THE GLOBAL ENVIRONMENT MONITORING SYSTEM

GEMS
SAHEL SERIES
MAIN REPORT

ROME
1988

Inventory and Monitoring of Sahelian Pastoral Ecosystems

UNITED NATIONS ENVIRONMENT PROGRAMME

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

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THE GLOBAL ENVIRONMENT MONITORING SYSTEM

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MAIN REPORT

AG:EP/SEN/001
Technical Report

INVENTORY AND MONITORING OF SAHELIAN PASTORAL ECOSYSTEMS

S E N E G A L

Report prepared for
the Government of Senegal
by
the Food and Agriculture Organization of the United Nations

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UNITED NATIONS ENVIRONMENT PROGRAMME

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS

Rome, 1988

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FAO. Inventory and monitoring of sahelian pastoral ecosystems, Senegal. Rome, 1988. 144 p., 69 figures. AG:EP/SEN/001, Technical Report.

SUMMARY

The report gives a concise account of the research carried out in Senegal from 1980 to 1984 on the inventory and monitoring of sahelian grazing ecosystems.

The method used is new inasmuch as it combines several techniques: orbital, aerial, and ground validation; in other words, the green herbage biomass present at the end of each rainy season is evaluated combining spatial advanced radiometer remote sensing with ground truth validation and low altitude systematic reconnaissance flights that allow for the evaluation of other parameters such as livestock and game densities.

The method utilized warrants the evaluation of the "offer" (green herbage biomass present at the end of each rainy season) and the "demand" (number of animals present in the same study area). The comparison of the two sets of data thus makes it possible to forecast the management needs for the nine months of the forthcoming dry season and therefore to rationally manage range and herds at regional and local levels knowing the amount of food available and the number of stock to be fed.

The project showed that this methodology is applicable on a large scale to the sahelian grazing lands.

Furthermore, the project suggests some improvements of the method and its generalization to the whole Sahel via a joint project allowing for a better and cheaper utilization of the resources and for a coordination of efforts of several states in order to reduce the cost of the availed data.

The Food and Agriculture Organization is greatly indebted to all those who assisted in the implementation of the project by providing information, advice and facilities.

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LIST OF ABBREVIATIONS

AVHRR	- Advanced Very High Resolution Radiometer
CEMPSE	- Centre for the Ecological Monitoring of Sahelian Pastoral Ecosystems
CTFT	- Centre technique forestier tropical
DGRST	- Délégation générale à la recherche scientifique et technique
EMASAR	- Ecological Management of Arid and Semi-arid Rangelands
GAC	- Global Area Coverage
GEMS	- Global Environment Monitoring System
GERDAT	- Groupement d'études et de recherches pour le développement de l'agriculture tropicale
GIS	- Geographic Information System
GREP	- Global Radiative Evaporation Potential
GRIZA	- Groupe de recherches interdisciplinaires en zones arides
GVI	- Grazing Value Index
IBP	- International Biological Programme
IEMVT	- Institut d'élevage et de médecine vétérinaire des pays tropicaux
IFAN	- Institut fondamental d'Afrique noire
IMRES	- Inventory and Monitoring of the Rangelands Ecosystems of the Sahel
IPAL	- Integrated Project in Arid Lands
ISRA	- Institut sénégalais de recherches agricoles
KREMU	- Kenya Rangelands Ecological Monitoring Unit
LAI	- Leaf Area Index
LAC	- Local Area Coverage
LAT	- Lutte contre l'aridité en milieu tropical

LNERV	- Laboratoire national d'élevage et de recherches vétérinaires
LTP	- Laboratory of Terrestrial Physics
MSC	- Maximum Standing Crop
MSS	- Multi-Spectral Scanner
NASA	- National Aeronautics and Space Administration
NDVI	- Normalized Difference of Vegetation Index
NOAA	- National Oceanic and Atmospheric Administration
ORSTOM	- Office de la recherche scientifique et technique d'outre-mer
PET	- Potential évapotranspiration
SISCOMA	- Société industrielle sénégalaise de construction mécanique et agricole
SPOT	- Système probatoire d'observation de la terre
SODESP	- Société de développement de l'élevage dans la zone sylvo-pastorale
SRF	- Systematic Reconnaissance Flights
TLU	- Tropical Livestock Unit
TM	- Thematic Mapper
UTM	- Universal Mercator Transverse

Chapter 1

INTRODUCTION

The present synthetic technical report is an attempt to summarize a number of reports and publications (quoted in references, whether published or not), the total of which is in excess of one thousand pages, produced either by the Project of Inventory and Monitoring of the Rangelands Ecosystems of the Sahel (IMRES) or by its staff members and consultants.

Furthermore, the following document contains many data collected and published by various research teams in the same area of the Ferlo, which seemed necessary to us for a better understanding of IMRES findings.

The present synthesis is not particularly aimed at remote sensing and monitoring specialists (although it may be of interest to some of those as well), but primarily to decision makers, research scientists, extension specialists and teachers who are not specialized in remote sensing or monitoring but may have to use these techniques: politicians, administrators, engineers, developers, range and livestock managers, veterinarians, agronomists, foresters, geographers, extension agents, etc.

This report contains, in a concise form, the main information produced by various monitoring projects which took place in the Ferlo from 1974 to 1984 inclusively.

The detailed and strictly technical aspects of the IMRES project have been developed in a series of technical appendices written by M.J. Sharman, a former expert in zooecology of IMRES, and published jointly by UNEP (GEMS-PAC) and FAO. These technical appendices are more precisely designed for the consumption of either monitoring and remote sensing specialists or of laymen who may wish to probe any deeper insight into particular aspects of the present synthetic technical report.

The technical appendices and their approximate length are shown in the following table:

Nº	Title	Approximate no. of pages: text	Approximate no. of pages: whole doc.
1	Introduction au Projet d'Inventaire et de Surveillance continue des Ecosystèmes Pâturés Sahéliens	9	18

Nº	Title	Approximate no. of pages text	whole doc.
2	Rainfall in the Ferlo since 1919	16	73
3	Use of light aircraft in the inventory and monitoring of Sahelian pastoral ecosystems	57	93
4	Sampling the Sahel	97	120
5	Monitoring pasture production by remote sensing	25 *	-
6	Inventory of water resources in the Ferlo	40 *	-
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8	Monitoring human populations in the Sahel	20 *	-
9	Preparing census data for a Geographic Information System (GIS)	15 *	-
10	Integrated approach to ecological monitoring in the Sahel	20 *	-

The overall IMRES final document (synthesis and appendices) may thus meet the requirements of various sets of potential users.

1.1 BACKGROUND AND JUSTIFICATION OF THE PROJECT

The pilot project on the Inventory and Monitoring of Sahelian Grazing Ecosystems originates from the objectives of both FAO and UNEP programmes concerning the ecological management and monitoring of arid and semi-arid rangelands: FAO's EMASAR programme (Ecological Management of Arid and Semi-Arid Rangelands) and UNEP's GEMS (Global Environment Monitoring System). These programmes were conceived and recommended by panels of experts and approved by the governing bodies of the two organizations in a series of conferences held from 1974 to 1977. For further details, see the references given in Appendix 1 listed under the headings of FAO and UNEP.

The GEMS programme, approved by the fourth session of the UNEP Governing Council specified in particular that: "monitoring activities will be undertaken and expanded following the recommendations of the group of government experts which will examine monitoring as a means of evaluating problems resulting from agricultural and land-use practices".

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* These figures are subject to major changes as the documents are drafted.

The UNEP Governing Council (UNEP G/C 7/7, 1977) recommends that an operational GEMS project will be set up in order: "... firstly to perfect and demonstrate methods designed to allow repeated inventories of natural renewable resources at various scales and at various time intervals, as adapted to national needs and as a baseline for resource planning and management; secondly, to collect data on the state of natural resources at national, regional and world levels".

At a FAO/UNEP experts meeting held in Rome in March 1977, it was decided to initiate this programme by monitoring the Sahelian rangelands in West Africa, within the framework of the GEMS and EMASAR programmes.

A FAO/UNEP study group visited West Africa from July to August 1978 in order to select an area for a pilot project. After careful consideration, this mission recommended that the project be set up in the Sahelian region of Senegal. This choice was essentially motivated by the fact that the Senegalese Ferlo is typical of the Sahel as a whole with respect to the nature and abundance of scientific data available on this area and the existing logistic facilities, both in the domain of infrastructure (i.e., accessibility, maintenance) and of research bodies (university, various institutes). An area of 30 000 km^2 in the Ferlo region was allocated to the project by common agreement between FAO, UNEP and the Government of Senegal.

1.2 OBJECTIVES OF THE PROJECT

The main objectives of the project were as follows:

- To define and test appropriate methods for the inventory and monitoring of Sahelian grazing ecosystems.

- To demonstrate these methods in a full-scale, realistic manner so as to help short-term decision-making in range and livestock management.

- To provide the Government and development agencies with the necessary basic data for the long-term planning of grazing and agricultural resources.

- To contribute to the establishment of a description of world arid land resources.

- To contribute to the establishment of a data bank on grazing resources on national, regional and world scales.

- To identify operational problems (logistics, labour, organization, execution) associated with the implementation of monitoring programmes in West African arid zones and to find appropriate solutions to the problems encountered.

- To contribute to the perfection of standard methods on an international level, for the inventory and monitoring of the rangelands; these methods should be compatible with those relating to data analysis.

- To provide, for the project area, the baseline data needed for the planning and operation of an EMASAR project in cooperation with the Government of Senegal.

- To provide appropriate data and suggest actions for national campaigns to combat desertification.

1.3 SELECTION OF THE PILOT PROJECT AREA

An area of 30 000 km^2 was selected by agreement between the representatives of FAO, UNEP and the Government of Senegal within the natural region known as the 'Ferlo', which covers an area of some 80 000 km^2. This choice was justified on the grounds discussed under the headings below.

1.3.1 Representativity

This area is almost ideally representative of the Sahelian zone as a whole in the following ways: its climate, encompassing the ecoclimatic zones of the Sahel *sensu stricto*, the Sudano-Sahelian transition zone and the North Sudanian zone, in the currently accepted definitions of these terms (le Houérou, 1976, 1977, 1980; Boudet & De Wispelaere, 1976; Boudet, 1984; Breman & De Wit, 1983; Le Houérou & Popov, 1981; Le Houérou & Gillet, 1985, etc.); its geomorphology and its soils: its banks and alluvial plains along the Senegal river valley representing similar areas along the Niger, Chari, Logone and Nile valleys; the zones of the fossil 'ergs' or sand seas of the central Ferlo which are representative of some 1.5 million km^2 from the Atlantic to the Nile; the zone of the 'Ferrugineous Ferlo', representative of the southern fringe of the Sahel and of the northern Sudanian zone from Dakar to the Nuba Mountains.

The vegetation of the selected pilot zone is also representative of the Sahel, being similar to that described and mapped in the other Sahelian countries (Boudet, 1975; Le Houérou & Grenot, 1986). Land use in most of the pilot area is no less representative of the various Sahelian systems of nomadism, transhumant pastoralism, agropastoralism, agro-sylvo-pastoralism and semisedentary and sedentary systems.

1.3.2 Abundance and quality of basic scientific data

The Ferlo has been the subject of a number of research studies and surveys that have resulted in numerous publications concerned with the inventory and mapping of vegetation and range types, with the functioning, dynamics and productivity of grazing ecosystems and with its soils, geology, geomorphology and hydrology. The whole project area and its neighbourhood are, for example, entirely covered by vegetation and range maps (1/100 000 to 1/200 000), including Audru & Lemarque, 1966; Fotius & Valenza, 1966; Diallo, 1968; Valenza & Diallo, 1972. These surveys have been complemented by numerous studies on the composition, ecology, dynamics and productivity of the rangelands (Raynal, 1964; Naegelé, 1967, 1971; Valenza, 1970, 1979, 1981; Valenza & Diallo, 1970; Bille, 1977; Bourlière, 1978; Poupon, 1980; Cornet, 1981; Poulet, 1982; Boudet, 1980, 1981, 1983; Barral, 1982; Barral *et al*, 1983; Dieye, 1981, 1983).

Diachronic studies and monitoring of the Ferlo were also begun as early as 1974 (Valenza, 1975, 1979, 1981, 1984; De Wispelaere, 1980 a and b, 1981). Livestock and animal production systems were not neglected (Calvet et al, 1965; Denis & Valenza, 1971; Meyer, 1980; Planchenault 1981, 1983; Barral, 1982; Barral et al, 1983). Wildlife and its impact on vegetation were studied by a team of resident research scientists within the framework of a research project by the French section of IBP (International Biological Programme) in collaboration with ORSTOM (Office de la recherche scientifique et technique d'outre-mer). This field-work took place between 1969 and 1978, particularly at the Fété Olé field research station, to the northeast of Mbidi (Bourlière, 1962, 1978; Gillon & Gillon, 1974; Lepage, 1974; Morel & Morel, 1972, 1974; Poulet, 1972, 1974, 1982; Bille, 1972, 1974, 1977; Poupon, 1972, 1974, 1982).

In addition, substantial data relating to the dynamics, management and productivity of the rangelands have been gathered over the past 25 years in the 'Centre de recherches zootechniques' (CRZ) of Dahra-Djoloff and the ranch of Doli, managed by SODESP (Société de développement de l'élevage dans la zone sylvo-pastorale).

This area is entirely covered by two panchromatic aerial photo sets at the scale of 1/50 000 dating from 1954 and 1978/80 and by sets of topographic maps (1/200 000) and various thematic maps including those for geology, geomorphology, soils and vegetation.

Such an abundance of basic data on a relatively restricted area of 30 000 km^2 is probably unique in the 3 million km^2 extent of the Sahel.

1.3.3 Infrastructure

The pilot area is easily accessible, being almost entirely surrounded by asphalt roads and crossed by many tracks and firebreaks. There are also four airstrips for light aircraft at Linguère, Richard-Toll, Podor and Matam; fuel is available at Dahra, Linguère, Richard-Toll, Dagana, N'Dioum, Podor crossways and Matam.

1.3.4 Host organizations

Through its National Livestock and Veterinary Research Laboratory (LNERV), a part of the Senegalese Institute of Agricultural Research (ISRA), the host country provided an ideal host structure which was functional and experienced, employed a relatively large number of highly qualified personnel and was equipped with adequate research facilities. Lastly, the city of Dakar, its university, the Fundamental Institute of Sub-Saharan Africa (IFAN) and the numerous research and development bodies, both national and international, constituted an appropriate intellectual environment for such an innovative project.

1.3.5 Demarcation of the project area

The selected test area occupies some 30 000 km^2 lying to the north of the fossil valleys of Ferlo and Lombol and of the road between Linguère and Matam. The Senegal river lies to the east and north and the Lake of Guiers, periodically overflowing into the valley of the Ferlo, to the west. This is an elliptical area, some 280 km from west to east and 150 km at its widest, on a north-south line from Podor to Linguère. The geometrical centre of the area is located between Labgar and Yare Lao (to the north of the village and borehole of Labgar), some 80 km northeast of the town of Linguère (cf. Figures 1, 20, 24, 25, 26, 39).

