloud Dynamics

More information is needed about the number of rainfall events per ten days and per month in a certain area to decide whether effects of cloud dynamics may be disregarded.

4.3.2. Feasibility analysis of rainfall estimates in Zambia, using the Reading method

Introduction

In order to use METEOSAT data for the estimation of area rainfall, the Department of Meteorology at the University of Reading (U.K.) has developed the so called Cold-Cloud Duration (CCD) technique of rainfall estimation.

Initially the Reading researchers concentrated on the seasonally arid regions of West Africa but in 1986 the activities were extended to Sub-Saharan Africa east of 15 degr. E to investigate the applicability of the method developed so far for the Sahel.

The basis for the rainfall estimation technique is that in the Sahel region most of the rain comes from thunderstorms and that these extend high into the atmosphere: they can therefore be recognised in the Meteosat Thermal Infrared (TIR) satellite imagery by their cold tops. There is, however no unique relationship between cloud-top temperature and rainfall. Through the life-cycle of a storm the cloud-top temperature drops rapidly during the development stage, reaches a minimum, then increases slowly over a period of hours. The storms which dominate in West Africa produce most of their rainfall at about the time that the clouds reach their lowest temperature. What that temperature is and the amount of rain produced depend on the physical and dynamical structure of the atmosphere at the time. Hence, to estimate the rainfall from satellite TIR data, one must identify those characteristics which are associated with active storms and deduce the empirical relationships between the observed characteristics and the rainfall.

The basic rainfall estimator is the presence of cloud below a particular temperature threshold. If several storms affect a region, the variations of intensity of the individual storms may be averaged out. So, over a period which is likely to include several storms, the total duration of cold cloud may be used as a rainfall indicator. This is the technique used for producing ten-day and monthly rainfall estimates. Daily estimates, however, require modulation factors which reflect the activity of the storm at the time it affected the area.

The climatic situation in Zambia is rather different from the situation in the Sahel. The rain-bearing systems for instance are much smaller and have shorter lifetimes, moreover they show hardly any organization in relatively well-defined structures. It is therefore not yet unequivocally clear that the Reading method is direct applicable to the Zambian situation. The following section attempts to shed some light on this issue. For the more detailed analysis reference has to be made to HUYGEN, VAN DIJK (1987).

Analysis of the METEOSAT data

Four decades (January, February 1987) of Meteosat data covering Zambia have been analysed according to the CCD technique:

- 24 hourly images (slots) are read from 1600 bpi (bits per inch) computer compatible tape;
- 34 pixels, corresponding to the 34 meteorological stations in the Zambian climatological network, are extracted from each slot;
- For those pixels the raw counts are converted into temperatures, with the help of appropriate calibration factors;
- For each slot the absolute temperatures of the selected pixels are compared to three threshold temperatures, -40, -50 and -60 degr. C respectively. Pixels showing temperatures below one or more threshold temperatures are adding to a score that is kept for each treshold temperature. After a ten day period the total score is called Cold Cloud Duration (CCD, hours).

Linear regressions of measured rainfall on cold cloud duration have been calculated for three threshold temperatures and over the four decades.

Results

Table 18 shows the regression equations. It appears that the optimum threshold temperature is -50 degr.C for the first three decades and -40 degr.C for the last decade (See: HUYGEN, VAN DIJK, 1987 for motivation). The last decade is incidentally also the one with the least amount of rain.

Conclusions

The analysis has shown that the CCD-technique of rainfall estimation has potential, in spite of the fact that the climatic situation in Zambia is quite different from the situation in the Sahel.

Although the standard deviations of the regression equations are rather high (2 to 3 mm per day), the method should enable us to distinguish areas with ample rain from areas that suffer more or less from grought, which is after all one of the main tasks of an Early Warning System.

The analysis suggests that is will not be possible to work with a fixed algorithm to estimate the rainfall. The constants in the linear regression equation vary from decade to decade as does even the optimum temperature

Table 18. Linear regressions of rainfall and cold cloud duration for three temperature thresholds over four decades

	-40	-50	-60
21/31 JANUARY	P =3.13D - 23.73 R :0.92 SD:18.8	P =4.54D - 0.38 R :0.81 SD:30.0	P =6.18D + 27.52 R :0.57 SD:41.3
1/10 FEBRUARY	P =2.00D - 6.78 R :0.61 SD:31.1	P =2.81D + 0.74 R :0.61 SD:31.0	P =6.23D + 5.37 R :0.84 SD:19.8
11/20 FEBRUARY	P =1.90D - 8.42 R :0.95 SD:11.8	P =2.66D - 3.04 R :0.94 SD:12.0	P =5.53D + 8.09 R :0.77 SD:27.7
21/28 FEBRUARY	P =2.09D - 0.27 R :0.73 SD:18.0	P =1.42D + 23.45 R :0.38 SD:24.5	P =2.32D + 29.49 R :0.41 SD:24.2

-40 threshold temperature of -40 degr.C
-50 threshold temperature of -50 degr.C
-60 threshold temperature of -60 degr.C
P precipitation (mm/decade)
D cold cloud duration (hours/decade)
R correlation coëfficiënt
SD standard deviation (mm)

threshold level. It is probably inevitable to always use the Meteosat images in combination with good quality raingauge measurements and recalibrate every decade or whatever timebase is used. In this respect it is nonetheless striking that the regression lines found for the secound and third decade match very well with the optimum algorithm found by Milford and Dugdale (1987) for the climatic conditions of Sudan: P=2.7*CCD, with a threshold temperature of -50 degr.C.

The full potential of the CCD method can only be revealed after an extended period of investigation and thereafter in the course of years once the ARTEMIS System becomes operational.

5. LINKING ARTEMIS OUTPUT TO MARS DATA BASE FOR ZAMBIA

5.1. THE ARTEMIS DATA STRUCTURE AND GEOGRAPHICAL REFERENCE SYSTEM

A detailed description of the ARTEMIS data formats is given in NLR (1987). Here an overview of the end products and their organization will be given.

5.1.1. End product specifications

Three different types of end products are distinguished:

- main products are those outputs from the system that are essential for its operational function in the area of interest as defined by FAO and are implemented and tested by NLR;
- additional products are those products that the system is capable of producing additionally with the soft- and hardware developed by NASA/GSFC;
- optional products are outputs that are considered as an essential growth potential for the operational system, but for which no provision has been made as yet.

5.1.2. Main products

The system shall be capable of producing the following main products:

- raw NOAA/GAC imagery
- raw METEOSAT imagery
- the Decade Composite NDVI map
- the Monthly Composite NDVI map
- the Decade Estimated Rainfall map
- the Monthly Estimated Rainfall map
- the Number of Estimated Rainfall days per Decade map
- the Number of Estimated Rainfall days per Month map

The common geographic format of all mapped images shall be:

- in an equal area projection (Hammer-Aitoff)
- with 7.3 km resolution
- in a fixed grid of 1280 by 1024 pixels

The system shall produce the thematic maps:

- the Monthly estimated rainfall anomalies map in mm
- the Monthly estimated rainfall anomalies map in percentages of normal
- the Decade PBAF map
- the Crop moisture availability map
- extracted areas (from maps in the common geographic format)
- map point data lists

The appropriate methodologies and algorithms shall be developed by FAO. Other thematic derived maps can be implemented as the algorithms do not include the use of knowledge-based data.

5.1.3. Image data base specifications

The thematic processing system shall maintain a database which shall be split into two parts:

. user defined products

. main products, including:

- raw NOAA/GAC imagery
- raw METEOSAT IMAGERY
- the Decade Composite NDVI map
- the monthly Composite NDVI map
- the Decade Estimated Rainfall map
- the monthly Estimated Rainfall map
- the Number of Estimated Rainfall days per Decade map
- the Number of Estimated Rainfall days per Month map
- the Monthly estimated rainfall anomalies map in mm
- the Monthly estimated rainfall anomalies map in percentages of normal
- the Decade PBAF map
- the Crop moisture availability map
- extracted areas (from maps in the common geographic format)
- map point data lists

The database shall be partly located on disk, partly on magnetic tape.

5.1.4. Map format

The maps in the common geographic format (when displayed on the screen) have the following properties:

- 1024 lines of 1280 pixels;
- center point of the map, pixel (11512,P640) is located at 1 degree North and 17 degrees East;
- the grid cell size is 7.61 km;
- the map is in the Hammer-Aïtoff polyconic and LAT, LON with origin 0.0 in the upper left corner is as follows:

$$\text{PIX} = \text{INT}\left(\left(640-84.142227\ \frac{\text{SQRT}(2)\ \ 10\ \ \text{SIN}(\text{LAT}-1)}{\text{SQRT}(1 + \text{COS}(\text{LAT}-1)\ \ \text{COS}((\text{LON}-17)/2))}\right) + 0.5\right)$$

$$\text{LINE} = \text{INT}\left(\left(512-84.142227\ \frac{2\ \text{SQRT}(2)\ 10\ \text{COS}(\text{LAT}-1)+\text{SIN}((\text{LON}-17/2)}{\text{SQRT}(1 + \text{COS}(\text{LAT}-1)\ \ \text{COS}((\text{LON}-17)/2))}\right) + 0.5\right)$$

where:

PIX : X-coordinate

LINE : Y-coordinate

LAT : the geographical latitude

LON : the longitude in degrees

Earth radius: 6378.38 Km

Pi : 3.141592654

Example : 35 degrees North, 52 degrees East + Line 69, pixel 143

5.1.5. List of ARTEMIS interfaces

<u>Inter assembly interfaces</u>:

1. PDUS communication - Image selection and mapping
2. METEOSAT transformation matrix generation - METEOSAT image selection and mapping
3. METEOSAT image selection and mapping - Rainflow
4. NDVI - PBAF
5. Database management - other assemblies
6. Image files in common geographic format
7. Mailboxes

External interfaces:

1. METEOSAT PDUS - HP
2. National boundary overlay
3. Day timer
4. NDVI level slicing/colour coding parameters
5. PBAF level slicing/colour coding parameters
6. ERF level slicing/colour coding parameters
7. Absolute rainfall anomalies level slicing/colour coding parameters
8. Relative rainfall anomalies level slicing/colour
9. Crop moisture availability level slicing/colour
10. NOAA GAC tape format
11. PBAF weighting matrix
12. (Deleted) Engineering values of external data
13. PDUS protocol interface
14. (Deleted) Data format floppy disk
15. External map tape format

5.2. THE MARS DATA STRUCTURE AND GEOGRAPHICAL REFERENCE SYSTEM

MARS aims at the establishment of a linkage between the data provided by meteorological satellites, i.e. METEOSAT and NOAA, a.o. through the forthcoming ARTEMIS system of FAO HQ and the operational requirements of crop yield forecasting and monitoring at the national level.