1.4 ESTABLISHMENT AND EXECUTION OF THE PROJECT

The project began in January 1980 and ended in July 1985. Its budget was some $US 2 100 000, 1 600 000 (75 %) of which was provided by UNEP, $US 200 000 (10%) by FAO and $US 300 000 (15%) provided by various sources; the Government of Senegal contributed in kind with the provision of personnel and facilities. The executive agencies were FAO for the UN and LNERV for the Government. The Director of LNERV, A.K. Diallo, acted as National Director, while C.L. Vanpraet, FAO expert, was the International Team Leader. The national counterparts, besides the national director, included K. Dieye, range ecologist, A. Diop, veterinarian and four technical assistants. The FAO team included, in addition to Vanpraet, A. Gaston, an expert in range management with a long field experience in the Sahel in Chad, M.J. Sharman, zooecologist in charge of the systematic reconnaissance flights (SRFs), and four associate experts. The international team was complemented by several consultants, one of whom played an eminent role: C.J. Tucker, radiometry and remote-sensing specialist, at the Earth Sciences Laboratory - later the Laboratory of Terrestrial Physics (LTP) - at the Goddard Space Flight Center of NASA (National Aeronautics and Space Administration), Greenbelt, Maryland, United States of America. The satellite data from NOAA 6 & 7 was analysed by Tucker and his team at LTP. P. Duncan, zooecologist, contributed to the implementation of SRFs. Other specialists from FAO Headquarters, including F. Padovani, computer scientist, W. Langeraar, remote-sensing specialist and Mrs. C. Boelcke, agronomic statistician, contributed in various ways to data processing analysis and interpretation. Other consultants were: B. Debongnie, socio-economist, R. Smith, statistician, D. Macluder, specialist in information science, A. Bellocq, agrometeorologist, and J. Valenza, agrostologist, LNERV.

Coordination at FAO headquarters was ensured by T. Ionesco, Principal Technical Officer in charge of the EMASAR Programme. Coordination within UNEP was the task of H. Croze, scientific officer at GEMS. Ionesco and Croze also took part in the mission to select the project area in 1978 and in a tripartite evaluation mission in 1982.

The Senegalese Government established, by ministerial decree, a coordination committee under the chairmanship of the Director of Agricultural and Agroindustrial Research in the Ministry of Science and Technology. He committee included the following:

- The Director of LNERV;

- The Director of the National Centre of Forestry Research;

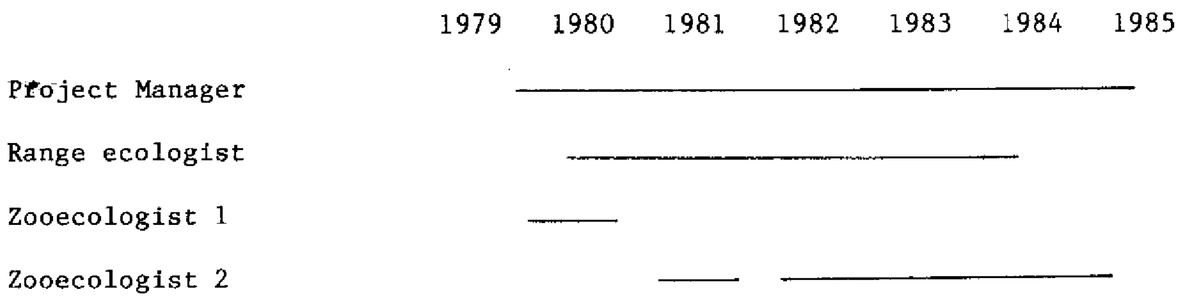
- The Director of the National Animal Health and Production Department;

- The Director of the Office of the Protection of the Environment;

- The Director of Sahelian Pastoral Ecosystems Project.

This committee met twice annually and facilitated the coordination between the project and national organizations; it provided suggestions and advice on the work plan and the evaluation of results. It also helped to maintain connections with various organizations such as SODESP and foreign aid agencies including ORSTOM, GERDAT, IEMVT, CTFT, West German Aid and USAID. The link between research and development was thus fully ensured through the coordination committee.

The international personnel was present during the project period as shown in the following diagram:



Chapter 2

BACKGROUND INFORMATION ON THE SAHELIAN RANGELANDS

Sahelian ecologists now define the limits of the Sahelian ecoclimatic zone by the 100 and 600 mm isohyets of annual rainfall (Keay, 1959; AETFAT, 1959; Le Houérou, 1972, 1976, 1977, 1979, 1980; Boudet, 1975, 1984; Boudet & De Wispelaere, 1976; Le Houérou & Popov, 1981; Le Houérou & Gillet, 1985; Le Houérou & Grenot, 1986; De Vries & Djiteye, 1982; Breman & De Wit, 1983). The Sahel thus extends across the continent from the Atlantic Ocean to the Red Sea in a strip 400-600 km wide over a distance of almost 6 000 km from west to east, covering a area of nearly 3 million km^2.

The Sahelian ecoclimatic zone is usually subdivided into three subzones:

- Saharo-Sahelian transition subzone, 100-200 mm of mean annual rainfall;

- Sahel *sensu stricto* subzone, 200-400 mm of mean annual rainfall;

- Sudano-Sahelian subzone 400-600 mm of mean annual rainfall.

Despite their simplicity, these limits are not arbitrary, being correlated with many other ecoclimatic parameters, including plant distribution and vegetation patterns, wildlife species, livestock species and breeds; cultivation and land use, production systems and ethnic groups and their ways of life.

The mean annual rainfall increases along a north-south gradient by approximately 1 mm/km (Le Houérou, 1979).

2.1 THE SAHARO-SAHELIAN TRANSITION SUBZONE

Although this subzone is not represented in Senegal, it is found at a short distance to the north, in Mauritania. The vegetation of this subzone is characterized by an open steppe of highly xeromorphic perennial grasses and graminoids, including *Panicum turgidum*, *Lasiurus hirsutus*, *Cymbopogon proximus*, *Aristida papposa*, *Aristida pallida*, *Stipagrostis pungens*, *Cyperus conglomeratus* and *Cyperus jeminicus*. Woody plants are confined to depressions, cliffs and sand dunes; trees and shrubs are mostly thorny or ephedroid species such as *Acacia tortilis* subsp. *raddiana*, *A. ehrenbergiana*, *Capparis decidua*, *Leptadenia pyrotechnica* and *Ochradenus baccata*. The whole vegetation is a mixture of Saharan and dry-tropical species, hence the name of this subzone.

The geomorphology and soils include large tracts of dunes and bare drifting sands. It is an area of nomadism and transhumance; livestock are essentially camels and goats with some sheep and occasionally zebu cattle.

2.2 THE SAHEL SENSU STRICTO

The Sahel sensu stricto is characterized by the predominance of sandy formations of fossil ergs (particularly the Ogolian sand dune system) which are covered by a fairly continuous mantle of vegetation dominated by annual grasses and sparsely dotted with shrubs and small trees.

Annual grasses represent about 70% of the herbaceous biomass (Le Houérou & Grenot, 1986). Typical grasses of this subzone include *Aristida mutabilis*, *A. funiculata*, *Cenchrus biflorus*, *Schoenefeldia gracilis* and *Chloris prieurii*. Shrubs and trees are predominantly thorny including deciduous microphyllous Mimosoideae, such as *Acacia tortilis* subsp. *raddiana*, *A. ehrenbergiana*, *A. senegal* and *A. laeta*, or thorny representatives from other families such as *Zizyphus mauritiana* and *Balanites aegyptiaca*, with some sclerophyllous broad-leaved evergreens like *Boscia senegalensis*, *Cordia sinensis* and *Grewia bicolor*. This is an area of pastoral nomadism and transhumance with some rain-fed gamble cropping of pearl millet (*Pennisetum typhoides* = *P. americanum*), and some retreat-flooding subsistence crops of millet and sorghum (*Sorghum bicolor*). Livestock include Zebu cattle (*Bos indicus*), sheep, usually of the hair type (*Ovis aries sudanica*), goats (*Capra hircus*), dromedaries (*Camelus dromedarius*), donkeys (*Equus asinus*) and horses (*E. caballus*). Wildlife is typically 'Ethiopian', i.e. Afro- tropical. Wild ungulates and their predators have been decimated over the past 50 years. For a few decades the rangelands have been increasingly subject to excessive clearance for the gamble cropping of millet with poor yields and very high risks of crop failure (200 kg/ha harvest for 4/5 seasons).

This subzone is widely represented in Senegal, particularly in the area known as the Sandy Ferlo, between the Senegal river and the 15°30' point of latitude, notably in the forest-grazing reserve, Koya, locally known as the 'region of the six boreholes'.

The Sahelian zone of the Sandy Ferlo has been the subject of in-depth studies, carried out by an ORSTOM team of resident scientists affiliated to the French section of IBP, on the structure, functioning, dynamics and productivity of Sahelian ecosystems (Bille, 1977; Poupon, 1980; Cornet, 1981; Poulet, 1982; Lepage, 1974; Morel & Morel, 1974; Gillon & Gillon, 1973, 1974; Bourlière, 1978). Their findings will be discussed later in this report.

2.3 THE SUDANO-SAHELIAN TRANSITION SUBZONE

This transition subzone has well-developed red tropical ferrugineous soils of light to medium texture (Luvisols in the FAO/Unesco Taxonomy, Eutrochrepts, Peleustalfs & Plinthustalfs in the US Taxonomy), which are covered by a Combretaceae savannah with predominantly annual grasses. Among the woody species are broad-leaved, fairly malacophyllous species such as:

Combretum glutinosum	Sclerocarya birrea
C. ghazalense	Bombax costatum
C. aculeatum	Adansonia digitata
C. micranthum	Maytenus senegalensis
C. nigricans	Sterculia setigera
Guiera senegalensis	Pterocarpus lucens
Anogeissus leiocarpus	Bauhinia rufescens
	Piliostigma reticulata

The herbaceous layer of annual grasses is often continuous, except on shallow soils and iron hardpans, with occasional traces of perennial species, notably Andropogon gayanus. The characteristic dominant annual grasses are as follows:

Cenchrus biflorus	Schoenefeldia gracilis
Aristida mutabilis	Loudetia togoensis
Andropogon pseudapricus	Elionurus elegans
A. penguipes	Ctenium elegans
Diheteropogon hagerupii	Eragrostis tremula
Schizachyrium exile	Chloris prieurii
Panicum laetum	Tragus berteronianus
Dactyloctenium aegyptium	Pennisetum pedicellatum

Taken together, these grasses usually represent 70 to 80% of the herbaceous biomass (cf. Tables 1 and 2). In terms of land use the Sudano-Sahelian transition subzone is an area of sharp competition between pastoralism and subsistence farming, in the Djoloff for example. Productive farming is only found further south in the Sudanian ecoclimatic zone, beyond the 600 mm isohyet of long-term mean annual rainfall. The main crops are pearl millet, cowpea, groundnut, sorghum, guinean sorrel, watermelon and some occasional maize.

Livestock is principally Zebu cattle, which represent some 70% of the metabolic biomass, and smallstock, which make up another 25% (cf. Tables 3 and 4). There are few camels in this subzone because of both traditional reasons linked to the nature of the human population (the Falani practise little or no camel-raising) and problems of disease control in the Sudanian zone (Hoste et al, 1984), while donkeys and a few horses represent 3-5% of the metabolic biomass.

The Sudano-Sahelian zone is equally well represented in Senegal, particularly in the southern and western half of the IMRES project area. This latter area is sometimes called the 'Ferrugineous Ferlo', as opposed to the 'Sandy Ferlo'.

Chapter 3

THE PILOT PROJECT AREA: THE FERLO

3.1 GEOGRAPHIC ZONATION AND ADMINISTRATIVE ORGANIZATION

As mentioned earlier, the pilot area may be subdivided into three to four subzones, corresponding with the local Fulani terminology (Santoir, 1977; Barral, 1982):

- The alluvial plain of the Senegal River valley or Walo in the Fulani language;

- The seasonal dry-season transhumance zone along the river valley locally known as Diêri, which is a strip some 50 km wide along the river valley. Diêri, in turn, is subdivided into lower Diêri or Diédégol at a distance of 0-25 km from the river and upper Diêri located some 25-50 km from the river. The upper Diêri used to be grazed for the early dry season (November-December).

- The Koya or 'Sandy Ferlo' in the central and western part of the project area. This is the traditional transhumance zone of the rainy season.

- The 'Ferrugineous Ferlo' to the east and southeast. This is the traditional dry-season grazing land because of the permanent water supply in wells dug in the Ferlo valley and some of its tributaries.

The region is divided for administrative purposes into two regions and six departments (cf. Figures 1 and 20):

i. River Region

Dagana Department
Podor Department
Matam Department

ii. Louga Region

Linguère Department
Kebewem Department
Louga Department

3.2 CLIMATE

3.2.1 Rainfall 1/

Mean annual rainfall for the period 1920-69 varied from 320 mm to the north 2/ (Richard-Toll 330, Dagana 318, Podor 313) up to 520 mm to the south (Linguère 517, Matam 520, Dahra 526) 3/ (cf. Tables 5 and 6 and Figures 3 to 16).

But rainfall in the years from 1970 to 1984 was, on average, less than 60% of these amounts. Over this period of 15 years not one single year attained the 1920-69 mean. There were three years of severe drought, 1972, 1983 and 1984, where rainfall was only 30 to 40% of the 1920-69 mean. In individual stations in some of these years, the amount of annual rain was only 10 to 20% of the 1920-69 mean, for example 33 mm at Fété-Olé in 1972, 79 mm at Mbeuleuke in 1983, 84 mm at Mbidi in 1984 and 77 mm at Mbar Toulab in 1984. For six years (1970, 1971, 1973, 1977, 1980, 1982) of this same period of 15 years, the mean varied from 40 to 60% of the 1920-69 average; six years (1974, 1975, 1976, 1978, 1979, 1981) had a mean between 60 and 80% of the 1920-69 figures and only one year (1981) had some 90% of that value. Since 1970, all the years have fallen below the 1920-69 average and 60% (9/15) have been well below.

Variability in annual rainfall is high and increases with aridity (cf. Table 5). The annual median is slightly below the mean and this difference also increases with aridity, from 2% at 500 mm to 6% at 300 mm:

Mean $\bar{X}$ (mm)		Median $\bar{m}$ (mm)
300	$\simeq$	282
400	$\simeq$	390
500	$\simeq$	490

The rate of reliability of annual rains (ratio of 0.8 probability to the mean: $f(0.8)/\bar{X}$) is 0.68 $\pm$ 0.02 between the 300 and 400 isohyets and 0.77 $\pm$ 0.03 between the long-term 400 and 500 mm isohyets (Le Houérou, 1986). In other words, in four years out of five, rainfall will reach 205 mm or more at the 300 mm isohyet and 385 mm or more at the 500 mm isohyet (Dancette, 1979).

Rainfall probabilities for a given isohyet are shown in Table 6 (Le Houérou, 1986; Le Houérou & Grenot, 1986).

1/ Detailed rainfall data analysis is provided in Appendix 2.

2/ Dagana: 1920-69; Podor: 1923-69; Matam: 1923-69; Dahra: 1934-69; Linguère. 1934-69.

3/ Dahra is situated outside the pilot project area, 35 km to the south of Yang-Yang (cf. Figure 24).