The operational ARTEMIS system is, as described in the preceding section, an integrated system that shall be capable of real-time acquisition of METEOSAT data and processing the imagery from METEOSAT and NOAA satellites. The ARTEMIS system shall be capable of producing the following main products:

- the composite Normalized Difference Vegetation Index (NDVI) map (per decade and month);
- the estimated rainfall map (per decade and month);
- the number of estimated rainfall days map (per decade and month).

The system shall be capable of delivering subsets (i.e. at country level) of any output product (i.e map or imagery).

An outline of the MARS system is given in Fig. 14. The system will improve the real-time information on the crop specific production per major

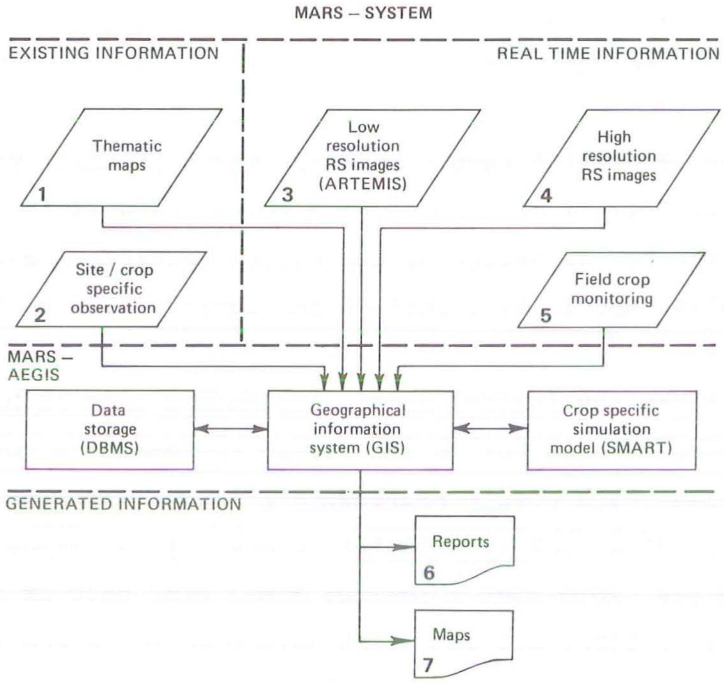


Fig. 14. MARS-Agro-Ecological Geographical Information System (MARS-AEGIS)

agro-ecological zone in Zambia. This will be achieved by the implementation of the MARS Agro Ecological Geographical Information System (MARS-AEGIS) within the framework of the Zambian Crop Forecasting and Early Warning Unit (CFEWU). MARS-AEGIS consists of a (commercial/low budget) Geographical Information System (GIS) with digital remote sensing processing possibilities, a Data Base Management System (e.g. Oracle DBMS) and the crop specific numerical simulation model SMARTies, acronym of Simulation Model using ARTEMIS Real-Time information and environmental specifications (see Section 4.1). The SMART model consists of the components of the model WOFOST, SWATRE and QUEFTS (Section 4.1.1).

The MARS hard- and software configuration will be accommodated within the Zambian CFEWU procedures, such as the current data acquisition on the crop yields and cropping areas (see Fig. 14, item 5) and the reporting (items 6 and 7). However, the MARS methodology will use additional information, comprising:

- already existing information, a.o. available at the agricultural research institutions, such as (see also Chapter 3.):

  (item 1): thematical information, e.g. a soil map, physiographical map, landuse and vegetation map and topographical maps;

(item 2): location/site specific information on weather, soils and crops;

- real-time acquired data using remote sensing, subdivided in

  (item 3): low resolution remote sensing images obtained from the meteorological satellites and available via the forthcoming ARTEMIS system at FAO HQ;

  (item 4): high resolution remote sensing images (Landsat TM, SPOT).

The outline of Fig. 14 appears to be a rather good way of presenting the MARS system. However, the design of the system requires a more detailed logical information model. As a part of the contribution to MARS-PPDS, NLR participated in the drafting of such a model (VAN DE LAAN, et al., 1987).

Fig. 15 describes the logical model. The method used is based on information flow concepts. Each box in the figure represents a logically related set of information; each circle represents a logical process, i.e. a transformation of one set of information into a new set. An arrow indicates a flow of information. Note that a logical model aims only at describing which tasks must be performed and which data have to be manipulated. How these tasks are performed or how the data is stored is irrelevant.

The processes distinguished will be fully described in VAN DE LAAN, BERKHOUT and VAN INGEN SCHENAU (1987). A summary description of the important processes is given here.

Process 1: delineation of the agro-ecological zones to be used during a new growing season. The delineation will be performed before the start of the growing season on basis of the geographical reference system of the CFEWU (i.e. Province, District, CSE, SEA; see section 1.4) and the available thematical information. In this respect, the definition of the MARS geographical reference system is important (see below). Updates of the agro-ecological zones maps will be a result of the experiences in the preceding growing season.

Process 2: definition of the statistical weather generator per meteorological station. The historical weather data sets are required to define the weather generator.

Process 3: determination of the start of the growing season over the country per agro-ecological zone. The information used are the agronomical and meteorological field observations and the NOAA-ARTEMIS NDVI maps.

Process 4: determination of the normative production levels over the country per defined crop, agro-ecological zone (incl. start of growing season and standard/statistical weather) and main, possibly sub-main farming system in the agro-ecological zone. The normative production figures results from the SMART model, using the information as described in section 4.1.1. Statistical accuracy boundaries are obtained by means of the application of the weather generator.

Process 5: estimation of the relative production reduction due to the possibly unfavourable weather conditions. These values result from the water balance module of the SMART model using: the ARTEMIS rainfall and rainday estimate or the actual meteorological observations. The resulting fraction of crop growth reduction factor is applied to reduce the normal production levels (process 4).

Process 6: estimation of the agricultural production by the Department of Meteorology applying the procedures currently in use (section 1.4).

Process 7: estimation of the acreage of the distinguished crops using high resolution satellite imagery. The multi-temporal analysis methods, described in section 4.2.6 will be applied. However, in regard to the number of frames and the costs involved, the MARS system will use only a limited number of representative frames (see section 4.2.7).

Process 8: estimation of the total agricultural production (mainly acreage) by the CFEWU, applying the MAWD-CSO methods. These methods are described in section 1.4; however, to increase the current accuracy, the CFEWU should merge these methods.

Process 9: estimation of the total agricultural production using the MARS system: the production figures will be obtained by merging the results of process 5 and process 7.

Process 10: estimation of the CFEWU forecast using the MARS methodology and the currently applied procedures. After several years of experience, a new procedure comprising the processes 5 up to 10 may be defined.

According to the National Preparedness Plan (NPP) of Zambia it has to be noted that the processes 5-10 will have to be executed each month during the growing season; according to the current practices of the CFEWU only the following data collection activities are perfomed:

- the preliminary forecast (January, February)
- the forecast (March)
- the post-harvest production estimation (August)

The definition of the MARS-AEGIS geographical reference grid is based on:

- the defined ARTEMIS grid system (VAN INGEN SCHENAU, et al., 1986), having a 7.3 km resolution, mapped in an equal area projection;

- the quality assessment of the available thematical information, particularly the soil-physiographical map of Zambia;
- the intended level of accuracy of MARS crop forecasting methodology, which implicitly includes the number of calculations to be performed to estimate in real-time the Zambian agricultural production (i.e. available micro-computer time).

As a preliminary result of the information quality assessment, it appears that the Landuse map of SCHULTZ (1974) is possibly the most valuable map, containing information regarding the landuse as well as -implicit- the physiography and soils of Zambia. Based on a.o. its map scale, the smallest mapping units, the total number of mapping units, it can be concluded that the loss of information is neglectable if MARS-AEGIS uses a resolution of 3.65 km (4 MARS grids into 1 ARTEMIS grid). Other considerations will be given in NLR by VAN DE LAAN et al. (1987).

Note that the MARS reference mapping system will be defined as compatible with the ARTEMIS reference system. This results from the fact that ARTEMIS output products will be major inputs of the MARS system:
- the NOAA NDVI maps to estimate the start of the growing season (process 2). A major research option will be the analysis and the definition of the procedure to apply the NDVI observations to monitor the whole growing season;
- the METEOSAT rainfall and rainday maps to estimate the production reduction due to water shortages (process 5).

Another research option will be the analysis and definition of procedures to derive synoptically other meteorological variables (e.g. irradiance using the cloudiness).

5.3. INTERFACING ARTEMIS OUTPUT WITH THE DATA PROCESSING SYSTEM INVOLVED IN THE NEXT MARS PHASES

5.3.1. General

It is currently foreseen that most data analysis during the forthcoming MARS-phases will be carried out by means of the image processing systems available to the Institutions participating in the project. For such cooparation to be effective a simple and reliable interfacing procedure must be

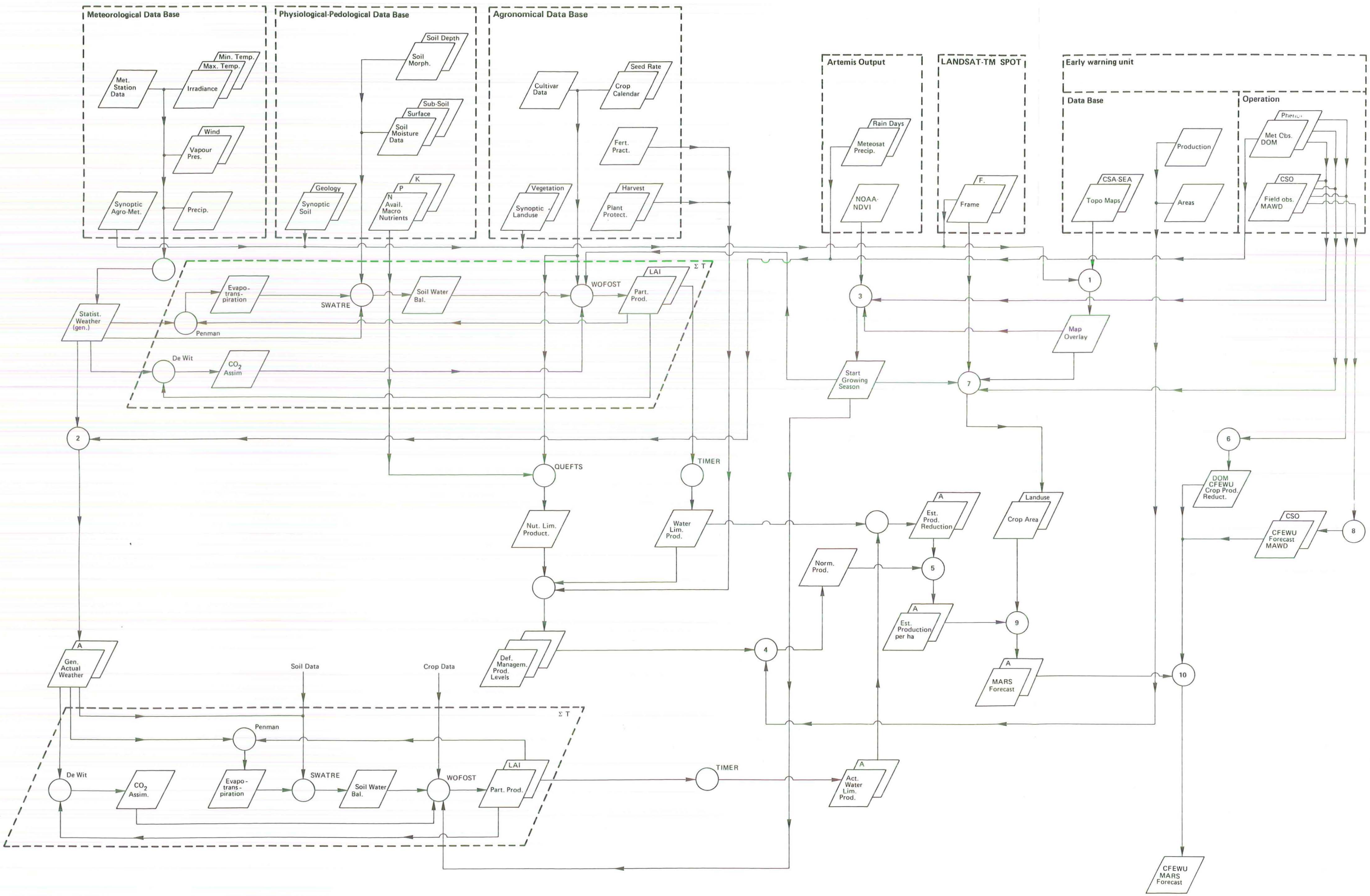


Figure 15. MARS activity diagram

defined to exchange data between these systems. In this section each system is briefly described and then such procedure is specified. Detailed descriptions, including hardware configuration charts, are given in DHV (1987a).

5.3.2. Synopsis of the image processing systems

Agricultural University of Wageningen: Remote Sensing System

This system is one of the older image processing systems in the Netherlands and consists of a self written computer package for remote sensing image processing combined with a tailored statistical package called Patima. This system will be replaced in the near future by a VAX based system. The system is for educational purposes but is to a limited extent accessible to others.

DHV Consulting Engineers: ERDAS Geographic Information System and Remote Sensing Image Processing System

DHV's ERDAS image processing system was the first of a series of ERDAS systems installed at different institutes in the Netherlands. The ERDAS image processing system has a microcomputer. The choice for a microcomputer driven image processing system is based on the recent rapid increase in performance cost relation, in comparison to minicomputer driven systems. Also the use of this system is very economical compared to the minicomputer based image processing systems. Another important issue was the need for thematic mapmaking and analysis of remote sensing data together with other information. The ERDAS system not only has a package for remote sensing image processing but also an integrated raster based Geographic Information System. This makes it very suitable for the above mentioned tasks and planning activities such as land evaluation. In addition to the ERDAS system, DHV also uses a low cost faster Geographic Information System called CRIES. CRIES is ERDAS compatible and suited for processing on IBM PC/XT or other microcomputer. This system can be used as a front end system for digitizing and analysis of thematic maps for local use in projects. The files can be sent on floppies to the central ERDAS system for further analysis, for instance in combination with remote sensing imagery. DHV is also equipped with a vector based Geographic Information System which has integrated relational Database Management System, called IGOS. In the near future this system will be integrated with the ERDAS Geographic Information and Image Processing System.

ICW/Stiboka: ARC/INFO-ERDAS Geographic Information System and Remote Sensing Image Processing System

This combined Geographic Information System - Remote Sensing System will be installed in mid 1987 and will be used by four Dutch agricultural institutes. These are:

- Institute for Land and Water Management Research (ICW)
- Soil Survey Institute (Stiboka)
- Research Institute of Nature Management
- Dorschkamp

The central part of the system is the ARC/INFO Geographic Information System, which will be installed at the central facility. Workstations will be installed in the institutes for interactive editing and plotting of maps. In addition an ERDAS image processing workstation is connected to the central computing facility on which ERDAS modules for batch processing are installed.

ITC: Context Vision-PDP11/44 Remote Sensing Image Processing Facility

At present the Image Processing Laboratory (IPL) of the ITC is the largest remote sensing image processing facility in the Netherlands. The system, which is mainly used to educate students and for research, consists of different image processing systems. These are:

- a PDP 11/44 image processing system, with an in-house developed remote sensing image processing software package;
- a DIPIX ARIES II subsystem;
- a Context Vision image processing system;
- a group of BBC microcomputers with in-house developed image processing software and a vector based Geographic Information System.

The PDP 11/44 image processing system has a central Digital PDP 11/44 minicomputer, two Ramtek colour video terminals, an array processor for fast vector calculations, printers, including a Gould electrostatic printer, a total of 1 GigaByte of disk storage. The image processing system has two 1600 BPI tape units. An ARIES II DIPIX subsystem and a context Vision image processing subsystem are interfaced through the PDP 11/44 image processing system. The ARIES II system of ITC is the same as the ARIES II system of the National Aerospace Laboratory (NLR) except that a PDP 11/23 minicomputer is used. The special features of the Context Vision are the high speed performance and the unique capacity to analyse the structural features of objects.

NLR: RESEDA Remote Sensing Image Processing System

The Remote Sensing Image Processing System, RESEDA (Remote Sensing Data Analysis) of the NLR is a DIPIX ARIES II system. It is used for the processing of remote sensing data collected on board of aircrafts and spacecrafts. NLR acts as the National Point of Contact (NPOC) for the distribution of ESA data of the Earthnet satellite ground station network for ESA and SPOT Image.

5.3.3 Interface Procedures

It is anticipated that the MARS project will use the different image processing systems described above. Therefore interface procedures have to be defined. Because all the systems involved have or will have (ICW/STIBOKA ARC/INFO-ERDAS System) a tape unit of at least 1600 BPI, computer compatible tapes (CCT's) will be used for data exchange. In addition the two ERDAS systems can exchange data on MS-DOS floppy disks of 360 KB and 1.2 MB; if limited quantities of data are involved.

Exchanging remote sensing data on standard tapes

A variety of different tape formats can be read by the image processing systems involved. These are BSQ, BIL Landsat Thematic Mapper and Multi Spectral Scanner, SPOT, BIP Landsat MSS and NOAA/AVHRR standard tape formats. Reading of tapes in which one record consists of a number of image lines can be a problem. This holds especially for the image processing system of the Agricultural University of Wageningen. Tapes written in 6250 BPI have first to be converted to 1600 BPI before they can be processed by most of the image processing systems. This conversion can be done at most participating institutes and companies on their mainframe computer systems. It is recommended to select the BSQ tape format and 1600 BPI as standard. In addition one record should consist of one image line. This will facilitate the exchange of remote sensing data between the image processing systems.

Exchanging remote sensing data on non-standard tapes

All image processing systems are capable of written simple non-standard BSQ and BIL tape formats. An exception for the image processing system of the Agricultural University of Wageningen exists because tapes cannot be written in BIL format. The DIPIX system of the ITC and therefore NLR are also able to write the International Data format. Because the image processing software of the Agricultural University does not contain a program for writing remote sensing images to tape, use must be made of the standard PDP 11 RT-11 operating system tape write programs. These tapes can have reading problems with the other image processing systems. Although this system forms an exception, a non-standard BSQ can be employed for exchanging remote sensing images between the systems. In this format one record of a file should consist of one image line.

Exchanging non-remote sensing image vector data

The optimal way to exchange digitized data vector between the image processing systems is a grid or raster format. This format is compatible with remote sensing data which can be read in a variety of formats by the participating image processing systems. The conversion takes place through a vector-raster conversion algorithm. But this program is not available on the DIPIX systems and no information was obtained whether this algorithm is available on the Context Vision system. The software of the image processing system of the Agricultural University of Wageningen has a limitation, because the vector information is converted to a raster by the use of the video memory of the Genisco colour monitor. Only small raster files of the size of the video memory (512*512*8 bit) can be created, as the system does not contain software to mosaic these rasters into larger files. The ERDAS systems of DHV and the one of ICW/STIBOKA as well as the DIPIX systems of ITC and NLR can exchange vector data files without first converting them to a grid or raster format. In addition the ERDAS systems can exchange vector data on floppies. The advantage is that vector files requires less storage capacity then raster files. It is suggested to perform the digitizing activities in the MARS project on the two ERDAS systems as they are able to convert the vector format into a raster format. Also these systems can write the raster data to tape in a format that can be read by all the image processing systems participating in the MARS project.