3.2.2 Evaporation and potential evapotranspiration

Annual pan evaporation (Class A) shows little variation throughout the area: 3 550 mm/yr at Podor and 3 360 mm/yr at Linguère. Potential evapotranspiration (PET) (Penman) reaches 1 724 mm/yr at St. Louis, 1 859 at Podor, 2 116 mm at Guédé, 1 690 mm at Linguère and 1 675 mm at Matam (Frère & Popov, 1984). The mean monthly values of 0.35 PET are shown in Figures 6 to 16. These figures show that there is little difference in length of dry/rainy seasons whether one selects the threshold criterion of P=2t or P=0.35 PET (Le Houérou & Popov, 1981). The rationale behind the selection of the 0.35 PET threshold has been discussed by Le Houérou & Popov (1981); it stems from the fact that evaporation from bare unsaturated ground is usually between 0.3 and 0.5 PET. Whatever amount of rain exists above 0.35 PET is available for plant growth. This value is therefore a good criterion for the discrimination of rest and growing season. According to this criterion, the growing season lasts from an average of 75-80 days in the north to 100-110 days in the south (also shown in Figures 6-16).

3.2.3 Air humidity

The influence of the Atlantic Ocean is scarcely felt beyond 30 km from the shore, to the east of a line joining Richard-Toll - Louga - Thiès (Giffard, 1974; Bille, 1977). However, the mean annual air humidity, 45% at Podor and 49% at Linguère, is clearly higher than the mean for the Sahelian zone, i.e., 35% (Le Houérou & Grenot, 1986). The mean minimal monthly values are usually below 20% and never reach 50%. The mean monthly maxima vary from 24 to 50% in the dry season and 50 to 90% in the rainy season.

3.2.4 Temperature

The mean annual maximum temperature varies from 35 to 37°C and the mean annual minimum from 19 to 21°C. The mean maximum of the hottest month (May) may reach 41-42°C and the mean minimum of the coldest month (January) does not drop below 13-15°C.

3.2.5 Incident radiation, insolation and photoperiodism

Global radiation varies from 400 Ly/day in December to 600 Ly/day in June with an annual average of 520, i.e., nearly 190 Kly/yr which corresponds to a Global Radiative Evaporation Potential (GREP) of 1 615 mm (Le Houérou, 1972, 1984) 1/. The annual number of sunshine hours is 2 730 at Linguère and the daily photoperiod varies from 11 h/day at the winter solstice and 13 h/day at the summer solstice, i.e., a difference of two hours. The average annual cloudiness is 4 octets (i.e. half the sky covered), ranging from 6/8 in August to 2/8 in March.

1/ GREP (Global Radiation Evaporative Potential): 0.5 Rg/59 = 95 000 Ly/59 = 1 615 mm, Rg being Global Radiation and 59 mm the latent heat of vaporization.

3.2.6 Wind

The continental trade winds and the Harmattan blow from the east and northeast in the dry season and the Gulf of Guinea monsoon blows from the southwest in the rainy season. Wind speed averages 2.4 m/s at 2 m above ground; it is higher in February-March (2.9 m/s) and lower at the end of the rainy season in September-November (1.8 m/s).

3.2.7 Seasons

The Fulani calendar year recognizes five seasons based on temperatures, rains, water availability and grazing land phenology, all of which rule the daily life of pastoralists and use of resources. They are as follows:

- Dabundé, the cool dry season from December to February;
- Tchedio, the hot dry season from March to April;
- Setsellé, the pre-rainy season in May-July;
- N'duggu, the rainy season in August-September;
- Kaulé, the post-rainy season in October-November.

3.3 SUBSTRATUM

3.3.1 Geology

During the Mesozoic and Cenozoic eras, a sedimentary deposit, several hundred metres thick, accumulated in the Senegalese-Mauritanian Basin. These sediments are the Maestrichtian sands, clays and limestones, Paleocene, Lower Eocene marls and limestones and Lutetian limestones towards the south. The tertiary marine series grows thicker from north to south from about 20 m west of Dagana to more than 50 m near Yaré-Lao to the southeast. After the Lutetian era, the central and eastern part of the Ferlo rose above sea level and continental sediments of clayey sandstones, the 'Continental Terminal', were deposited over a depth of 10-50 m from the northwest to the southeast. The Continental Terminal is topped by a thick and compact iron hardpan 1-2 m thick, overlain by 5-40 m of fluviolacustrine deposits, more or less weathered into laterite/ferralite. Local sediments contain ferrugineous chippings of limonite originating from the dismantled iron duricrust during the pleistocene erosion cycles (cf. Figure 17).

3.3.2 Deep-water resources (Audibert, 1966)

Groundwaters include three aquifers. The Maestrichtian water level, discovered in 1938 and exploited by some 70 boreholes, 200-300 m deep, has been drilled since 1949. These boreholes yield 20-100 m^3/hour. The Maestrichtian aquifer covers an area of some 100 000 km^2 and therefore extends far beyond the limits of the project area; its water reserve is estimated to be about 5×10^{12} m^3 (cf. Figures 17, 18, 19, 20 and 24).

There is also a discontinuous aquifer of little importance, 30-100 m deep, at the bottom of the Continental Terminal deposits. This aquifer is reached by ordinary, stone-built wells and produces small discharges of a few cubic metres/day.

A shallow phreatic aquifer is also sometimes present at the bottom of the Pleistocene sands at the point where the latter touches the fluvio-lacustrine deposits. However, this is a sporadic and unreliable aquifer of little importance.

The project area has some 600 surface wells, 488 of which were in service in 1984; 252 of these discharge 0 to 2 m^3/day, 183 yield 2-5 m^3, 53 produce 10-20 m^3/day and 112 are in disuse.

3.3.3 Geomorphology

The sand dune formations, or Seno (pl. Tchênê) in Fulani, include three geomorphic units. The older one, ante-Inchirian, is probably 50 000 to 60 000 years old. It is an old, smoothed, levelled erg 1-5 m thick, constituting what geologists usually call the 'covering sands'.

The Ogolian system of red dunes, about 15 000 to 20 000 years old, is made up of asymmetric ridges (Tullê in Fulani), 10-30 m high, 20-50 km long and 0.5-5.0 km wide, spaced 1-5 km apart. These sand ridges face a NE-SW direction, that of the Continental Tradewinds and of the Harmattan. This orientation is of primary importance when planning the Systematic Reconnaissance Flights (SRFs).

The Ogolian dunes have been reshaped in places into smaller parabolic barchanoid dunes facing a NNE-SSW direction, also called transverse dunes, and aged approximately 7 500 years. These are distinctly asymmetric and of a lighter colour than the Ogolian sands (yellowish vs reddish).

The sand cover may be up to 50-100 m thick. Ridges are separated by longitudinal depressions with greyish clay-sands, calcareous in places, and subject to temporary water-logging, locally known as Baldiol in Fulani. These Baldiol form the beds of the temporary rainy season ponds.

3.3.4 Soils (cf. Figures 21, 22 and 23)

The sandy soils of the dunal systems (the Subarid Red and Brown-Red soils of the French taxonomy) are neutral to slightly acidic, i.e., $5.8 < pH < 7.2$. They contain 90-95% coarse sand and 3-5% clay in the surface layers and 80-90% sand and 8-10% clay in the lower layers. Their Fe_2O_3 content is 1.5 to 3.0% and porosity is high, at 18-26%. Water content at pF 4.2 ranges from 1.1 to 3.5% and at pF 3.0, 2.0 to 5.0%. Organic matter content varies from 1 to 4%. These soils are saturated or nearly so with Ca^{++} and Mg^{++} cations: 2-4 mEq/100 g. They are deficient in N, with 0.1-0.4% and in P at 0.05-0.15%. Clayey-sandy brown subarid soils of the Baldiol depressions were developed in the fluvio-lacustrine deposits of soft limestone, and may contain 0.3-35% CO_3Ca.

The ferrugineous tropical soils (Oxysols) locally known as Dior soils are of a sandy or sandy-clayey texture and a strong red colour; they are found in the so-called Ferrugineous Ferlo or Iron Hardpan Ferlo. Mineral colloids (clay & iron) are slightly leached off in these soils and their organic matter content is low (0.2-0.5%).

The Senegal River valley has mainly water-logged soils of either the superficial hydromorphic pseudo-gley type locally known as Fondé, which constitutes a fair quality for irrigation or the heavy-clay vertisol, locally called Walo, which is much more difficult to utilize and develop.

The early Pleistocene iron duricrust soils cover some 5% of the project area, in the southeast. the duricrust is subhorizontal and 0.5-1.0 m thick, overlaying continental terminal sediments; it is dissected in places by linear or gully erosion.

The areas occupied by the principal soil categories are shown in Table 7 and Figures 21, 22 and 23.

3.4 SURFACE WATER

The area of the Sandy Ferlo is virtually areic; there is no organized hydrologic network. Run-off is always localized, in small watersheds of a few hectares feeding temporary rainy season ponds. Water may remain from one to five months in these ponds, which, at the peak of the rainy season in August, may cover up to 5% of the land surface. Ponds begin to fill up in July and to dry out in September-October. They usually provide most of the drinking water for humans and animals during the three months of the rainy season.

The Ferrugineous Ferlo, on the contrary, has an organized hydrologic network with periodically functional main streams and side channels or 'Marigots' (Loumbol, Tiangol, Louggère, Tiangol, Kossas, Mboune, etc.) whose outlet is the subfossil Ferlo valley and its lower reaches, the Bounoum valley, leading to the Lake of Guiers; but this watercourse is no longer functional. Many wells and céanes (funnel-shaped, unmasoned water holes, are dug in these valleys, which have small outputs and provide water for localized transhumance towards the southern border of the project area.

3.5 VEGETATION, RANGELANDS

In the Ferlo, as in the Sahel as a whole, the natural vegetation is a Mimosaceae scrub to the north, and a Combretaceae savannah to the south. This vegetation has been studied and described with great detail in its various aspects in more than a dozen major publications. Raynal, 1964; Adam, 1966; Audru & Lemarque, 1966; Fotius & Valenza, 1966; Naegelé, 1967, 1971; Diallo, 1968; Valenza & Diallo, 1972; Bille, 1977; Poupon, 1980; Cornet, 1981; Dieye, 1981, Boudet, 1980, 1983; Barral et al, 1983, Valenza, 1984: A good synthesized description to which the reader could refer was produced by Naegelé and published by FAO in 1971.

Where the rangelands are concerned, the local Fulani terminology, which is accurate and realistic, will be followed. The Fulani divide the rangelands into four main types, based on their geomorphological features which in turn determine the nature, composition and productivity of the range. They are the Seno range-type on sandy more or less dunal soils, the Baldiol in the depressions of the same name, the Tiangol range-type in the dry valleys and the Sangaré range-type on duricrust or iron grit in the pediplains. These main range types are associated with various sorts of browse and with particular vegetation types of limited extent around termitaria, ponds and fallows, etc.

3.5.1 The Seno range-types

These may be further subdivided into upslope, downslope and shelf, according to their topography, which influences the water budget and hence the botanical composition and productivity (Bille, 1977; Boudet, 1983; Barral et al, 1983).

Among the commonest dominant annuals, there are some 30 main annual grass species, which altogether represent over 70% of the herbaceous biomass at any site:

Aristida mutabilis	Cenchrus biflorus
A. stipoides	Ctenium elegans
Brachiaria hagerupii	Elionurus elegans
Eragrostis tremula	Digitaria gayana

There is also a small number of rare perennials:

Aristida sieberiana 1/	Andropogon gayanus

In addition to these grasses, there are some 30 common species of forbs belonging to various botanical families, among which are found a few legumes. The distribution of species, productivity and forage value of the main range-types are analysed in Table 1. The classification of species in relation to their forage value is shown in Table 2.

The main woody and browse species associated with the Seno range are as follows:

Mimosaceae:	Acacia tortilis A. senegal A. laeta A. macrostachya	Capparidaceae:	Maerua crassifolia Capparis decidua Cadaba farinosa
Anacardiaceae:	Sclerocarya birrea	Combretaceae:	Combretum aculeatum C. glutinosum Guiera senegalensis
Burseraceae:	Commiphora africana	Simaroubaceae:	Balanites aegyptiaca
Asclepiadaceae:	Leptadenia pyrotechnica Calotropis procera	Tiliaceae:	Grewia bicolor

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1/ A. sieberiana = A. longiflora + A. pallida.

3.5.2 The Baldiol range-types

These range-types are dominated by the two annual grasses:

Aristida funiculata	Schoenefeldia gracilis.

The woody layer includes:

Acacia seyal	Adansonia digitata
Boscia senegalensis	Combretum micranthum
Capparis corymbosa	Grewia bicolor
Zizyphus mauritiana	Cordia sinensis
Adenium obesum	Dichrostachys cinerea

3.5.3 The Tiangol range-types

These develop in dry valleys of the Ferrugineous Ferlo with a fairly dense woody layer of thickets under which is found the perennial Andropogon gayanus.

3.5.4 The Sangaré range-types

These are linked to iron-grit and iron hardpan soils and are characterized by the annual grasses:

Loudetia togoensis	Diheteropogon hagerupii
Andropogon pseudapricus	

The woody layer is dominated by:

Pterocarpus lucens	Acacia ataxacantha
Combretum nigricans	Bauhinia rufescens

3.6 WILDLIFE

Game animals seem to have been relatively plentiful until the beginning of this century, including the elephant, giraffe, roan antelope, bubal hartebeest, topi, greater koudou, oribi, waterbuck, kob, gazelle (red-fronted, dama, dorcas), addax, scimitar-horned oryx, aardvark, warthog, lion, leopard, cheetah, spotted hyaena, striped hyaena, hunting dog and the ostrich. In the past, the biomass may have reached 2 000 kg/km^2 (Boulière, 1978). In the similar ecological conditions of the Kalahari the biomass of the large ungulates was still 4 kg/ha in 1984. In the Ferlo the destruction of predators with strychnine has been encouraged by the Livestock Service since 1950 and further reinforced by the settlement of the nomads.

Most of the large mammals are now extinct; only a few red-fronted gazelles and still fewer dama, some striped hyaenas, warthogs, jackals and small mammals (hare and rodents) may still occasionally be found (Poulet, 1972, 1974, 1982). The mammalian biomass is currently less than 20 kg/km^2 with a large proportion of rodents; that is, less than 1% of the theoretical potential.

3.7 LIVESTOCK

According to the estimates of the Livestock Health and Production Service (DSPA), based on vaccination campaigns and some field surveys, the 30 000 km^2 of the project area had in 1981 the stock numbers shown in Table 3. Nevertheless, since the limits of the project area did not correspond to those used by the administrative units in their calculations, the number of animals within the project area was calculated by multiplying the number of animals found by DSPA in each administrative unit by the proportion of this unit within the project area. The coefficients were: Department of Linguère 0.4, Department of Podor 1.0, Department of Matam 0.3, Department of Dagana 0.3. The figures in Table 3 are rounded to the nearest hundred.

The conversion rate of various species into TLUs (Tropical Livestock Units) used in the table is based on the ratio between mean population metabolic weight and metabolic weight of TLU: cattle 0.81, small stock 0.18, horses 0.8, donkeys 0.53, camels 1.16.

The proportions between species, as expressed in TLUs, are quite typical of the Sahel as a whole (Le Houérou & Grenot, 1986) except in the cases of camels, for which they are lower than the zonal mean, and horses, for which they are higher. The average density in the project area is thus 3 000 000 ha ÷ 407 000 TLU = 7.4 ha/TLU. The average density of cattle found by counting at three main boreholes (Tatki, Tessekré & Belel-Boguel) in 1980 was 27 738 in an area of 183 000 ha, i.e., 6.6 ha/TLU (Meyer, 1980; Planchenault, 1981, 1983; Barral, 1982; Barral et al, 1983).

It should be taken into account here that the conversion rates used by different authors may vary considerably, according to whether they are based on the ratio of liveweight or metabolic weight of the population and TLU. The degree of departure may be as high as 15% as is apparent from Table 8.

Naegelé (1971), using numbers derived from vaccination campaigns following a series of above-normal rainy seasons in the 1950s and 1960s, found overall densities of 7.2 ha/head of cattle in 1966/67; 8.3 ha/head in 1967/68 and 7.2 ha/head in 1968/69. This corresponds to an overall density, taking all species together, of 6.5 ha/TLU, for that period, in the Koya area. This area is similar to that studied by counting the cattle at boreholes, as mentioned in the previous section. Assuming that one head of cattle = 0.8 TLU and that cattle make up 70% metabolic weight of all livestock (cf. Table 4), there is a good correspondence beween the figures (less than 15% difference) in spite of a 20-year interval between the two studies.

3.8 EVOLUTION OF LAND USE (Barral, 1982)

3.8.1 The Ferlo before the existence of boreholes

Up to the completion of the first borehole, at Dodji in 1950, the Ferlo area was considered as a 'Desert' because of the scarcity of permanent water resources. The Ferlo desert was only visited for four to five months annually by Fulani pastoralists and their transhumant herds, in the course of the rainy season (Bonnet-Dupeyron, 1952) (cf. Figures 28 and 29). Transhumance took place from the part of the Senegal River valley near where herds spent the dry season and from the other part of the valley where wells and céanes (waterholes) allowed for small permanent or subpermanent settlements. Grazing was plentiful and perennial grasses such as Andropogon gayanus were found in dense stands, sheltering and feeding an abundant wildlife of elephants, giraffes, roan antelopes, topi, kobs, waterbucks, reedbucks, addax, scimitar-horned oryx, aardvarks, ostriches, lions, leopards, hyaenas, hunting dogs and caracals, etc.

Until the First World War, the area accommodated some 50 000 pastoralists for six months over 30 000 km^2, with an estimated 30 000 head of cattle and 100 000 head of smallstock, that is, a total of some 45 000 TLU, a density of 1.5 TLU/km^2 or less than 4 kg liveweight per hectare.

The Colonial Administration soon tried to fill this 'empty space' by establishing, in 1901, the 'Well Brigade', made up of the Engineering Corps of the Marines. In 12 years, 675 wells were dug in the whole country by 40 teams working mainly along the railway track from Dakar to the Djoloff, west of Linguère (Brasseur, 1952, cited by Barral, 1982). The Well Brigade disappeared during the First World War and it was only in 1925 that a policy of pastoral water development was put into action in the Ferlo. But lack of finances meant that its development was slow and, since only shallow aquifers with small outputs were being exploited, the number of animals served in the dry season remained small.

It was only after the Second World War, after the accidental discovery of the Maestrichtian aquifer at Kaolack in 1938 (Audibert, 1966), that an active pastoral water development policy began to develop rapidly during the 1950s.

In 1950, livestock density was still less than 4 heads of cattle/km^2 (8 kg/ha) in the Djoloff; this trebled from 1950 to 1975 (Santoir, 1980, cited by Barral, 1982) to reach over 30 kg/ha in the 1980s. At the same time, in order to safeguard the pastoral identity of the region, the Colonial Administration set up 'forest-grazing reserves' (reserves sylvopastorales) where forest cultivation and exploitation was banned and this ban seems to have been respected. These reserves cover some 15 000 km^2, of which some 10 000 km^2 are located in the project area: the Koya reserve, with six boreholes and covering 4 300 km^2, and the Louggéré, Dodji, Sogobé and Khaddar reserves. These reserves seem to have been fairly efficient in protecting the environment by saving the area from the expansion of agriculture which occurred in most regions of the Sahel after the Second World War. Thus, to a large extent, they fulfilled their role of safeguarding the grazing resources of the Ferlo.

3.8.2 The Ferlo after the establishment of boreholes

Between 1950 and 1980, 35 deep boreholes (80-322 m) and 33 boreholed wells (cf. Figures 18, 19, 20, 24, 25, 26) were dug, reaching the artesian Maestrichtian aquifer. The static level of the aquifer is subartesian, close to ground level. One single borehole exploits the Paleocene aquifer, at Belel-Boguel in the northwest. Borehole exploitation involves pumping from a moderate depth. The total discharge is 7×10^6 m^3/yr of which

4.8×10^6 m^3 comes from boreholes and 2.5×10^6 m^3/yr from boreholed wells. Individual discharge varies from 10 to 100 m^3/hr; 85% of the installations are in the 20-50 m^3/hr yield bracket. The quality of the water is good, with about 0.15-0.75 g/1 (150-750 ppm) of mineral residue.

Deficiency in phosphorus provoked the spread of the 'borehole disease', a hydric botulism resulting from aphosphorosis. This condition is spread by the consumption of bones by livestock and the pollution of water by small mammals, particularly rodents. The growth of aphosphorosis was tied to the changes in traditional husbandry practices brought about by boreholes, particularly the abandonment of the 'salt cure' (Calvet et al, 1965). The establishment of boreholes and their equipment deeply upset the traditional pastoral practices by facilitating the settling, or rather partial settling, of the Fulani pastoralists. Each borehole thus created an area dependency where more or less permanent camping grounds and villages have been established (cf. Figures 25, 26 and 27). The older boreholes were more affected because their discharge is usually larger; their area of dependency reaches a radius of 15-20 km (70 000-125 000 ha). However, the average area of dependency is currently only 13 000 to 73 000 ha for the 68 boreholes.

The theoretical water requirements in the project area, outside the area of dependency of the Senegal River valley, is shown in Table 6. These figures were calculated on the basis of 270 days/yr, as the stock are watered at the ponds for an average of three months annually. The demand thus calculated is 6.3 million m^3/year and is therefore 15% below the volume theoretically pumped, i.e., 7.3 million m^3/year. To this output must be added the variable, but low, outputs of constructed surface wells and waterholes. The presently available water resources are therefore amply sufficient from the quantitative standpoint.

3.8.3 Consequences of borehole development on range utilization

In the traditional management system, pastoralists and their herds used to remain strongly aggregated because of the scarcity of water resources and because of the need for protection of the herds against predators (mainly lions and spotted hyaenas). In the dry season the Walo Fulani used to cultivate retreat-flooding sorghum in the valley of the Senegal River using the flooded pastures in the valley (*Echinochloa stagnina*, *Oryza barthii*, *Sporobolus helvolus* and Cyperaceae), while smallstock made use of browse (*Acacia nilotica*, *A. seyal*, *Zizyphus mauritiana*). In the rainy season, they would congregate for the transhumance to the Seno and Baldiol grazing lands of the central and northern Sandy Ferlo. Each group had its own pond or group of ponds to which they came every rainy season. The group camping grounds, or Rumano, was made up of a variable number of Gallê (household camping grounds). The Walo Fulani owned relatively few cattle, their herds being mainly smallstock. Watering took place daily at the ponds while grazing was unattended and would take place in daytime only, because of predators. Stock was confined at night in thorny enclosures (Galdê) at the camp. Each Rumano was surrounded by a reserved zone (the Houroum) within which some rainfed millet was cultivated. In the Houroum, grazing was prohibited to animals belonging to other groups. In this system, the stock benefited from year-long green feed and daily watering.

By contrast, the Diéri Fulani used to cultivate rainfed millet in the Sandy Ferlo (but had no retreat-flooding sorghum cropping in the valley). They moved between the Diédégol, a strip 25 km wide on the southern bank of the Senegal River valley, and the Ferlo. Then from the Ferlo, during the rainy season, they moved again to the Djoloff in the southwest (the region of Linguère, Yang-Yang, Dahra along the lower Ferlo valley, also called Bounoum). The latter transhumance included the salt cure in the Bounoum valley between Yang-Yang and the Lake of Guiers. In the dry season the stock were watered in the Senegal river and its side channels (Marigots), but they did not graze in the valley (where grazing rights were restricted to the Walo Fulani. The animals were watered every second day in the dry season. On the day of watering the animals would graze between the camping ground and the Walo, in a strip 10-15 km wide. On the day without watering, they would graze further south in the Diédégol, some 10-15 km south of the camping grounds. The width of land used for grazing during the dry season was thus a 25 km-wide strip along the western and southern bank of the Senegal River.

At the onset of the first significant rains, both the Walo and Diéri Fulani would start moving to their rainy season quarters in the Sandy Ferlo and would sow their millet there. But in contrast to the Walo, the Diéri would send most of the their cattle to a second-stage transhumance for the salt cure to the Djoloff, further south. These herds were only attended by a shepherd, while the household, with some milking cows and most of the smallstock would stay at the Rumano in the Ferlo throughout the rainy season. The return from the salt-cure transhumance would occur in September, before the harvest of the millet crop. After the harvest, the whole group would move back to the dry season quarters in the Diédégol to the south of the river in October-November, depending on the drying out of ponds along the trail.

Thus the whole area was used for four to six months in the annual cycle. The grazing space between each Rumano was subdivided into two areas: the Diéi, reserved for certain groups and owned and managed by them, and the Laddé which was free range available to all. The Diéi areas were divided into sections or Houroum, each corresponding to a Rumano. There were no boundary markers but everyone knew the divisions and would tacitly abide by them. Landscapes and territories were thus organized around a pond or a group of ponds and divided into Houroum, Diéi and Laddé. The Houroum thus constituted an organization somewhat similar to the old system of 'finage' in medieval Western Europe. However, once the millet crop had been harvested, the notion of Houroum disappeared; all the land then became Laddé, so that after the harvest all was common grazing.

The establishment of mechanized boreholes progressively reduced transhumance. From 1950 onwards, the boreholes acted as poles of attraction for settlement in the dry season. As a consequence, the rainy season Rumano have tended to become permanent, but, paradoxically, mobility was hardly reduced, at least in the beginning, but rather strengthened. It also became a sort of anarchic 'Brownian movement'. The Fulani remained pastoralists and did not really settle down (Dupire, 1957; Grenier, 1957). A study undertaken in 1980 on 13 boreholes serving an area of 9 520 ha (one-third of the project area) concluded that there were 89 000 sedentary and 12 000 transhumant cattle for a population of 32 000 people, that is 9.4 ha/head of cattle, or 8.3 ha/TLU, all stock taken together, and a stock to human ratio of 3.3 TLU per person (Meyer, 1980, cited by Barral, 1982). The proportion of transhumant stock thus decreased from 60% in 1950 to 13% in 1980 (Bonnet-Dupreyon, 1952). The aggregation around ponds in the rainy season remained unchanged; thus movement was reduced to short journeys within the service area of each borehole. At the same time, groups have split into smaller units and the average number of Gallê per Rumano decreased from 12 in the 1950s to five in 1978/80. There are several reasons why the groups have split in this way:

- the elimination of predators;
- sharper competition for grazing resulting from the growth of stock numbers (an increase of 120% between 1955 and 1980);
- reduced primary production due to the drought of 1970/84 and relative overexploitation, equally linked to the drought.

To these physical and biological causes can be added socio-political reasons: the loosening of solidarity, encouraged by the vaccination campaigns, and the decline in the authority of the elders and traditional leaders to the benefit of the representatives of the State. The result has been the progressive disappearance of the Houroum since the 1960s, with the support of the administration after Independence. The Houroum is presently restricted to cultivated fields. Free ranging has become commonplace at the expense of the old Houroum-Diêi structure, thus creating the present anarchic situation.

There is some degree of movement between the areas of polarization of neighbouring boreholes during the dry season as a result of grazing availability, or when, for various reasons, the pumping station breaks down for some time, or when grazing is destroyed by a bush fire, etc. A new social structure and solidarity has thus developed around the boreholes. This new solidarity expresses itself in, for instance, communal purchase of spare parts and fuel and the communal maintenance of pumping stations. The present utilization of the rangelands in the rainy season depends on short-distance grazing (less than 5 km) around ponds and Rumano, with the livestock watering every day. The dry season brings the use of pastures further away from the Rumano, which may be temporarily abandoned for a short-range transhumance within a radius of 10-20 km from the nearest borehole; watering then takes place every second day. These temporary dry-season camps, called Sedano, may be moved two to three times in the course of a dry season, depending on grazing availability. The system is thus characterized by short-range micronomadism, not settlement - a kind of 'borehole endodromy' reminiscent of the system in the Gourma region of Mali and Burkina Faso described by Barral (1977).

There are occasionally exceptional migrations on a larger scale in years of extreme drought such as occurred in 1972, 1983 and 1984. In 1972 and 1983, most of the stock moved out of the project area to the south. They did not come back in 1984; because of extreme drought there was no grazing in the Ferlo. However, this phenomenon may occur outside drought conditions, in limited areas, for example when the range has been destroyed by a bush fire or when a borehole has broken down over a long period.

The mean density of human population in the Ferlo is 3 inhabitants/km^2 (cf. Figure 2); the annual growth rate for the past 60 years has been 0.9%.

These two figures for density and growth rate are among the lowest - if not actually the lowest - in the Sahel, which accounts for the relatively unspoiled conditions of the Ferlo as compared to most areas in the sahel.

3.8.4 Range and livestock development in the Ferlo

Grazing improvement in the Sahel was achieved by the State of Senegal through the technical services of the Ministry of Agriculture. Specific programmes include pastoral water development, establishment of the forest-grazing reserves, the creation and maintenance of firebreaks, extension veterinary services (prophylaxis), stratification of stock-farming and marketing facilities.

3.8.4.1 Pastoral water development 1/

There are 37 boreholes in the Ferlo; these are the deep, sub-artesian boreholes in which the static level of the aquifer varies from -3 to -60 m. There are also 37 boreholed wells; most of them are equipped with a diesel pumping station. They were all drilled and became operational between 1950 and 1980. These installations are fairly well distributed over the project area (cf. Figure 20). The area serviced by each borehole averages 810 km^2 and the overall density is thus one installation for 405 km^2. The theoretical discharge is 4.8×10^6 m^3/yr for the boreholes (13 150 m^3/day = 292 000 TLU/day) and 2.5×10^6 m^3/yr for the boreholed wells (6 850 m^3/day = 150 000 TLU/day); that is a total of almost 450 000 TLU, thus easily sufficient for the 410 000 TLU of the project area. All of these installations exploit the Maestrichtian aquifer, with the exception of the Belel-Boguel borehole set up on the Lutetian aquifer. They are all equipped with mechanized pumps, in general diesel-powered motors and pumps, and also some are wind powered in the eastern part of the area.

More than 600 surface wells have been dug, 488 of which were in service in 1982. Most of these exploit the Continental Terminal aquifer at depths varying from 30 to 100 m. Water is usually raised manually or by draught animals. The average discharge is 4.5 m^3/day, broken down as follows:

Discharge m^3/day	No. of wells	%
$D < 1$	137	28
$1 < D < 2$	115	23.5
$2 < D < 10$	183	37.5
$10 < D < 20$	46	9.4
$20 < D$	7	1.4

The céanes are non-lined, funnel-shaped water holes 3-10 m in diameter at the ground level, exploiting shallow, superficial and often temporary aquifers in the fossil valleys, particularly those in the Ferlo. Little is known of the number, yield and permanence of these céanes.