5.3.4. Conclusions

A number of Dutch institutes and companies will participate in the MARS project and use will be made of their remote sensing image processing capabilities. Therefore a clear and reliable interface procedure between the image processing systems is required. It is recommended to use 1600 BPI tapes as a means for exchanging remote sensing images, as all the systems have or will have at least a 1600 BPI tape unit.

However in most cases, reading and writing of 6250 BPI tapes can be performed on the central mainframe facilities of each participating institute. These tapes have to be converted to 1600 BPI tapes before processing can take place on a number of image processing systems. All the participating image processing systems can read a variety of tape formats. Tapes on which a record consist of a number of image lines can cause a reading problem for the image processing system of the Agricultural University of Wageningen. Ordering in BSQ tape format, with one record consisting of one image line, is recommended as it facilitates the exchange of data between the image processing systems. Because NOAA/AVHRR data can only be ordered in BIP, this format should be adopted. A BSQ or BIL tape format, with one record consisting of one image line, is recommended in exchanging pre-processed remote sensing images between the systems. Tapes written by the image processing system of the Agricultural University of Wageningen can cause difficulty when they are read by the other image processing systems.

It is suggested that the digitizing activities in the MARS project should be performed on the two ERDAS systems as they are able to convert them into a raster format. Furthermore these systems can write raster data to tape in a format which can be read by all the image processing systems that will participate in the MARS project.

6. MARS FOLLOW-UP

6.1. SUMMARY OF MARS-PPDS RESULTS

The main objectives of MARS-PPDS with regard to a possible application in Zambia were the definition of the proposed MARS information systems, the assessment of the proposed crop monitoring procedures and the availability of required agronomical data.

The results of the assessment of the feasibility of the proposed MARS procedures can be summarized as follows.

- The crop growth simulation model proved to be suitable to analyze the agricultural production of a high yielding variety of maize in Zambia. The main differences in production over the country can be related to differences in the natural agro-ecological conditions on the one hand and in types of farming system on the other hand.

The ratio between the yearly and the average water constrained production potential can serve as indicator for the yearly fluctuations in production due to temporary shortage or excess of water. Herein is the yearly water constrained production potential calculated on the basis of the actual meteorological data set and the average water constrained production potential on the basis of a statistically significant generated data set on the weather.

The agronomical data required to calibrate the proposed system with the other major crop types and varieties appears to be available at the research stations in Zambia. However, it will cost the MARS team a major effort to acquire all the proposed data sets. Available at reasonable scales are the information sources describing the spatial distribution of the relevant agro-ecological variables and the land use in Zambia. The assessment of these sources indicates a reasonable to good accuracy. These data sources appear to be suitable for use in the proposed MARS-AEGIS overlay procedures.

- The MARS procedure requires a proper assessment of the start of the growing season. The analysis of the available NOAA-NDVI data sets shows that -at least- the NDVI maps produced by the forthcoming ARTEMIS system can be applied to assess spatially the start of the growing season of the natural vegetation. Further research has to be performed to deduce the relations between this start of the growing season of the natural vegetation and the main agronomical activities per farming type of Zambia.

- The assessment of the Reading rainfall estimation method indicates that in the case of Zambia the method appears to be applicable. However, it will cost extra efforts to calibrate the method. Note, however, that the proposed procedure of the FAO ARTEMIS system will also require to be differentiated at a regional scale, possibly down to country level;
- The results of the assessment of the (digital) crop and land use identification procedure indicate the possibility of multi-temporal analysis of Landsat TM images, acquired during the growing season. Compared with the accuracy of the CFEWU crop monitoring results (in hectarages), the results of the MARS-PPDS exercises appear sufficient to good. However, a more detailed validation of the results is still necessary. The availability in a real time situation of Landsat TM and SPOT data sets are claimed to be guaranteed;
- The Mars system definition also required an assessment of the digital matching of maps with satellite images. The results derived with a low budget geographical information system with digital image processing possibilities (i.e. ERDAS, running on an IBM-AT) are considered to be very positive. The possible choice of an ERDAS system as the main hard- and sofware pivot of MARS-AEGIS appears to be quite reasonable. Moreover, the availability of these systems at the Dutch institutes, participating in the MARS project, and at UNEP-GRID in Nairobi are regarded as a support to such a choice.

The main conclusion of the assessment and system definition of MARS can be summarized as follows: the proposed MARS system is feasible in Zambia, although further calibration and validation activities are required.

The next chapter deals with the assessment of MARS by the Zambian authorities and staff of Institutions related to the FAO-CFEWU project in Zambia and FAO-HQ in Rome, Italy. The assessment resulted in the current MARS project proposal.

6.2. MARS-PPDS

The potential application of the innovative (MARSian) tools depends on the one hand on the availability of trained manpower and data processing facilities and on the other hand on agronomic and geophysical data sets, required to validate and calibrate the proposed methodology in Zambia. In this repect the MARS-Preparatory Phase and Definition Study (MARS-PPDS) was defined and approved by the BCRS and the participating Institutes SOW and ICW in the Netherlands.

The objectives of MARS-PPDS related to the MARS system assessment are treated in preceding sections of this report. An other important objective of MARS-PPDS was to define a cooperative agreement with government departments and institutions in Zambia related to the Crop Forecasting and Early Warning Unit and with involved FAO departments at FAO-HQ in Rome. A mission was send to Zambia with, according to the mission, the following results (FABER, et al., 1987b).

- in mutual consultation with the competent Zambian Authorities involved, the MARS proposal was formulated in detail including a budget, a personnel planning and a time schedule. The MARS proposal has been presented as a separate Annex of the Mission report (Anonymous, 1987b);
- the proposal was submitted to the Authorities in Zambia. It received their consent and was considered an improvement to and a useful extension of the ongoing early warning and crop forecasting efforts;
- the Zambian Authorities as well as the FAO (Headquarter and project staff) approved of a complete inter-linkage with the ongoing FAO project 'Crop Forecasting and Early Warning System' (GCP/ZAM/019/NET);
- the mission assessed the early warning and crop forecasting network on the global, regional and national level via consultations with the parties involved and was informed that the MARS proposal in no way overlaps or duplicates ongoing or planned efforts in this field;
- the mission feels that the Netherlands public funds as invested in the general early warning and crop forecasting models as designed by SOW and ICW will be put to proper use when developed in a situation with sufficient ground truth (field) data to appraise the applicability of the methodology. Zambia offers the conditions as required for this approach.

The mission recommended:

- to consider implementation and financing of the proposal once it has entered the funding channels of the donor organizations;
- once this stage is reached, to carry out the project as a bilateral effort as this will facilitate the links with the participating institutes in the Netherlands who developed the approach and the methodology;

- when the final appraisal stage is reached to consider to contract the implementation of the project to the Netherlands Institutes who initiated the MARS system, as the detailed knowledge about this system is mainly contained in these institutes.

The mission also focussed the attention to the following. The proposed project activities are geared to the local cropping seasons. Zambia has mainly a rainfed crop production system which means that the crucial planting time is narrowly defined in the period October through March. The information to be generated by the proposed project is required just in this period in order to contribute to the crop forecasting efforts. Therefore and in order to maintain the momentum, the mission proposes OCTOBER 1987 as a possible starting date for the development phase.

The following sections will deal with two important issues which are not or could not be treated well in the MARS project proposal.

6.3. TRAINING PROGRAM

One of the major bottlenecks Zambia faces, is the limited trained manpower available in the country. To secure the MARS project of the required skilled local staff during -and after-the MARS development phase, the project will provide a training programme for a limited number of staff members of the participating Institutions in Zambia. The training will be focussed on the use of remote sensing, data management (a.o. the use of land/geographical information systems) and the practical application of crop growth simulation models. The training programme will be drafted by the MARS project bureau and ITC, Enschede, supervised by ITC and possibly supported by the Regional Centre for Services in Surveying, Mapping and Remote Sensing in Nairobi; the training courses include standard post-graduate and possibly succeeded by advanced post-graduate and MSc degree courses.

The International Institute for Aerial Survey and Earth Sciences, internationally known as the ITC, was founded in 1951 jointly by the Delft University of Technology and the Agricultural University, Wageningen, as an independent institute of higher education. From the beginning, its tasks have been to provide training, to carry out research and to act as a consulting organisation in all branches of aerial survey and remote sensing. It operates as an autonomous institute, under the aegis of the Netherlands Ministry of Education and Science, and the Ministry of Foreign Affairs.

MARS aims at five fellowships of one year each, which are planned as follows:

(i) an agronomist of the Planning Commision of MAWD

(ii) a statistician (agronomy) of the Central Statistical Office

(iii) meteorologist of the Department of Meteorology

(iv) an agronomist and

(v) a soil scientist

both of the MAWD, Central Agricultural Research Station of Mnt. Makulu.

The following post-graduate courses are foreseen:

(i) ITC Post-graduate course in land and Geographic Information Systems (ITC GIS/LIS)

According to an ITC-LIS course brochure, the aim of this course is to make participants familiar with the available hard-and software for spatial analysis and survey and the possibilities of the use of these systems for resources management (development and conservation). Therefore the course has elements of computer technical/operational character, elements of resource surveys and elements of management and planning. At the end of the course, participants should be able to evaluate which techniques of data collection, processing, analysis and presentation could be developed and used in management of resources by participant's organizations and countries.

(ii) ITC Post-graduate course in rural and land ecology survey with specialization in rural settlement and infrastructure survey (ITC N9.2C)

According to the course programme, the aim of the course is to provide instruction and training in survey methods and the techniques of data collection in the applications of aerospace data in land resource inventories and evaluation of rural lands. Emphasis is placed on the interpretation of aerial photographs and other remote sensing images for collection of information on rural settlement and infrastructure, together with "terrain" (land form) in relation to the land as a whole.

Included will be the (optional) lectures and exercises on Capita selecta on human geography and on Geoinformation systems.

(iii) ITC Post-graduate course in rural and land ecology survey with specialization in agricultural vegetation and rangeland survey (ITC N9.2B)

During this rural and land ecology course the emphasis is placed on the interpretation of aerial photographs and other remote sensing images for collection of information on cultivated and natural vegetation, land use features together with "terrain" (land form) in relation to the land as a whole.

In the second half of the course the emphasis will be put on the interpretation (digital) of Meteorological satellite images. ICW will join the course supervision.

(iv) ITC Post-graduate course in rural and land ecology survey with specialization in agricultural land use survey (ITC N9.2A)

During this rural and land ecology course the emphasis is placed on the interpretation of aerial photographs and other remote sensing images for collection of information on cultivated and natural vegetation, land use features together with "terrain" (land form) in relation to the land as a whole.

In the second half of the course the emphasis will be put on the application of crop growth simulation models. SOW will join the course supervision.

(v) ITC Post-graduate course in soil survey using aerospace remote sensing techniques with specializations in land evaluation (ITC N5.2B)

According to the course programme, this course is for students who are concerned with the correct use of land in a particular setting, thereby concentrating on the bio-physical aspects of land evaluation. Certain factors may be highlighted by subjects from the rural survey and other courses. An interdisciplinary approach is therefore essential.

Included will be the N5.2B optional lectures and exercises on applied climatology and applied meteorology, and on aspects of agriculture.

The starting dates of the courses are, respectively, (i) in the last week of October, (ii, iii and iv) the last week of September and (v) the third week of October. To maintain the MARS momentum, it has to be recommendated to aim at to start at least two courses this year (1987).

Dependent on the training results acquired during the post-graduate courses, the opportunity should be offered to start a succeeding MSc programme. Admission to the MSc programmes usually requires a diplome from the relevant ITC post-graduate course, obtained with very good results (a weighted mean score of not less than 75 percent). The fellowships, however, for such MSc programmes are not included in the budget of the present MARS proposal.

Furthermore, two study tours to the Netherlands (SOW/ICW) of three months each are foreseen for senior Zambian staff. These tours are scheduled towards the end of the development phase and will be used to become acquainted with the MARS-AEGIS computer system before it is transferred to Zambia.

6.4. PROJECT MANAGEMENT

The executing agencies of MARS-PPDS are the Centre for World Food Studies (SOW; responsible), the Institute for Land and Water Management Research (ICW) in the Netherlands in cooperation with Institutions in The Netherlands on a competitive basis through a call for proposals.

Due to its simple structure in relation to the number of involved Institutions (and implicitely scientific disciplines) this management structure appeared to be quite effective during MARS-PPDS. However, some problems occurred related to the financial conditions set by the BCRS and the tight time schedule, especially in regard to the call for proposals in relation to the total duration of MARS-PPDS. In the future these problems must be avoided; it is expected that the introduction in the current MARS proposal of a MARS inception phase will solve the problems related to the timing of the MARS development phase.

In case after having reached the final appraisal stage of the current MARS project proposal, the Dutch Institutes who initiated the MARS project will be contracted to implement the project, an analogue management model is foreseen:

- the executing agencies will be the Centre for World Food Studies (SOW; responsible), the Institute for Land and Water Management Research (ICW) in the Netherlands and the Crop Forecasting and Early Warning Unit (MAWD-CFEWU) in Zambia, in cooperation with Institutions in The Netherlands on a competitive basis through call for proposals;
- the MARS activities in Zambia will be coordinated by the MARS project leader, who will stay in Lusaka, Zambia, during the development phase;

the project bureau and the project director will be located in Wageningen, The Netherlands;

- the training programme in the Netherlands will be supervised by ITC, Enschede, The Netherlands in cooperation with the MARS project bureau. The involvement of the Regional Centre for Services in Surveying, Mapping and Remote Sensing in Nairobi, Kenya has to be examined.

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LIST OF MAPS

LIST OF PHOTOS

GLOSSARY OF ACRONYMS

AGRISTARS	Agriculture and Resources Investory Surveys Through Aerospace Remote Sensing, US
AGRYMET	Centre regional de formation et d'application en AGRoMETeorologie et HYdrologie operationelle, Niamey, Niger
AISC	NOAA Assessment and Information Services Center, US
ARTEMIS	African Real-Time Environmental Monitoring using Imaging Satellites
AVHRR	NOAA Advanced Very-High Resolution Radiometer
BCRS	Beleids Commissie Remote Sensing, or Netherlands Remote Sensing Board, Delft, The Netherlands
CABO	Centrum voor Agro-Biologisch Onderzoek, or Centre for Agro-Biological Research, Wageningen, The Netherlands
CCD	Cold Cloud Duration method, University Reading, United Kingdom, Europe
CCT	Computer Compatible Tapes
CFEWU	Crop Forecasting and Early Warning Unit, Lusaka, Zambia
CIMMYT	Centro Internacional de Mejoramiento de Maiz y Tigro, Mexico
CRT	Commidity Research Teams, MAWD, Zambia
CSA	Census Supervisory Area, Zambia
CSO	Central Statistical Office, Lusaka, Zambia
CSSWB	Crop Specific Soil Water Balance
DADO	District Agricultural Development Officers, Tanzania
DANIDA	Danish International Development Agency
DAO	District Agricultural Officer, Zambia
DHV	DHV Consulting Engineers, Amersfoort, The Netherlands
DBMS	Data Base Management System
DGIS	Directoraat Generaal Internationale Samenwerking, or Ministry of Development Cooperation, Den Haag, The Netherlands
DUET	Crop growth simulation model, linkage WOFOST-SWATRE
EOSAT	Earth Observation Satellite Co., US
ERDAS	Earth Resource Data Analysis System (trade mark)
EROS	Earth Resource Observation Systems Data Center, US
ESA	European Space Agency
FAO	Food and Agricultural Organization of the United Nations, Rome, Italy
FAO-HQ	FAO Head Quarters, Rome, Italy
FAS	Foreign Agricultural Services of the USDA
FSP	Food Supply Projections
GAC	NOAA Global Area Coverage
GEMS	Global Environmental Monitoring System
GIEWS	Global Information and Early Warning System on Food and Agriculture
GIS	Geographical Information System
GIS/LIS	Geographical Information System/Land Information System
GLIM	Generalized Linear Interactive Modelling
GTS	WMO Global Telecommunication System
HYV	High Yielding Variety
IAC	International Agricultural Centre, Wageningen, The Netherlands
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics, India
ITCZ	Inter-Tropical Convergence Zone
ITD	Inter-Tropical Discontinuity
IGADD	Intergovernmental Authority on Draught and Development

ICW	Instituut voor Cultuurtechniek en Waterhuishouding, or Institute for Land and Water Management Research, Wageningen, The Netherlands
LACIE	Large Area Crop Inventory Experiment, US
LAI	Leaf Area Index
Landsat-MSS	Landsat Multi Spectral Scanner
Landsat-TM	Landsat Thematic Mapper
LUW	Landbouw Universiteit Wageningen, or (AU) Agricultural University, Wageningen, The Netherlands, departments:
-LS	Land Survey and Remote Sensing
-PM	Physics and Meteorology
-SG	Soil Science and Geology
-PE	Theoretical Production Ecology
MARS	Monitoring Agro-ecological Resources using Remote Sensing and Simulation
MARS-AEGIS	MARS Agro-Ecological Geographical Information System
MARS-PPDS	MARS-Preparatory Phase and Definition Study
MAWD	Ministry of Agriculture and Water Development, Lusaka, Zambia
NASA	National Aeronautics Space Administration, US
NCEW	National Committee on Early Warning, Zambia
NDVI	Normalized Difference Vegetation Index
NESDIS	National Environmental Satellite Data and Information Service, US
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium, or National Aerospace Laboratory NLR, Amsterdam, The Netherlands
NOAA	National Oceanic and Atmospheric Administration, US
NPP	National Preparedness Plan to cope with Food Emergencies, Zambia
PAC	Project Advisory Group SAPRO, IAC, Wageningen, The Netherlands
PAO	Provincial Agricultural Officer, Zambia
PDUS	METEOSAT Primary Data User Station
PET	Potential Evapo-Transpiration
PSF	NOAA GAC data resampled/reprojected into a Polar Stereographic Format
QUEFTS	Soil fertility model: QUantitative Evaluation of the Fertility of Tropical Soils, Agricultural University, Wageningen, The Netherlands
RCR	Rainfall and Crop Reporter, Tanzania
REWS	Regional Early Warning System, SADCC-FAO/DANIDA, Harare, Zimbabwe
REWU	Regional Early Warning Unit
RS	Remote Sensing
RSC	FAO Remote Sensing Centre, Rome, Italy
SADCC	Southern African Development Coordination Conference
SAPRO	Establishment of an Operational Satellite Remote Sensing System to Support Agricultrual Production and Desert Locust Monitoring and Forecasting
SEA	Standard Enumeration Area, CSO, Zambia
SMARTies	Simulation Model using ARTEMIS Real Time information and environmental specifications (MARS crop growth model)
SMMR	NIMBUS Scanning Multi-channel Microwave Radiometer
SOW	Stichting Onderzoek Wereldvoedselvoorziening, or The Centre for World Food Studies, Amsterdam/Wageningen, The Netherlands
SPOT	trade mark of SPOT Image, France
SWATRE	Soil Water - Atmosphere Transpiration Routine
TIR	METEOSAT Thermal Infra-red Band

UNEP	United Nations Environmental Program
UNZA	University of Zambia, Lusaka, Zambia
USAID	United States Agency for International Development, Washington, United States
USDA	United States Department of Agriculture
VIS	METEOSAT Visible channel
WMO	World Meteorological Organizaton, Geneva, Switzerland
WOFOST	Crop growth simulation model of the Centre for World Food STudies, Wageningen, The Netherlands
WRSI	FAO Water Requirements Satisfaction Index
ZAB	Zaire Air Boundary