Surface water

Apart from the Senegal River and its side channels left behind as the flood retreats, there are some 305 ponds in the project area used for

1/ A detailed analysis of surface water development data is given in Appendix 6.

watering stock in the rainy season. This is equivalent to about one pond for 10 000 ha of rangeland. Those ponds consequently water an average of 1 350 TLU each during the three months of the rainy season, that is, a consumption of 60 m^3/pond/day (cf. Table 9) or 5 400 m^3 per season. The periods for which each pond can be used and its capacity would be useful data for range management in the Ferlo and for improving the hygiene of these ponds (parasitism, access, storage capacity (over-excavating)). Unfortunately, neither the annual dates of filling up and drying out, nor the number of stock they serve, have been recorded. Such records could constitute a valuable objective for the monitoring of the Ferlo; perhaps high-resolution Spot images could be used.

3.8.4.2 Forest-grazing reserves, firebreaks

Some 10 000 km^2 of the project area have been demarcated by the Waters, Forest and Game Service of the Ministry of Agriculture. The areas concerned are the reserves of Koya, Sogobé, Khadar, Louggéré-Tioli, Barkhedji-Dodji, Ndiayène and Lérabé. A network of 2 700 km of firebreaks was established by the Water, Forest and Game Service, and fire-fighting committees were organized in each region and department. Mobile fire brigades to combat bush fires were envisaged but do not seem to have been set up except at Linguère (Naegelé, 1971). As early as 1971 Naegelé pointed out that these firebreaks were not very efficient since they are not wide enough and not properly maintained. He made suggestions for their expansion and improved maintenance. Judging from the SRF data on traces of fire, the present network and its maintenance still do not constitute an effective measure against bush fires.

3.8.4.3 Hay-making operations

A hay-making operation was launched in the Ferlo in 1961 and lasted until 1970, with the assistance of FAO (Naegelé, 1971). This operation was aimed at convincing pastoralists of the usefulness and feasibility of hay-making and conservation at the end of the rainy season. The first demonstrations organized by DSPA took place near Labgar in 1964 with a group of progressive pastoralists who volunteered for the experiment. In 1965 and 1966, the experiment was expanded to the areas served by the boreholes at Tatki (Department of Podor) and Yayatê (Department of Dagana). After three years of demonstrations in mowing, harvesting, hay-making, stockpiling and conservation, and ox-taming, the experiment was extended between 1967 and 1969, with the assistance of FAO and World Food Programme. The operation was so successful that priority action was signalled in the third Four-year Economic and Social Development Plan (1969-73).

Unfortunately, the programme then collapsed, after the departure of the FAO expert, Mr. Naegelê, because of problems in maintenance of equipment, particularly mowing machines; these problems had been underestimated and were not satisfactorily resolved for the remainder of the programme. Later attempts were also unsuccessful, in spite of the cooperation of SISCOMA 1/ (Le Houérou, 1974). One positive point has been learned - hay-making is technically feasible and socially acceptable to the pastoralists - all that remains is for the maintenance and management problems to be resolved.

1/ Société industrielle sénégalaise de construction mécanique et agricole.

3.8.4.4 Assistance to the pastoralists

Apart from vaccination campaigns against rinderpest and contagious bovine pleuropneumonia, which were developed in the 1950s (and gave rise to a sharp increase in cattle numbers in Senegal, as it did in the Sahel as a whole), the Senegalese Administration has set up a parastatal organization, SODESP, for helping the pastoralists in animal production. SODESP, a public industrial and commercial institution, was established by law on 2 June 1975, in order 'to promote livestock development and production'. Its strategy consists of:

- intensifying stock production through calving husbandry (until weaning);

- rearing of young in such a way to obtain faster growth and earlier maturity;

- fattening and finishing operations for young males and culled animals in order to improve the quantity and quality of the meat output.

The calving husbandry takes place in the forest-grazing area of the Ferlo, the rearing operation in the Senegal River valley, at the Doli ranch and in the so-called 'Groundnut Basin'. The fattening-finishing operations are carried out by contract with farmers in the Groundnut Basin (peasant-managed fattening) and in feedlots around the main cities (industrial fattening). Both utilize crop residues (groundnut stalk/hay and sugarcane tops) and agroindustrial by-products (cotton seeds, rice bran, groundnut meal and molasses).

Two independent extension areas (called channels) were operational in 1984 in the areas serviced by the boreholes of Labgar and Mbar Toubab, covering an area of 3 000 km^2 (10% of the project area). The calving husbandry operations concerned some 30 000 breeding cows and their calves and 9 000 ewes and their lambs, belonging to 1 300 pastoralists. The purchase and marketing of stock represented 213 and 279 millions CFAF ($US 0.71 and 0.93 million) respectively, in 1984. SODESP employs 165 people, 36 of whom are field extension technicians. It receives assistance and funds from FAC, FED and USAID; its annual budget is 3 billion CFAF ($US 10 million).

The performance of the stock husbanded through the SODESP channels is 60 to 80% superior to that raised by traditional practices in terms of total output. The programme is intended to extend to four more areas: Tatki, Gaye Khadar, Ranerou and Lindé. Such an expansion would raise the stock numbers to some 120 000 cattle units and 120 000 sheep units - that is, 50% of the cattle and 30% of the smallstock population of the project area.

Chapter 4

MONITORING

4.1 PROBLEMS AND GLOBAL METHODOLOGICAL APPROACH

The principles of ecological monitoring of natural resources combining various terrestrial, aerial and space remote-sensing methods were described and put into practice in the early 1970s in East Africa (Gwynne & Groze, 1975). None of these methods alone can provide all the complex information required for the ecological monitoring of ecosystems and natural resources, including data on geology, soils, water, vegetation, animals and human activities, their seasonal changes and long-term evolution. Decisive progress has been made over the past 20 years in the field of remote sensing by the improvement in various types of satellite imagery, the development of low-altitude Systematic Reconnaissance Flights (SRF) and the considerable (often underrated) improvement of conventional aerial photography, which now includes techniques using: infrared; false-colour; colour; high-sensitivity, high-resolution panchromatic emulsions and improved optics.

Each of these techniques permits information to be obtained at various scales, with varying detail and degrees of precision and at widely differing costs. There is, almost inevitably, a conflict to be resolved in a monitoring programme between cost and detail. For instance, one must decide if the programme needs a substantial amount of data of average quality at a low cost, or high-quality data that are necessarily more costly and therefore fewer. A sometimes difficult choice must be made to fulfil the objectives of the programme in the best way with the available means at the most advantageous cost. The wide range of data sources allows for such a choice.

4.1.1 Satellite imagery

Satellite images permit a global overview of large scenes (from 8 500 to 2 million km^2). As the spatial resolution of sensors became more refined from RBV, MSS, AVHRR, TM to Spot 1/, they have allowed increasingly large-scale utilization. The characteristics of various sensors and types of images are shown in Table 10 and Figure 30.

Because satellite images of the same area can be obtained at regular intervals they can be used to study exactly those ephemeral phenomena which

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1/ RBV = Return Beam Vidicon (ERTS 1 & 2); MSS = Multispectral scanner (LANDSAT); TM = Thematic mapper (LANDSAT 7). Spot = Système probatoire d'observation de la terre; AVHRR = Advanced Very High Resolution Radiometry (NOAA/Meteosat NOAA 6, 1980; NOAA 7, 1981, 1982, 1983; NOAA 8, 1984).

are so often important in ecological monitoring. This is particularly the case when assessing the green herbaceous biomass in the Sahel, a subject that will be discussed in detail later. Satellite-borne sensors also permit the selection of information using various bands or combinations of bands of the electromagnetic spectrum for different levels of interpretation.

Furthermore, the cost of images per unit of surface area is relatively small compared to other techniques. However, at the present state of civilian satellite technology, ecologically useful stereoscopic vision of the images is not available 1/; satellite images are also incapable of providing information on finer phenomena such as those needed for detailed evaluation of vegetation cover, the detection of early erosion stages (which can still be kept under control), detailed aspects of hydrology (wells, ponds and side channels), wildlife and livestock numbers, and many aspects of human activity.

4.1.2 Aerial photography

Conventional aerial photography is amenable to stereoscopic interpretation and can therefore be used to collect very detailed large-scale information, such as individual tree height, crown diameter, proportion of canopy cover and, sometimes, the specific botanical composition of the tree layer, as well as moisture in the upper soil layers, early stages of erosion, density and type of human settlement, crops and so on.

The scale may vary from 1/2 000 to 1/200 000. The cost has considerably decreased with the combined use of high-resolution emulsions and high-altitude (10 000 m) photography from jet planes, which allows for small-scale photographs (1/100 000), that can be enlarged four times or more. Nevertheless, the acquisition of an aerial cover is still costly and can rarely be justified for areas smaller than 1 000 km^2 because of this. Their cost means that aerial surveys are not frequently renewed and they are generally carried out once every 10 to 30 years depending on the area and country. This infrequent collection of data limits their use in ecological monitoring. However, aerial coverage does constitute reference data which are essential and, for the moment, irreplaceable, often providing baseline information against which conditions in the field may be compared.

4.1.3 Low-altitude systematic reconnaissance flights

Developed in East Africa in the 1960s, essentially for large game counts and censuses (Norton-Griffiths, 1975/78; Gwynne & Croze, 1975), SRFs make it possible to record very fine and temporary details of phenomena such as wildlife and livestock numbers, spatial distribution of rain, hydrology (wells, ponds, run-off, flooding) and seasonal and annual changes in vegetation.

Implementation is less costly than that of aerial photography, and as a consequence flights may be repeated much more often; as far as ecological monitoring is concerned, this involves a permanent organization. However,

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1/ Some stereoscopic effect is obtained from Spot ($\simeq$10 m); but this is not sensitive enough for the purpose considered here.

SRFs need precise and sophisticated sampling procedures and ground controls for validation. Furthermore it can be a physically dangerous tool in inexperienced hands.

4.1.4 Ground control validation

The three remote-sensing methods mentioned above have one common point: they require validation from the ground in order to calibrate the measurements made from the air or from space and to interpret remotely-sensed data. But collecting data on the ground is time consuming and costly and, because of this, a combination of remote-sensing and ground control allows for better accuracy at lower cost.

The project developed its activities along three main lines:

- Satellite evaluation of green herbaceous biomass on the range at the end of the rainy season (i.e., maximum standing crop);

- livestock census, evaluation of erosion, and the evolution of land use via SRF;

- control of remotely-sensed data, via ground sampling of the information gained from air and space.

Other studies were being undertaken at the same time by other teams in the project area. Of particular note were the diachronic studies of aerial photocoverages on land use, erosion and the evolution of the canopy cover of woody vegetation (De Wispelaere, 1980, 1981; Barral et al, 1983). These same organizations (DGRST/LAT/GRIZA 1/, LNERV, ORSTOM, IEMVT, CTFT) were also conducting several ground studies on the following:

- herbaceous vegetation (Boudet, 1980, 1981, 1983; Dieye, 1981, 1983, Valenza (1984);

- ligneous vegetation (Piot & Diaité, 1983; Valenza, 1984);

- livestock enumeration (Meyer, 1980; Planchenault, 1981, 1983);

- erosion (Valentin, 1981, 1983);

- socioeconomic and cultural aspects (Santoir, 1977, 1981; Barral, 1982);

- human health and nutrition (Benefice, 1980; Benefice *et al*, 1981).

1/ Délegation générale à la recherche scientifique et technique (DGRST), Lutte contre l'aridité en milieu tropical (LAT), Groupe de recherches interdisciplinaires en zones arides (GRIZA).

4.2 EVALUATION OF GREEN HERBACEOUS BIOMASS BY ORBITAL REMOTE SENSING

4.2.1 Introduction

The intention of this evaluation is to produce, at the end of the rainy season and at a moderate cost, a global, detailed and geographically precise map of the amount of green herbage standing-crop available for the following dry season. Such an evaluation should make it possible to establish appropriate range and livestock management objectives for each geographical zone of the Ferlo for every dry season. Decisions which could be based on this information include transhumance dates, exclosures, dates of opening or closing pumping stations, destocking, purchase and marketing of stock, number of animals to be fattened, purchase, dispatching and delivery of concentrate feed, culling rates and stratification.

In effect, the green herbaceous biomass accumulated at the end of the rainy season, at the beginning of October, represents the total grazing resources available for the nine months of the following dry season; this suggests a relatively strong case for forward planning, which is hardly encountered outside the dry tropical areas practising a monomodal, pluviometric system, like the Sahel, the Kalahari or Rajastan.

4.2.2 Methods

The method of measuring the green biomass by remote sensing is based on the radiation reflected from green plants which, in turn, depends on the absorption spectrum of electromagnetic radiation by chlorophyll. Chlorophyll only absorbs radiation included in the visible part of the spectrum, i.e., wavelengths from 0.4 to 0.7 µm, with two areas of maximum absorption toward 0.43 and 0.65 µm, that is, in the blue and in the red part of the spectrum. The area of maximum photosynthetic efficiency for chlorophyll alpha is located in the red part, that is, in wavelengths between 0.6 and 0.7 µm (6 000-7 000 Å) (Rabinowitch, 1958). It follows that reflectance of chlorophyllian plants is minimal for these wavelengths. As a consequence, the ratio between the low reflectance of λ of 0.6-0.7 µm (red) to the high reflectance of λ 0.75-1.1 µm (near infrared) is a good indicator of photosynthetic activity. Furthermore, it has been shown that this ratio is a reliable indicator of Leaf Area Index (LAI) and of the photosynthetically active biomass (Tucker, 1979; Tucker *et al*, 1981; Holben *et al*, 1980; Kimes *et al*, 1981; Markham *et al*, 1981; Weigand, 1979).

However, if the use of this ratio is reliable and straightforward for monospecific and homogeneous plant covers with a simple structure, either with erect or horizontal leaves, such as crops on certain types of forests, the situation is more difficult in mixed heterogeneous plant populations, the structure and architecture of which are variable and usually complex (Tucker *et al*, 1983). Such a complexity requires relatively precise, and numerous, ground validations for each main vegetation type in order to calibrate the relationships between reflectance indices and green biomass actually present. The project provided a particularly interesting and favourable opportunity to apply the method of diachronic integration proposed by Tucker and his associates (1981) to the concrete project of rangeland monitoring over a large territory. This innovation, resulting from the collaboration of the project and NASA, was greeted as a breakthrough by the world's scientific community.

The first attempts made by the project used the LANDSAT MSS images. However, this proved impractical because there were only enough cloud-free images usable for two rainy seasons since 1972. Furthermore, since there is no reception station in West Africa, no images were available from 1981 onward. Moreover, in order to cover the whole project area and its adjacent Mauritanian regions, it would have required two simultaneous LANDSAT scenes (Tucker et al, 1983). The interpretation of data on the photosynthetically active biomass requires frequent information at an interval of at least every 5-14 days so as to be able to estimate the temporal dynamics of the accumulation of green biomass. An example of this occurred in central Mauritania from 28 August to 13 September 1982. This period witnessed a clear-cut, but short, burst of green biomass which does not appear on the images on the images of 19 August or 21 September. This herbaceous growth pulse was recorded by AVHRR (individual images and integrated composites), but it would have escaped recording by LANDSAT, even if the cloud cover had permitted. The interval of 18 days between Landsat flybys therefore could not serve the project's goal (Tucker et al, 1983).

It was then decided to utilize the Advanced Very High Resolution Radiometer (AVHRR) sensors embarked on NOAA 6 and 7 satellites. NOAA 6 and 7 are heliosynchronous, polar-orbiting operational satellites in the TIROS-N series of spacecraft, which operate at an altitude of 850 km with equatorial crossing times of 02.30/14.30 local solar time. The AVHRR instrument has $\pm$ 56^{o} field of view and a 1.1 km nadir spatial resolution (Kidwell, 1979). The wide field of view (Landsat's, by comparison, is $\pm$ 5.6^{o}) results in effective coverage three consecutive days out of nine; the orbital period is 9.2 days. In the case of the Ferlo, the smallest vegetation unit necessary for the correct intepretation of the green biomass is the geomorphological unit constituted by the dune and interdune areas, which is usually 1-2 km wide. Thus the 1.1 km at nadir spatial resolution of AVHRR was well suited to the project's needs (Tucker et al, 1983). In spite of having wider spectral bands than LANDSAT, NOAA 7's AVHRR represented the only usable source of satellite data for conducting a large-scale study of grassland green-leaf biomass and total dry matter accumulation at high temporal frequency (cf. Figure 30 and Table 10).

Simulation studies using ground-collected reflectances in the AVHRR 0.55-0.68 and 0.725-1.10 µm bands, coupled with the atmospheric models of Dave (1979), indicated a level of uncertainty of approximately 10-15% using uncorrected data over the $\pm$20^{o} scanning range of the NOAA-7 AVHRR for a situation typical of the Ferlo (Tucker et al, 1983).

Seven GAC (Global Area Coverage resolution $\simeq$ 4 km pixels) images were available from 12 July to 25 October 1980, from the AVHRR/NOAA-6 data. In 1981, two GAC images from NOAA-7 were available from 13 July to 10 August and six LAC images (Local Area Coverage resolution $\simeq$ 1.1 km pixels) from NOAA-7. Sixteen images were used in 1982: 7 LAC and 9 GAC. Sixteen again were used in 1983: 16 LAC and no GAC, while 22 images were available for 1984: 14 LAC and 8 GAC (Tucker et al, 1985).

4.2.3 Data interpretation 1/

Interpretation of electromagnetic signals was undertaken using the method perfected by Tucker (1979, 1980), called by him the Normalized Difference of Green Vegetation Index (NDVI), but which is now routinely referred to as the Tucker Index. This index reads NIR - R / NIR + R or, referring to the AVHRR sensor, C2 - C1 / C2 + C1 (cf. Table 11).

Channel 5 (11.5-12.5 μm) may be used as an interactive cloud mask which facilitates the elimination of parasite reflectance from clouds (Tucker *et al*, 1982). The digital data was analysed at the Laboratory of Terrestrial Physics of the Goddard Space Flight Center on a Hewlett Packard 1000 interactive image-display system. These images constituted the polychromic visualization (Mercator Projection) of NDVI slides. Integrated images (INDVI) were constructed from a chronological series of images throughout a rainy season for each pixel (1.1 x 1.1 = 1.21 km^2 for LAC and 4 x 4 = 16 km^2 for GAC). However, individual images have, over a given period, a maximum value on the Tucker Index for each pixel. Images constructed using the maximum NDVI are MNDVI images. Correlations between ground-measured biomass on the one hand and INDVI or MNDVI values on the other hand have been calculated. The correlation coefficients for the two indices are quite similar at 0.79 and 0.76 respectively for the overall data between 1980 and 1983, as shown in Tables 12, 13, 14 and 15 (Tucker *et al*, 1983, 1985). The regression equation between ground-measured biomass and INDVI is expressed as follows:

$$Y = -74.3 + 7631.5 \text{ INDVI}$$

For data programming and storage reasons, LAC data are collected every three days by NASA, while that of GAC, 16 times more extensive, is available every day, which considerably increases the probability of obtaining cloud-free pictures during the rainy season. The existence of a reception station in West Africa would allow the daily reception of all LAC data, at present. The correlation between the two indices is very high, at r2 = 0.97 : GAC = 0.95 LAC (cf. Table 14).

The differences between the figures for green biomass deduced from the values supplied by NASA/AVHRR and those measured at ground level may arise from the following causes:

- less than optimal ground sampling;
- biomass consumption by livestock (grazing);
- presence of atmospheric haze;
- crown cover of woody vegetation above 10%;
- presence of less than 250 kg DM/ha of green herbaceous biomass;
- errors in the collection and processing of data;
- different people measuring ground samples result in errors in site location. Finding exact sites on the ground is difficult in the Sahel as a whole and in the Ferlo in particular, because of the lack of clear landmarks.

1/ Detailed interpretation of radiometric data is given in Appendix 5.

The regressions which appear in Figure 33 suggest a lack of sensitivity of satellite data for green biomass below 250 kg DM/ha (Tucker et al, 1985), but correlations between satellite data and ground validation are very good whenever annual rainfall reaches 250 mm or more.

4.2.4 Image exploitation, construction of biomass maps

Digital NDVI figures are used to construct images by the computer procedure mentioned above. Images are available in several forms: as colour prints and colour transparencies (19 x 24 cm), and 24 x 36 mm slides. Computer analysis may provide images at various scales according to the area to be processed and the detail that is required. Often the scale used is 1/3 000 000, which is hardly sufficient to detect each colour pixel. Occasionally the scale of 1/1 000 000 or 1/2 000 000 is used for more complex areas. Within the project, maps were constructed from 19 x 24 cm paper prints of INDVIs or from slides (24 x 36 mm). Maps were made out of transparencies at the scale of 1/500 000, so that each GAC pixel covers 20 mm^2 (= 16 km^2 on the ground) and each LAC pixel represents 5 mm^2 (1.21 km^2 on the ground). Figures 66 to 69 map the green herbaceous biomass for 1981, 1982, 1983 and 1984. These maps were made available to the users in October-November of each year. The 1980 map, however, was drawn later (cf. Figure 65).

When delivered to the users (DSPA, SODESP, LNERV, etc.) each map was accompanied by an explanatory note and directions for use, including comments on the overall situation and with qualitative notes on pastoral value. This information was collected during the sampling for ground validation. The regional forage budget was established from the collected information.

Mapped isoproduction lines were based on satellite data, preferably from integrated NDVI at the end of the growing season. This document allows the primary production of herbage to be evaluated spatially. Green biomass is divided into 12 classes of 200 kg DM/ha, each corresponding to 12 brackets of Tucker's Index values and their matching colours (Gaston et al, 1983) (cf. Tables 15 and 16 and Figures 31 to 37). Unfortunately, the confidence interval (or the standard error) within each class was not indicated.

From the digital data, it is possible to derive the mean, the median or the mode of vegetation indices from each pixel within the area under consideration. It should be noted that reflectance from woody cover is integrated in the satellite data, whereas it is not in the hand-held radiometer data. The contribution from the woody layer could, in principle, be subtracted from the final integrated seasonal index value by subtracting the early rainy season index values from the final ones. However, this was not judged useful nor desirable, because the woody layer also contributes significantly to the overall forage biomass and livestock feeding (Le Houérou, 1980; Sharman & Nging, 1983).

It is regrettable that the percentage of crown cover of the woody layer and its foliar biomass were not taken into account in the field sampling procedures. Including green biomass of woody species would not have greatly increased the workload of the surveyors since foliar biomass can be related to allometric parameters (stem diameter, height and crown diameter). The relationship between these parameters had been previously studied in the

Ferlo (Bille, 1977; Poupon, 1980). Moreover, the in situ study of the woody layer had been undertaken on 1 ha plots at 40 sites in the Ferlo from 1979 to 1981 (Piot & Diaité, 1983; Valenza, 1974). The data gathered by this LNERV-DGRST/CTFT were - regrettably - not used by the project, which instead undertook a study of 25 one-hectare plots on the Mbidi dune and followed through some of the observations carried out by the IBP/ORSTOM project at Fété-Olé from 1969 to 1978. The conclusions reached in this study will be examined later.

4.3 GROUND EVALUATION OF RANGE PRODUCTION

4.3.1 Background

Ground samples were used to calibrate the satellite data obtained from AVHRR. Ground sampling was effected in two ways: by the classical method of hand-clipping and weighing samples and by using a hand-held radiometer, the Mark II device, designed by NASA and similar to the AVHRR embarked on NOAA 6 & 7 (Tucker et al, 1981). The field radiometer thus has the same three channels as AVHRR in the red, near-infrared and thermal infrared wavelengths. The device was powered by batteries available locally. Hand-clippings were made in order to calibrate the radiometer and thus improve its utility in Sahelian rangelands. Over the same period, other diachronic studies on primary production were being undertaken in the Ferlo by two different research teams in close cooperation with LNERV and ISRA (Valenza, 1984) and the other with DGRST/LAT/GRIZA (Boudet, 1981, 1983; Piot & Diaité, 1983).

4.3.2 Sampling (Figures 29 & 43)

Ground sampling was stratified. It was first undertaken in 1974 in order to monitor the impact of boreholes on the vegetation of the pastures in the Ferlo.

Permanent plots were selected on aerial photographs using the following various criteria.

Range type was based on the 1/200 000 map by Valenza & Diallo (1972).

Distance from boreholes was used, along specific directions oriented as a function of the range-types crossed (as indicated on the pastureland vegetation map and checked on the site). Permanent plots were located at 0.5, 2 to 3, 4 to 6 and 8 to 10 km from each borehole under study. Three boreholes were monitored from 1974 to 1976 and six from 1976 to 1984: Tatqui, Mbidi, Viendou-Tiengoli, Amali, Tessekré and Labgar. This resulted in a total of 16 transect lines and 60 sites (Valenza, 1981, 1982, 1983, 1984). The project monitored a total of 30 sites along a transect from Ndioum to Namarel from 1981 to 1983 (cf. Table 17). In addition, as mentioned before, 25 one-hectare plots were established near Mbidi, on a northeast/southwest transect, to monitor woody vegetation. At the same time, the DGRST/LAT/GRIZA teams monitored 112 sites for herbaceous production (cf. Table 2) (Boudet, 1983) and 40 sites for browse (Piot & Diaité, 1983). A total of 126 sites was thus sampled in the Ferlo for herbaceous data while 100 other sites were concerned with the monitoring of woody vegetation. The monitoring took place over periods varying from three to ten years. Such a density of data over time and space is unique in the Sahel.

Observations were made once each year in September-October, at the time of Maximum Standing Crop (MSC), and in December-February for the woody layer, at the peak of the dry season.

Observation plots were marked with a ring of brightly coloured paint (usually red or yellow) on the stem of four trees demarcating a quadrangle of about 1 ha. The position of plots were indicated by other landmarks, also painted, along tracks and firebreaks, etc.

The observations and measurements were taken of the percentage of canopy cover of herbaceous biomass and bare ground, using line interception (Canfield, 1941) along the perimeter of each 1 ha plot and its two diagonals. Three classes of ground cover were recorded (low < 20%, medium 20-80% and high > 80%). Mean herbaceous height was noted along the lines.

Botanical composition was assessed by selecting two 20 m lines near the centre of the plot, one of which lay parallel to the contour and the other perpendicular to it. The degree of precision (confidence interval) must be equal to or lower than 5%, according to the formula:

$$\pm 2 \frac{\sqrt{n\ (N - n)}}{N^3} \times 100$$

where N is the total number of individual plants recorded, and
n is the number of individuals of the dominant species.

This measurement shows the frequency of each species on each site for each year. In the DGRST/LAT/GRIZA studies, the interception line was replaced by the point-quadrat method (Levy & Madden, 1933) with a reading every 20 cm, i.e., 100 readings per line and thus 200 readings per site.

Above-ground herbaceous biomass was measured along each transect line. A number of 1 m^2 quadrats were randomly selected for the hand-clipping and weighing of herbage. The grass and herbs were clipped 5 cm above ground in the LNERV studies and at ground level in the DGRST sites. The number of quadrats clipped per site depended on the homogeneity of the grass layer, which was usually 10-20 and occasionally up to 30 (Levang & Grouzis, 1980). The number of quadrats was determined, in principle, by the cumulated average weight per quadrat so as to reach a confidence interval of 5% or less: $p = 2\ \sigma\ /\ m^n$, where p is confidence interval; σ standard deviation; m = mean; n = number of quadrats sampled. In highly heterogeneous herbaceous layers, the parameter n + 1 was used (Boudet, 1983). Herbage was clipped and weighed by cumulative weighings up to 1.5 kg at 95% of DM so as to reduce errors arising from insufficient samples.

In the project sites, the number of 1 m^2 quadrats sampled varied from 5 to 13 per site (cf. Table 17), a figure that seems less than optimal (Levang & Grouzis, 1980) (cf. Figures 39 and 43) 1/.

1/ The problems of biomass sampling in the Sahel are examined in detail in Appendix 4.

The grazing value of the plant species was recorded and collected and classified into eight categories (cf. Tables 1 and 2) (Boudet, 1983) as follows:

Grasses	) of good grazing value	G 3
	) of medium grazing value	G 2
	) of low grazing value	G 1
Legumes	) of medium grazing value	L 2
	) of low grazing value	L 1
Miscellaneous species	) of medium grazing value	M 2
	) of low grazing value	M 1
Unpalatable species		0

This method allows a synthetic grazing value index to be determined according to the method devised by De Vries (1950) and modified by Daget & Poissonet (1969). The latter method results in a grazing value index (GVI) from 0 to 100. Following this method the mean GVI of the Ferlo grasslands varies from 70 to 83%, depending on range-type (cf. Table 2).

The woody layer was measured by compiling an inventory of shrubs and trees for each site over an area of 1 ha, i.e., a 56.40 m radius circle. The centre of this circle was the centre of the site-plot (Piot & Diaité, 1983; Gaston & Boerwinkel, 1982). The individual trees and shrubs were divided into ten height classifications of 25 cm up to 2 m then 2-4 m and > 4 m. Observations were made in December-February. For each individual, its species, stem circumference at 10 cm above ground and vegetative stage and vigour were recorded. In multistemmed individuals only the larger stem was recorded, but the total number of stems was listed. In the Mbidi sites the one-hectare plot method was compared with the classical 'point-centered quadrat method' (Cottam & Curtis, 1956). The two methods gave quite similar results (Gaston & Boerwinkel, 1982).

Each individual tree or shrub in each plot was thus allocated an index card. All cards were grouped in various ways: by site, by species, by year, by serial type, by vegetation type, by vegetation stage or vigour or size, by age, by distance from borehole, etc., and finally by ligneous communities and range types as a function of:

- Presence/absence
- Density/frequency
- Demography (age/size classification)
- Structure (vertical/horizontal)
- Vegetative stage
- Productivity (woody/forage-perennial/deciduous)
- Environmental condition: ecoclimatic zoning, soil type, drought, distance from borehole, etc.

Seventy sites belonging to five range-types and 14 soil types have thus been monitored by the DGRST/CTFT/LNERV team since 1979 (Piot & Diaité, 1983; Valenza, 1984). The analysis of the data accumulated by the project will be examined later.

4.3.3 Calibration of the hand-held radiometer (Gaston *et al*, 1983; Sharman & Vanpraet, 1983)

Calibration of the field radiometer is intended to serve two main purposes:

- study the relationships between data from destructively sampled biomass (hand-clipping) and establishing the correlation between this data and the Tucker Index (NDVI). These correlations should make it possible to determine the green biomass from the radiometric indices produced by AVHRR of NOAA 6 and 7; and

- finding a quick, easy and reliable non-destructive evaluation of green herbaceous biomass which would constitute a particularly efficient monitoring tool since it would warrant a much larger amount of data being collected by given logistic means and personnel.