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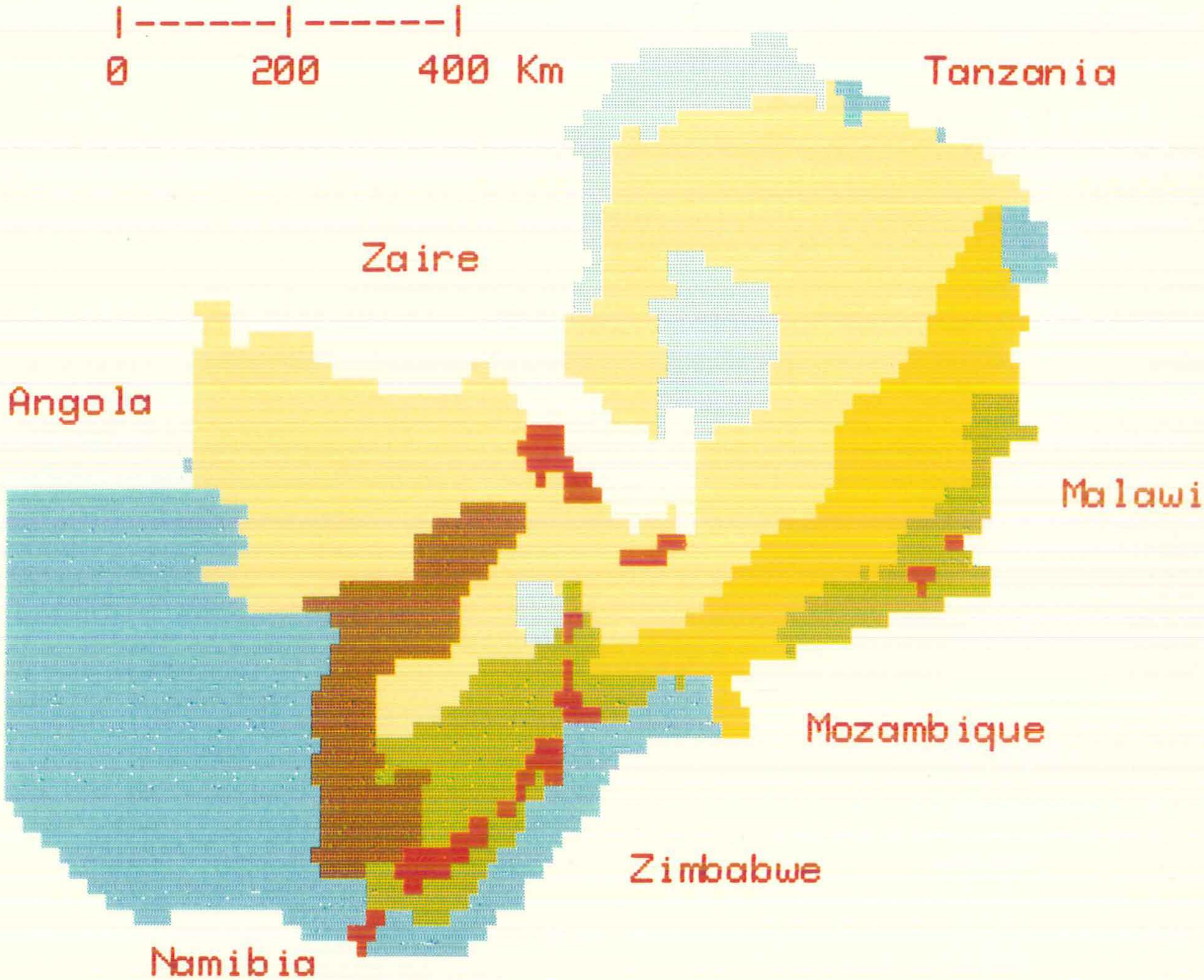
MAP 4 : MAP OF LAND USE SYSTEMS (Source: Schultz, 1974).

Republic of Zambia



Land Use Map of Zambia

Legend

- Shifting axe an hoe cultivation.
- Semi-permanent hoe cultivation.
- Fishing and semi-perm. hoe cultiv.
- Semi-perm. hoe and ox-plough cultiv.
- S-comm. ox- and tractor-plough cultiv.
- Commercial farms.
- Not in agricultural use.

S.O.W. 29-JUL-87

Photo 1 . Map of Zambia where the digitalized national boundaries are in blue and the digitalized mask of Central province is in red; for explanation of digitalization procedure see text.

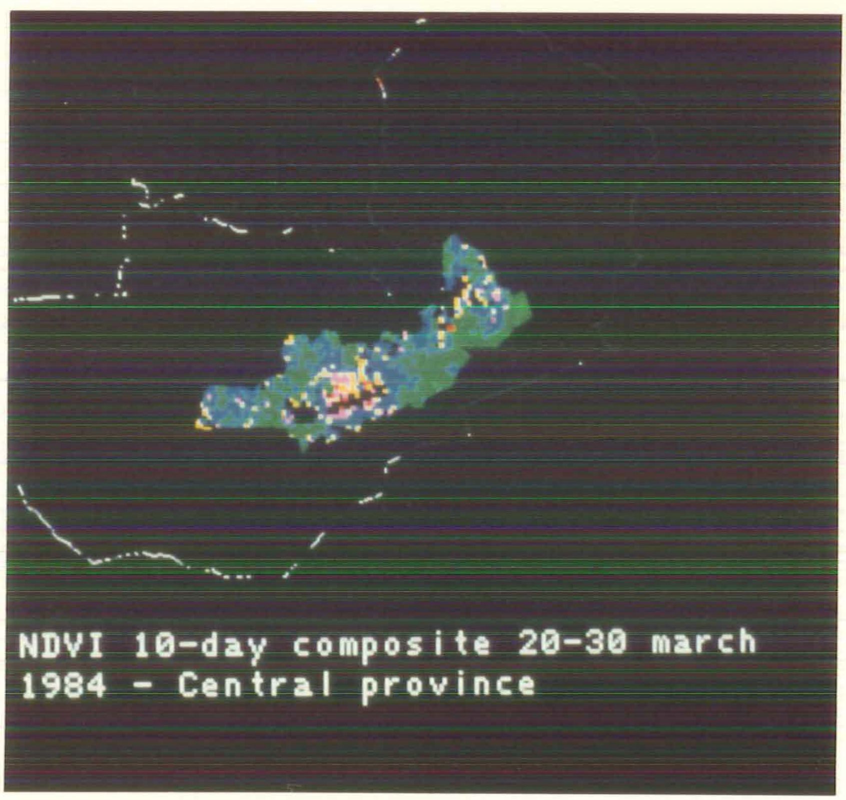
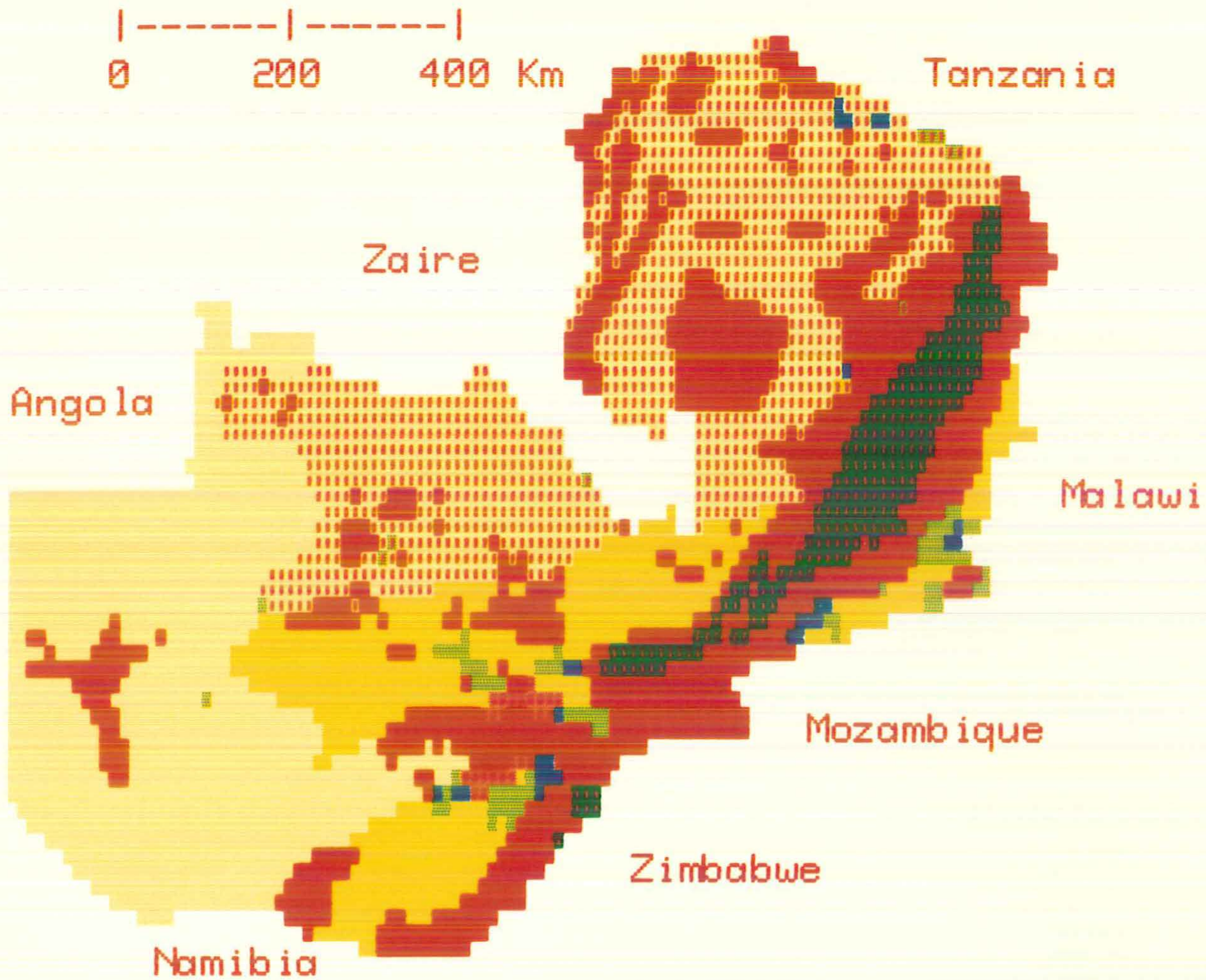


Photo 2 . Example of NDVI 10-day composite 20 to 30 march 1984 for Central province; red:128-140, magenta:141-153, yellow:154-165, blue:166-178, dark green:179-191, light green:192-204.