The radiometer used is the Mark II type, built by NASA and having the same sensing channels as AVHRR, as mentioned earlier. The principles behind these measurements are discussed in Section 4.2.2.

The device looks like a box 20 x 17 x 17 cm in size, and is carried hanging from the neck like a camera. It is equipped with three dials corresponding with the three wavelength channels showing digital displays graded in W/m^2 and powered by easily available batteries. The radiometer is equipped with a handle, by which it can be held vertically, pointing to the ground and facing the sun, at a height of about 130 cm above ground when taking a reading. Before and after each reading, the device is calibrated above a plate coated with barium sulphate, providing the maximum reflectance under the prevailing conditions; these conditions are susceptible to changes according to atmospheric transparency and sky brightness. The risks of error are thus eliminated, including those resulting from different devices, with their small but inevitable variations in calibration. The total number of calibrating measurements undertaken was 618, as shown in Table 17.

The calibration studies led to the following conclusions:

- The radiometer data are all the better if they are taken from monospecific or quasi-monospecific grass populations with a strong dominance of one single species. The regression curves are given in Figures 40 to 42.

- Co-dominant or subdominant species introduce a bias that may be very important in relation to monospecific or quasi-monospecific stands.

- The device cannot be used in a reliable way in heterogeneous vegetative covers, particularly in years with deficient rainfall when herbaceous cover is scarce, sparse and irregular. Such a situation would often apply to the Saharo-Sahelian ecoclimatic zone with mean rainfalls below 200 mm.

- Calibration may vary from one year to the next as a function of the physiognomy and botanical composition of the herbage, which are a reflection of rainfall and seasonal conditions.

It may be concluded that the radiometer can be profitably, although cautiously, used for the evaluation of green herbaceous biomass in order to improve the output and efficiency of observers in the monitoring exercise of Sahelian rangelands. However, the radiometer calibration should be continuously monitored and its utilization by non-specialized personnel should be avoided.

Similar conclusions have been drawn from an identical study in the Sahel of Burkina Faso (Grouzis & Méthy, 1983). The same remarks also emerged from measurement operations undertaken in northern Kenya by the IPAL (Integrated Project in Arid Lands) team (Herlocker & Dolan, 1980).

The correlations found in this work facilitated a satisfactory statistical interpretation of orbital NOAA 6 & 7 data for the evaluation of annual green herbaceous biomass in the Ferlo of Senegal (Tucker et al, 1983, 1985; Vanpraet et al, 1983).

Further research is envisaged using SRF at an altitude of 300-500 m so as to integrate the woody layer in the radiometric measurements and thus come closer to the NOAA data, using three levels of perception: ground, air and space. This should permit a more complete integration and thus a refinement of the method (De Leeuw, 1983).

4.4 LOW-ALTITUDE SYSTEMATIC RECONNAISSANCE FLIGHTS 1/

4.4.1 Background

This method was perfected in the 1960s by zooecologists in East Africa for the inventory of large game. Several syntheses of the numerous studies on this method have been published (Jolly, 1969; Pennicuick et al, 1977; Norton-Griffiths, 1975/78; Gwynne & Croze, 1975, etc.). The project undertook four SRFs over the whole project area at the end of the dry season: in 1980, 1981, 1982 and 1983. Two more flights were planned which could not be achieved, one because of a breakdown in the navigation system of the aircraft usually utilized, and the second, in 1984, when most of the stock abandoned the project area because of extreme drought. An additional SRF in 1984 would, however, have perhaps allowed the evaluation of the importance of the influx of camels from Mauritania into the Ferlo at that time; they were said to be numerous and this influx became a controversial issue. Several project reports were devoted to SRF (Duncan, 1980; Sharman, 1982, 1983 a & b; Alirol, 1983). The main themes examined were as follows:

- game numbers;
- livestock numbers;
- ligneous cover;
- bare soil;
- bush fires,
- aeolian erosion;
- water erosion;
- distribution of standing hay.

1/ This matter is examined in detail in Appendix 3.

4.4.2 Methods and means

The aircraft used was a light twin-engine six-seater with high wings (Partenavia P68), belonging to ILCA. This aircraft, based in Mali, was equipped with a sophisticated navigation system (Global Omega) coupled with an automatic-pilot system which, in principle, permits accurate repeated flights along the same axes. The aircraft was also fitted with a radar altimeter with digital recording allowing elevation control of $\pm$ 10' (3 m). This altimeter may also be coupled with the automatic pilot system. Flying altitude was 150 m $\pm$ 10 (510' $\pm$ 30). The wing struts were fitted with two wood or fibreglass rods which permit the delineation of a 200 m wide sampling belt on each side of the flight line (cf. Figure 44). Flight lines were 10 km apart and parallel, in a north-south direction (cf. Figure 45). The sampling rate was thus 4%. These lines could be transcribed on to a UTM grid. The selection of the sampling procedures and intensity resulted from statistical considerations, too numerous and complex to be developed here (see Jolly, 1969, 1979, 1981; Jolly & Watson, 1979); Pennicuick et al. 1977; Norton-Griffiths, 1975/78; Gwynne & Croze, 1975; Smith, 1981; Watson & Tippett, 1977, 1981 a & b; Milligan et al, 1979; Grimsdell et al, 1981, etc.).

The north-south direction was dictated by the area's geomorphology and distribution of vegetation; also taken into account was the position of boreholes, which influences stock distribution patterns in the dry season (cf. Figure 45). The mean flying speed was 212 km/h $\pm$ 20. Deviations from preset transect lines did not exceed 2 km over a maximum distance of 140 km; these deviations do not seem significant where the stratification of the sampling of spatial distribution of livestock is concerned. Flights always took place in the morning between 07.00 and 11.30. The total length of lines flown by the SRFs was 3 070 km, with a flying time of 14.30 hours (i.e., an average speed of 212 km/h). Flights become virtually impractical in the afternoons because of the high temperature in that season (June t^o > 40^o C), poor visibility due to haze, aircraft instability resulting from the thermal turbulence, the observers' weariness and also because animals are more difficult to see as they tend to rest under shade during the hot hours.

Statistical interpretation is difficult, mainly because of the contagious distribution of livestock, particularly in the dry season when they tend to concentrate around boreholes. This type of distribution produces a high variance in density and therefore poor precision results. This variability may be reduced, to some extent, by dividing the flight lines into segments during the data processing and by substratifying the samples in areas of high density of livestock. This subdivision allows for the digitalized definition of quadrats measuring 10 x 10 km. The high-density areas, near the boreholes, are treated separately, with the possible use of oblique photography, taken from the air. The stock densities on the borderlines of each quadrat (segments of flight lines) are assumed to represent the density within each of the 300 quadrats of the project area. But the number of animals ascribed to each quadrat is 'levelled' by balancing it against the density in its eight surrounding quadrats. The central quadrat is ascribed a 4/10.8 value, the quadrats N, S, E and W are valued 1/10.8, while the quadrats NE, SE, SW and NW are allocated a 0.7/10.8 value. This balancing technique is as follows:

0.7	1	0.7
1	4	1
0.7	1	0.7

Besides the pilot in charge of navigation and control of altitude, SRFs carry three observers: one in the front seat alongside the pilot and two in the middle seats, the rear seats being occupied by various equipment. The front observer uses a tape-recorder and a digital bell-chronometer, which sounds regularly every minute. He records general ecological data (e.g., geomorphology, soils, woody cover, herbaceous cover, burnt areas, erosion, presence of humans, etc.). The two observers behind him are equipped with a tape recorder to record the number of animals noted by the observers and a 35 mm (24 x 36) camera with a 50 mm lens for recording groups of ten or more animals. The total information collected by any one SRF represents about 4 000 recorded observations. The data from the first two flights were processed in Nairobi by a specialized firm (Ecosystems Ltd). Those from the last flight were processed by the project at Dakar. The computer programs used would need some modification in order to allow for a greater flexibility regarding the number and nature of entries and the incorporation of complementary information from other sources (satellite, ground). Small amounts of data may be processed on programmable pocket calculators.

4.4.3 Reliability of SRF data

The techniques used by SRF are liable to a number of shortcomings, limitations and biases, including difficulties in eliminating human errors (unseen animals hidden by trees, erroneous estimates of the number of animals within groups); naturally, errors increase with the weariness of the observers, even though observation periods never exceed three hours a day.

In addition, the wide variability in animal densities and their contagious distribution, result in high variance, large confidence intervals and therefore mediocre precision. The 95% confidence interval in SRFs led to a possible error of 20 to 30% in the evaluation of stock numbers. Therefore variations in numbers of less than 20% around the mean may not be significant (Sharman, 1983a).

These drawbacks, however, are reduced during the rainy season when animals are much more regularly distributed. Nevertheless, the most important information remains that concerning animal numbers and distribution for the second half of the dry season (April/June). These difficulties can be overcome to some extent by increasing the rate of sampling, up to 10% or even more in areas with high densities of animals, and also by breaking down the transect lines into segments in the interpretation process, as mentioned above.

Because of stock being very mobile and their mobility being variable with respect to different years and seasons, the evolutionary trends in numbers cannot be evaluated without a sufficient number of SRF surveys. Each SRF constitutes only an instantaneous image of a reality which is fluid, fluctuating and difficult to perceive.

Two populations, P1 and P2, obtained from n1 and n2 transects are different if:

$$(P1-P2) / \sqrt{var1/n1 + var2/n2} > t\ [(a/b)-2]$$

where $a = (var1/n1 + var2/n2)^2$;

$$b = \frac{(var1/n1)^2 / (n1-1) + (var2/n2)^2}{n1 - 1}$$ (Pollard, 1977).

Ecological observations are difficult because of the fact that evaluations are made under an oblique angle and therefore instantaneous demarcation of any sample necessarily lacks precision.

Systematic biases in observers' evaluations are unavoidable. Generally speaking, it is accepted among SRF specialists that observers tend to underestimate the number of animals, particularly in woodlands or tree savannahs such as the Mimosoideae scrub and Combretaceae savannah of the Sahel (Norton-Griffiths, 1975/78; Watson & Tippett, 1981). In the case of the Ferlo, Sharman (1983a) estimated this underevaluation to be 3.5%.

The main errors and biases in SRFs are the following:

- Insufficient organization of flight planning and/or execution.
- Poor interpretation of the data, inadequate utilization of correction factors.
- Poor calibration of extent of transects.
- Insufficient control of altitude.
- Crabwise flight resulting in a drift that tends to widen the transects.
- Lack of precision in transects caused by the absence of landmarks, a quite common situation in the Sahel.
- Sharp turning at the end of each line resulting in an ill-defined end-of-line and therefore erroneous transect length.
- As a result of the noise made by the aircraft, fleeing animals enter and leave the sampling strip at the same time, which makes enumeration difficult.
- High herd and flock densities lead to a permanent underevaluation of their numbers.
- The sitting position of the observers tends to become lower as they grow tired. The width of the transect seen from the eyes of a weary

observer is larger than that of a fresh one, because of the change in the angle of vision.

- The number of unobserved animals grows with the density of the tree cover; the degree of underestimation therefore depends on the latter.

- The orientation of the flight lines and the angle of these lines to the direction of the sun may considerably reduce the visual acuity of the observers in the direction of the sun, but will increase it in the opposite direction.

4.5 PRACTICAL RESULTS

4.5.1 Satellite data

The correlation between INDVI and the green herbaceous biomass, at the end of the 1981-83 rainy seasons, resulted in a determination coefficient $r^2 = 0.69$ ($n = 204$: $p < 0.001$); the regression is expressed as follows:

$$Y = 87.9 + 82.3\ X_I$$

where Y = green biomass in kg DM/ha and X_I = INDVI.

The correlation between MNDVI and the biomass for the same period produced a determination coefficient $r^2 = 0.64$ ($n = 204$: $p < 0.001$); the regression is expressed:

$$Y = 226.7 + 4537.4\ X_M$$

where Y = green biomass Kg DM/ha and X_M = MNDVI (Tucker et al, 1985) (cf. Figure 33).

In practical terms, the data from ground sampling are shown on tracing paper in classes of 200 kg. This tracing is then superimposed on the colour map of Tucker's Index; this gives mean and median values of biomass for each of the 12 classes of the Index. Each class of colour is thus given a mean and median biomass equivalent. Five maps in a scale of 1/500 000 were thus produced, showing the green herbaceous biomass and forage availability at the end of the rainy seasons of 1980, 1981, 1982, 1983 and 1984 (cf. Figures 65-69). In the present report, for printing reasons these maps are reduced to approximately 1/1 000 000.

Six to eight classes for colour/biomass were identified for each year. Comparisons between years are thus possible, and the amount of forage available within the dependence area of each borehole can be mapped and measured with a surface integrator. This amount makes it possible to determine the number of stock that can be fed until the next rainy season, and therefore to know whether there is a gap to bridge or not, hence whether or not transhumance will have to take place or not, or whether supplementary feeding will be needed or not.

The biomass/colour classes used within the project were as follows (Gaston et al, 1983):

INDVI class	Colour	Green biomass class kg DM/ha/yr
1 - 2	Grey	B < 200
3 - 4	Sepia	200 < B < 400
5 - 6	Yellow	400 < B < 600
7	Pale green	600 < B < 800
8	Green	800 < B < 1000
9	Dark green	1000 < B < 1200
10 - 12	Red	1200 < B

These figures are provisional orders of magnitude, which would need further refinement as additional data are recorded, stored and retrieved. This is because, as mentioned earlier, the data may be biased by the ligneous cover wherever canopy cover reaches 10% of the ground or more. Differences in signature may also take place, according to the dominant species present as shown in hand-held radiometer studies (Gaston et al, 1983). Such a difference in signature also depends on the degree of greenness of the herbaceous layer at the time when the reflectance is sensed. This may considerably vary within a few days towards the end of the rainy season, a limiting factor which is not totally eliminated with the use of the integrated index (INDVI). Significant progress could be achieved through the establishment of a space-receiving station in West Africa and with the participation of field research staff in the interpretation of the unprocessed satellite data.

4.5.2 SRF data (Sherman, 1982, 1983 a and b)

Four SRFs were undertaken within the project from October 1980 to June 1983. No flight took place in 1984 as most animals belonging to the Senegalese pastoralists had left the project area because of the drought.

4.5.2.1 Wildlife

The June 1982 flight registered the following wildlife over a sample of 1 200 km^2 (4% of the project area):

7 gazelles (*Gazella rufifrons*)
4 warthogs (*Phacochoerus aethiopicus*)
2 ostriches (*Struthio camelus*)
2 jackals (*Canus adustus*)

Other large mammals, though known to be still present in the area, were not seen; for example the spotted hyaena (*Crocuta crocuta*), and the striped hyaena (*Hyaena hyaena*), the dorcas gazelle (*G. dorcas*) and the dama gazelle (*G. dama*) (Poulet, 1972, 1974). These figures constitute only very crude orders of magnitude; however, they show how rare game animals have become in the Sahel - probably less than 0.4 kg/km^2 of liveweight, that is, 0.1% of the present ungulate biomass under very similar ecological conditions in the Kalahari and 0.02% of the theoretical potential (Bourlière, 1978; Le Houérou & Gillet, 1985; Le Houérou & Grenot, 1986) 1/.

1/ In northern Kordofan, Watson et al (1977), using SRF data, found 0.7 kg/km^2.