MAP 3: SOIL FERTILITY CLASSES AND RELATED NUTRIENT-LIMITED YIELDS OF MAIZE.

Republic of Zambia



Soil Fertility Classes Zambia

Legend

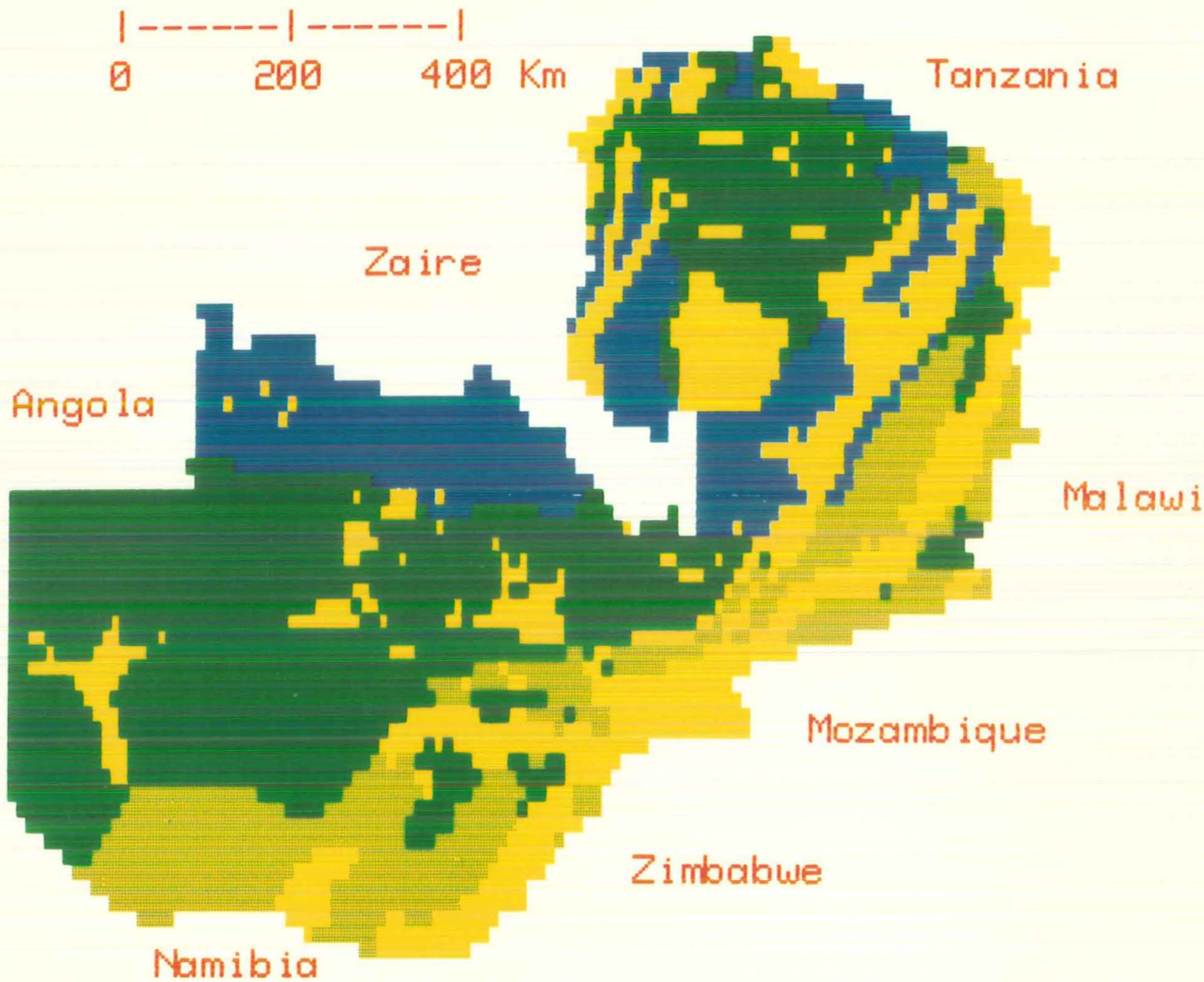
- Class B
- Class D
- Class E1
- Class E2
- Class F
- Class C/F
- Class D/F
- Class E1/F
- Class E2/F
- Class E3/F

Soil fertility class	Nutrient-limited grain yields of maize (12% moisture)
B	3600 kg/ha
C	2400
D	1600
E1	1200
E2	800
E3	400
F	No yield

S.O.W. 29-JUL-87

MAP 1: WATER-LIMITED YIELDS OF MAIZE.

Republic of Zambia



Water Limited Yields of Maize

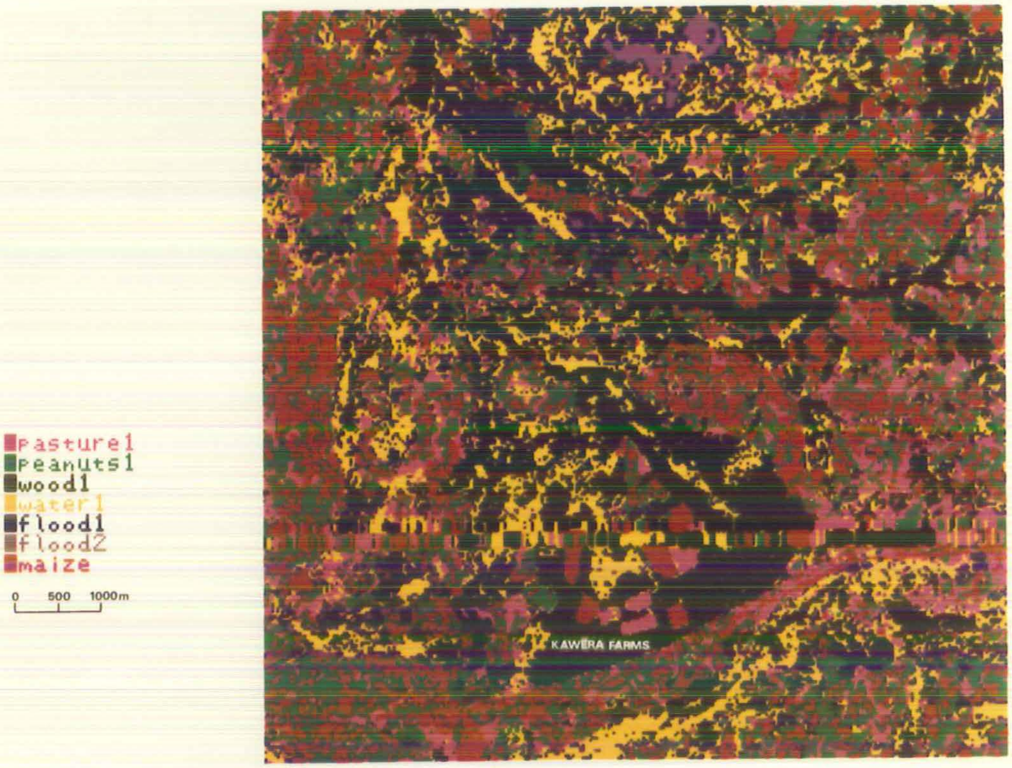
Legend

- No estimates
- 7 - 9 (T/ha)
- 9 - 11 (T/ha)
- 11 - 13 (T/ha)

Yields: dry matter in grains.

S.O.W. 29-JUL-87

Fig. 4.2.6.2. False colour LANDSAT-TM sub-image (300 lines by 300 pixels) of band 4 showing landuse classification, colour assignment is according to the legenda; 16 January 1985, LANDSAT-TM data, Petauke district.



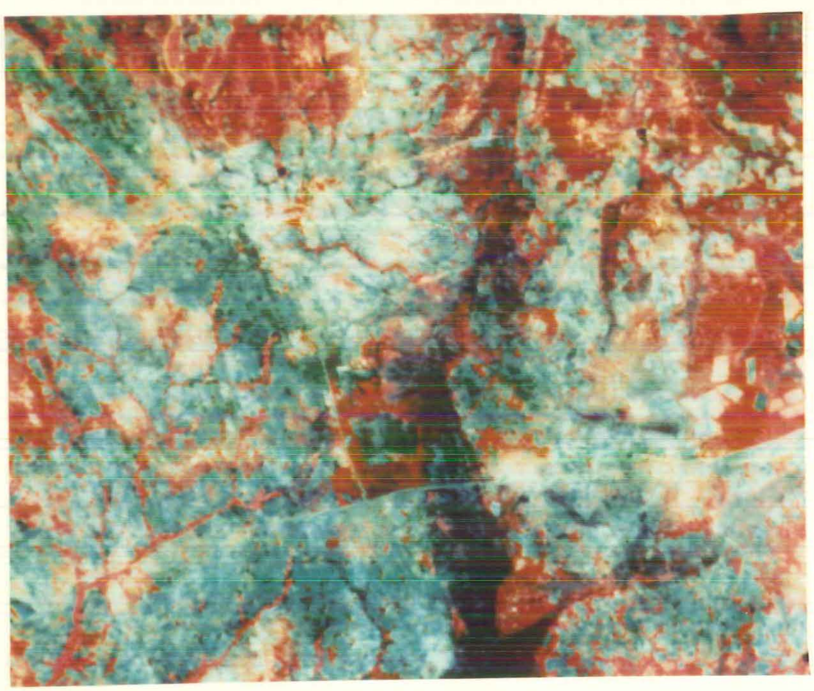


Photo 6 . Colour coded (bands 4/3/2) TM-image of part of Petauke district in Eastern province where full green vegetation is red and bare soil is whitish-gray; LANDSAT-TM data, 29-11-1984.

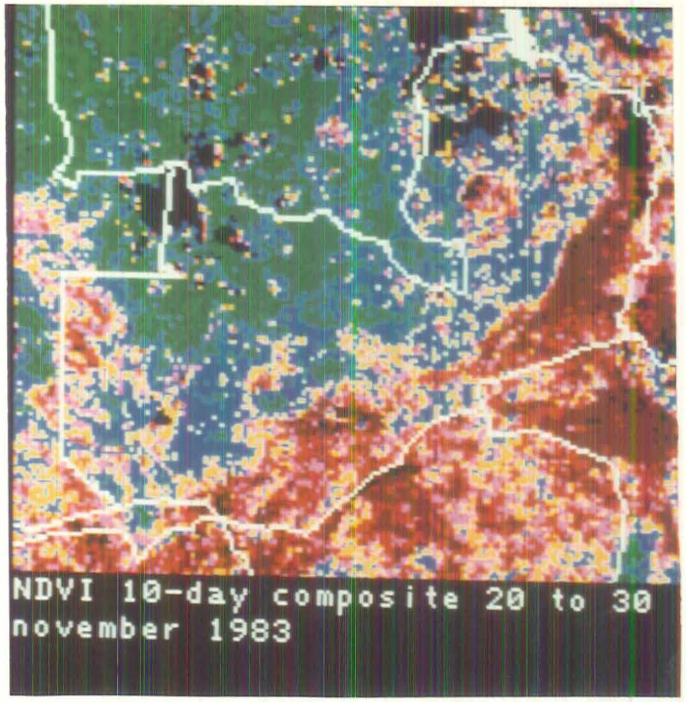


Photo 3 . Example of NDVI 10-day composite 20 to 30 november 1983 for Zambia, national boundaries in white; for colour assignment to NDVI values see photo 2.

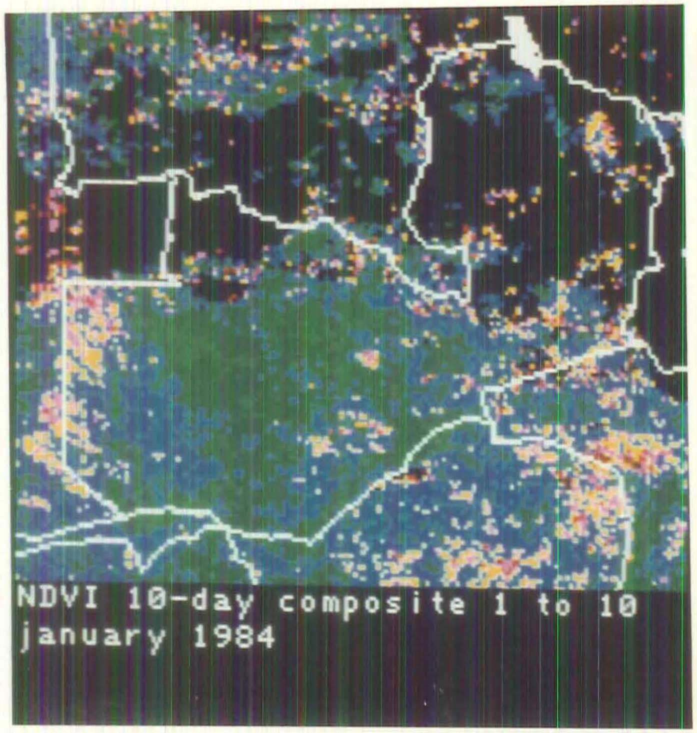


Photo 4 . Example of NDVI 10-day composite 1 to 10 january 1984 for Zambia, national boundaries in white; for colour assignment to NDVI values see photo 2.

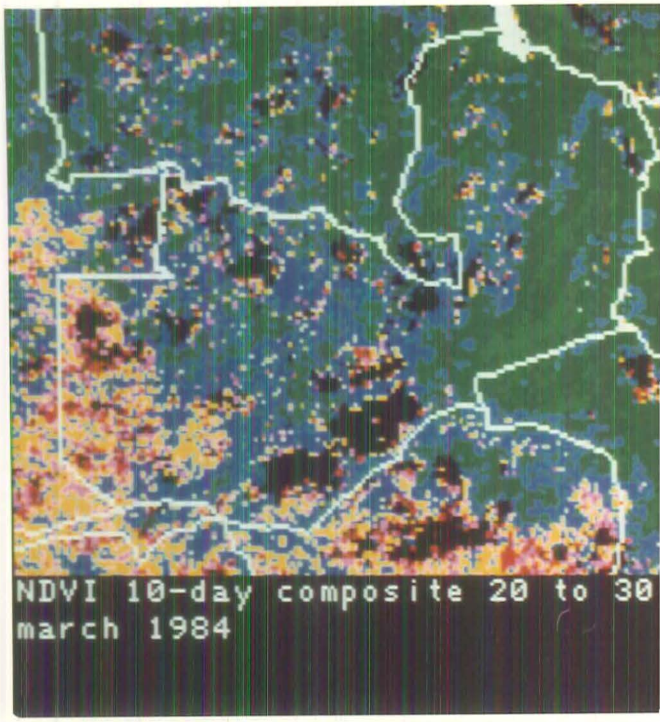
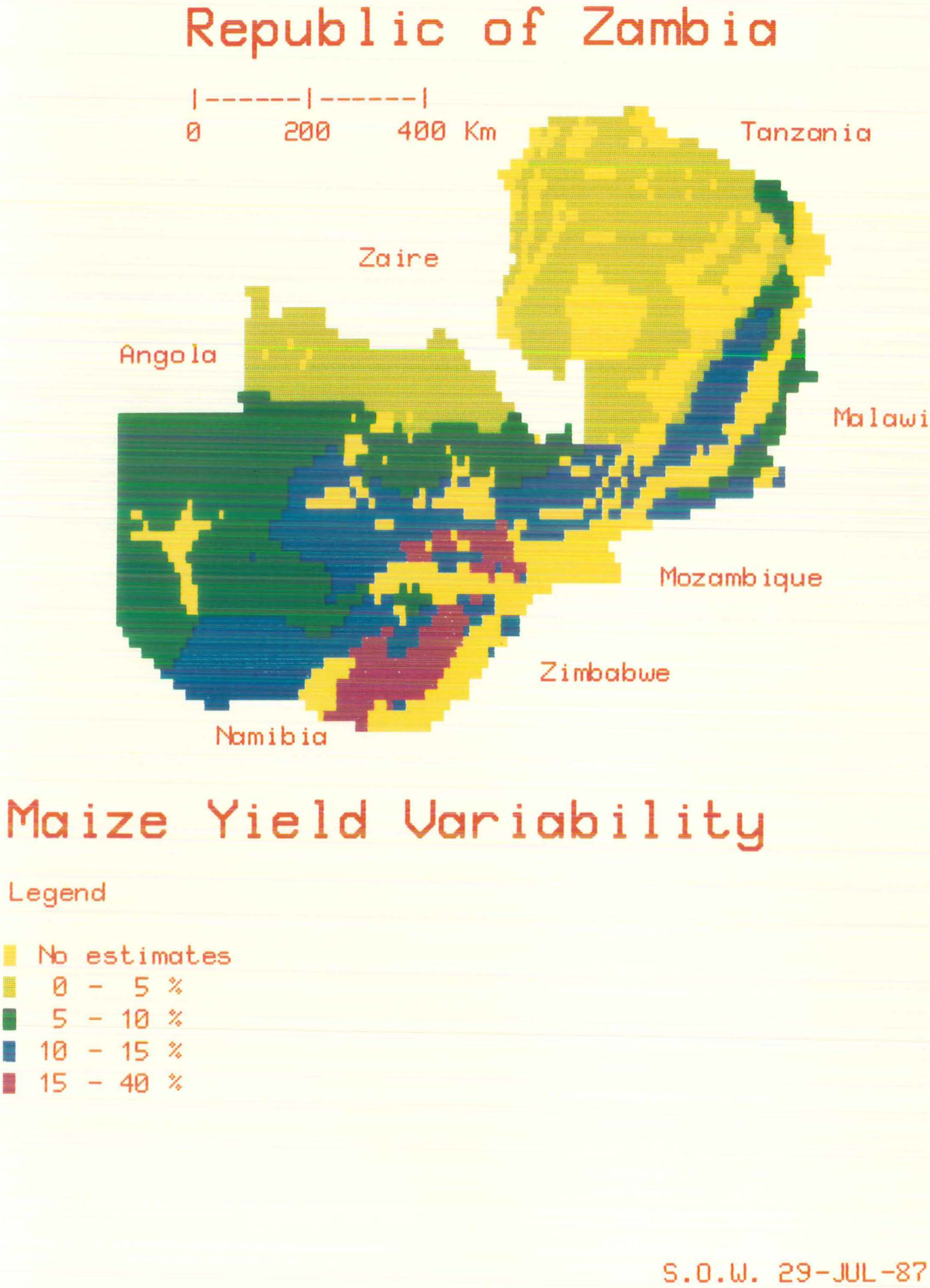


Photo 5 . Example of NDVI 10-day composite 20 to 30 march 1984 for Zambia, national boundaries in white; for colour assignment to NDVI values see photo 2.

MAP 2: VARIABILITY IN WATER-LIMITED YIELDS OF MAIZE.



There is a growing awareness in the international community of the structural, rather than the meteorological nature of food shortfalls in a number of African countries. The food production potential of such countries is poorly exploited, thus enhancing the sensitivity of food production to meteorological vagaries. Scarcity of timely and reliable information on food production and availability has serious consequences for the short and long term food security policy of the Government.

The purpose of the MARS project is to establish a link between the data provided by meteorological satellites (through the forthcoming ARTEMIS system of FAO) and the operational requirements of crop yield forecasting and monitoring at the national level. The main objective of the project is to examine whether satellite remote sensing information, i.e. high and low resolution images, in combination with a geographical information system and the implementation of a numerical simulation model, based on the water balance – oriented SWATRE (ICW) and the more agronomic – oriented WOFOST (SOW), will improve the real time information on the agricultural production per major farming system and major agro-ecological zone in a country like Zambia.

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