4.5.2.2 Livestock (Figures 46 and 50)

The livestock recorded in the four SRFs is shown in Table 3. The average figures for the period 1980-83, converted into TLUs, are shown in Table 4.

Clearly, the 1981 flight is inconsistent with the three others. But the various species of stock have the same rate of increase with respect to the mean of the three others (except for camels); this coefficient is 1.7. The assumption of an influx of animals from Mauritania can only explain 5% of the overevaluation. Moorish cattle can easily be distinguished from the Senegalese 'Gobra' breed of zebu since the former are reddish in colour while the Gobra have a uniformly white coat; this, of course, does not exclude the possibility of some Moorish cattle belonging to Senegalese pastoralists and vice-versa.

Various assumptions have been examined in an effort to explain these apparently aberrant 1981 figures, including an afflux of animals from the south. The most likely hypothesis seems to be that of a sampling error (Sharman, 1983). The corrected figures retained are the number observed divided by 1.7 (cf. Table 4).

An attempt was made to compare the SRF figures with the Administration (DSPA) estimates for 1981. These estimates were based on vaccination; they were used as the reference baseline in the official planning operations (National Scheme of Land Use, 1984). The comparison, however, is neither simple nor straightforward since the DSPA estimates are given for administrative units that are unrelated to the project boundaries and therefore do not compare with SRF figures. However, if the number of animals estimated in each administrative unit is multiplied by a coefficient equal to the ratio between the surface of this unit within the project area boundaries and the overall surface of this unit (a procedure that to be valid assumes a more or less regular distribution of stock within each administrative unit), one then reaches the figures shown in Table 3, i.e., 407 000 TLU for the whole project area.

There is a 98.5% agreement with the latter figure and the overall SRF evaluation:

$$100 - [(413-407) \div 413 \times 100] = 98.5$$

The two figures correspond in an ideal fashion (which does not prove that they are correct).

However, the same order of magnitude is confirmed by ground surveys undertaken by the DGRST/LAT/GRIZA-LNERV project 1980-83, based on two types of estimate: vaccinations and counts at the boreholes in the dry season (Meyer, 1980; Planchenault, 1981, 1983; Barral et al, 1983). These surveys result in an average density of 6.6 ha/TLU (5.6 to 8.6) over an area of 183 000 ha in the Sandy Ferlo (boreholes of Tatki, Tessekrê and Belel-Boguel).

For the Department of Podor, which is entirely included within the project area, the DSPA estimate for 1981 was 191 000 TLU over an area of 16 700 km^2, i.e., 8.74 ha/TLU for all species taken together; and 12 ha/TLU for cattle alone (the cattle/livestock ratio being 0.728). It may therefore be safely concluded that the SRF data, after correction for 1981, are quite plausible and most likely within a 20% interval from the actual figures.

With regard to variation of numbers in time and space (Figures 59 and 60), it is assumed that the 95% confidence interval is of the order of magnitude of 20% around the multiannual mean (Sharman, 1983a), the result is the significance threshold shown in Table 18, whereas the numbers recorded in the various flights are given in Table 14. It can be seen that the differences between the various SRFs are less than 10% of the mean for cattle and smallstock and less than 20% for equines; the differences found between SRFs are therefore not significant. The above is not, however, true for the camels, whose significance threshold is probably much higher than 20% because of their small numbers at the time of the SRFs; they represent only 0.6% of the total stock numbers expressed in TLUs and had therefore a negligible pastoral impact on the Ferlo rangelands at the time.

Variations observed in space confirmed facts that were already known, if not accurately quantified (Sharman, 1983a):

- There is a larger concentration of smallstock along the Senegal River valley in the dry season, while cattle are, generally speaking, better represented in the southern half of the project area. This distribution, incidentally, is quite typical of the Sahel as a whole and fully justified on ecoclimatic grounds (Le Houérou & Grenot, 1986).

- Cattle distribution varies substantially from one year to the next (cf. Figures 46-50): a tendency to concentration in the east and in the west in 1980, 1981 and 1982 can be seen, and a more even distribution in 1983 (cf. Figures 46 and 48);

- For all livestock taken together, the distribution in 1983 is opposite to that of 1982. In 1982, there was a sharp increase in the north (50 to 200%), while in 1983 there was a similar increase in the southern half of the project area (cf. Figure 50).

- The density of animals in the dry season is closely linked to the distance from boreholes (cf. Figure 59). Density in smallstock is around 15 head/km^2 between 0 and 10 km from boreholes; it then decreases to 8-10 head/km^2 at a distance of 20 km and down to 6-8 head/km^2 towards 30 km. The decrease is more regular when cattle are concerned: from 12 head/km^2 near the boreholes to 8 head/km^2 at 20 km and 6-8 head/km^2 at 30 km. The distance from boreholes does not seem to influence the density of donkeys and camels, as might be expected.

4.5.2.3 <u>The woody cover</u> (Figure 52)

Figure 51 shows that the estimation of ligneous cover is strongly influenced by the personal bias of the observers, since the estimates in 1980, 1981, 1982 and 1983, made by four observers, show large differences that could not possibly be explained by actual evolution. Figure 52 averages the four different estimates; it shows a high ligneous density in the Ferrugineous Ferlo to the southeast, with canopy covers of 30-50%. Canopy cover is also relatively high to the west in a strip some 60 km wide, to the east of the Lake of Guiers with covers of 20%. In the other parts of the

Ferlo, ligneous cover varies from 5 to 15%, figures which are in agreement with those from ground surveys (Poupon, 1980; Piot & Diaitê, 1983). For the time being, SRFs do not permit any conclusions to be drawn on the evolution of the woody layer in the Ferlo; but clear-cut conclusions emerge from other surveys that we shall discuss further on.

4.5.2.4 Importance of bare ground in the Ferlo (Figure 54)

The proportion of bare ground (less than 20% plant cover) was very high in the Senegal River valley and the northern half of the Ferlo in 1983: 60 to 100% bare ground against 20 to 40% in the southern half (cf. Figure 54). The rate of bare ground was lower in the southeastern Ferrugineous Ferlo (10-20%), an estimate which corroborates the observations on the woody cover.

4.5.2.5 Extension of bush fires (Figure 57)

The areas that had undergone the effects of some fire at least once in four years represent 32% of the project area, almost totally situated in the southern half (cf. Figure 57). However, this figure constitutes a minimum as fire scars are often difficult to detect at the end of the dry season, since the land affected by these fires undergoes wind erosion and sand deposition, which tend to obliterate the scars (Sharman, 1983a).

4.5.2.6 Wind erosion (Figure 55)

Wind and water erosion were not treated separately in the first two SRFs. Apart from the Senegal River valley, the maps of wind erosion and of soil denudation are in good agreement, as might be expected. Wind erosion affected 30% of the Ferrugineous Ferlo, 40% of the waterlogged soils and 70% of the sandy soils; that is, an overall average of 50% of the project area in 1983 (which was a drought year, as mentioned above) (cf. Figure 55).

4.5.2.7 Water erosion

Generally speaking, water erosion is less intense than wind erosion in the Ferlo. Sheet erosion occurs mainly in the Ferrugineous Ferlo affecting to various degrees some 50% of the quadrats in the UTM (Universal Mercator Transverse) grid against only 5% of those in the Sandy Ferlo. Rill and gulley erosions are mainly active on the rim of the Ferrugineous Ferlo and in some waterlogged soils of the Senegal River valley; it also occurs to various degrees in some 20% of the most densely inhabited parts of the Sandy Ferlo (Sharman, 1983a).

4.5.2.8 Distribution of standing hay biomass at the end of the dry season (Figure 53)

The distribution of standing hay contrasts, as expected, with the distribution of bare ground, bush fires and erosion. SRFs evidenced the absence or the scarcity of standing dry grass at the end of the dry season in a strip 50 km wide along the Senegal River valley, in the northeast and west of the Ferlo, which altogether represents some 40% of the surface of the project area. The absence of standing dry grass at the end of the dry season is a clear indication of overgrazing and ovestocking. In contrast, standing hay was present in the central Sandy Ferlo, for one to three years out of three during the month of June, that is, over 60% of the project area. Overgrazing therefore occurred over 70% of the overall project area in two years out of three from 1980 to 1983 (cf. Figure 53).

4.5.3 Conclusions on SRFs (Figures 61, 64, 65 and 69)

The interpretation of the data gathered in the course of four SRFs from 1980 to 1983 leads to the conclusion that the Ferlo has been overstocked since at least 1980, with a total elimination of standing hay at the end of the dry season over at least 45% of the project area; of this 45%, 40% is located in a 50 km wide strip along the Senegal River valley and Lake of Guiers. This overgrazing, aggravated by bush fires, leads to considerable wind erosion.

The aerial study of livestock numbers led to conclusions which were in agreement with ground data collected through various methods. The overall livestock density in the pilot area was in the order of 7.5 ha/TLU between 1980 and 1983. Assuming an annual utilization rate of 30% of the green herbaceous biomass, this density corresponds to an overall average annual rate of 1 000 kg DM/ha, excluding browse. But the integrated overall production figure deduced from the combination of NOAA data with ground validation figures was only 640 kg DM/ha/yr (112-1400) from 1980 to 1984 (Gaston et al. 1983; Tucker et al. 1985) (cf. Table 13 and Figures 37 and 38). For the period 1979-81, the mean intersite rainfall over ten reliable weather stations in the Ferlo was 379 mm, while the average herbaceous biomass recorded over 112 quadrats from 30 sites in the same aea for the same period was 908 kg DM/ha/yr (Boudet, 1983) (cf. Table 18 and Figures 63 and 64). Rain Use Efficiency was 3.04 kg DM/ha/yr/mm in the former case and 2.9 in the latter (cf. Tables 13 and 18).

The figure of 640 kg DM/ha/yr for the 1980-84 period results from two very dry years, 1983 and 1984, when intersite precipitation was less than 30% of the 1920-69 mean (116 mm against 400 for the whole area); herbaceous biomass then dropped to 178 and 55 kg DM/ha/yr respectively over the whole project area in 1983 and 1984. It follows that the present stocking rate is adequate in 'normal' years, when rainfall is close to the long-term mean or above, but much above the carrying capacity of the rangelands in time of drought. It also follows that the gap between demand (1 000 kg DM/ha/yr) and supply (500 kg DM/ha/yr) was filled by browse production (and over-utilization), which in turn resulted in the receding of the woody layer, as examined below, and unusual transhumance to the south outside the project area to the so-called 'ground-nut belt' (Bassin Arachidier). The interpretation of the SRF data shows that bush fires affected 12% of the Ferlo in 1982 while 32% was affected over the four-year period in spite of the two very dry years. This is in complete agreement with previous observations (Naegelê, 1971), keeping in mind that fuel load for this four-year period was far below normal. This also suggests that firebreaks are insufficient in density and in width or are not being properly maintained.

SRFs also demonstrated the fact that the proportions of smallstock increase with the density of human population (cf. Figures 49 and 56) and with the concurrent depletion of vegetation. It would seem that the goat/sheep ratio would evolve in a similar manner, a plausible assumption which should be checked.

4.5.4 Evolution of range vegetation

The studies carried out by LNERV for over ten years in the Ferlo led to the following conclusions (Valenza, 1983, 1984).

The density of the herbaceous layer depends more on the annual rainfall conditions than on range exploitation.

Above-ground herbaceous biomass is often greater and richer in nitrogen around boreholes than away from them, because of soil enrichment in organic matter and minerals (faeces, urine).

The botanical composition, in contrast, is strongly influenced by range utilization: dominant species, in particular the annual grasses, depend to a large extent on the distance from boreholes. Areas close to boreholes favour species such as Cenchrus biflorus and Dactyloctenium aegyptium, while the opposite is true for four other species: Aristida mutabilis, Chloris prieurii, Schoenefeldia gracilis and Eragrostis tremula. Among the legumes, Zornia glochidiata tends to proliferate around boreholes, which is a clear indication of its being increasingly used in the rainy season since this is a species promoted by rainy-season grazing (Boudet, 1975). The latter fact is thus an indication of increasing year-round settlement of pastoralists around boreholes. Conversely, the contribution of forbs to total herbaceous biomass tends to increase with the distance from boreholes: Borreria spp, Merremia spp, Polycarpa linarifolia, Fimbristylis hispidula, Cleome tenella, etc.

The overall importance of woody species is in steady decline: 15-25% decrease in numbers in the 40 sites studied under the DGRST/LAT/GRIZA/LNERV programme between 1979 and 1981 (Piot & Diaite, 1983). Similar facts were reported from remotely-sensed data via aerial photography (De Wispelaere, 1980; Barral et al, 1983).

At the same time, a turnover of species by the replacement of more or less mesic species by more xerophilous ones can be noted. This fact is clearly shown by comparing the rates of survival and the sclerophylly indices (cg of leaf DM/cm^2). Boscia senegalensis and Balanites aegyptiaca thus clearly appear as 'increasers' (using a range-management term). Conversely, more fragile species, having a lower sclerophylly index, are clearly decreasing. Grewia bicolor, Sclerocaryo birrea, Combretum glutinosum. In other words, in terms of bioclimatology and phytogeography, one observes a receding in the proportion of species of Sudanian affinity and an expansion in the rate of taxa of Saharo-Sahelian origin. Not only do the absolute numbers of individuals in woody species decrease, but there is, in addition, an evolution towards more xerophilous woody populations.

Project studies at M'bidi and Fété-Olé, for instance, reached the following figures (Vanpraet & Van Ittersum, 1983):

Species	Sclerophylly index cg/DM/cm^2 1/	Mortality rate % population/yr
Boscia senegalensis	1.24	4.6
Balanites aegyptiaca	0.82	1.9
Guiera senegalensis	0.53	20.6
Acacia senegal	0.31	19.9
Sclerocarya birrea	0.20	high
Commiphora africana	0.18	10.4

1/ The sclerophylly index used is as from Poupon, 1980.

Valenza (1984) published the following data from 44 sites in the project area monitored from 1979 to 1982 (before the last drought):

Species in expansion:	Combretum aculeatum	Commiphora africana
Stable species:	Zizyphus mauritiana	Sterculia setigera
	Dalbergia melanoxylon	Acacia senegal
	Boscia senegalensis	Acacia tortilis
	Balanites aegyptiaca	
Species on the decline:	Sclerocarya birrea	15.6%
	Combretum glutinosum	26.9%
	Calotyropis procera	32.3%
	Guiera senegalensis	50.5%
	Grewia bicolor	50.0%
	Acacia seyal	63.6%

It should be noted that the latter conclusions are based on a four-year period and regression rates are expressed in absolute numbers of individuals within species and not in their proportions in the overall woody populations. The latter may be quite different as a result of initial numbers and of differential rate of regeneration/mortality.

The decrease in population densities is more acute near boreholes: 25% decrease at 2 to 3 km from boreholes and 15% decrease at 5 to 6 km.

The correlation between survival rates and a number of parameters monitored by SRF have been calculated (Gaston & Boerwinkel, 1982). Survival rates are positively correlated with the distance from camping grounds and the presence of standing hay. They are negatively correlated with the rate of bare ground and density of track roads. In other words, the rate of survival is inversely correlated with the intensity of human activities.

As a conclusion it could be said that the data emerging from the project study fully support other data from other teams using different methods, that is, a dramatic decrease in the woody population of the Ferlo, a consequence of the combined effects of persistent droughts (15 years) aggravated by a concurrent overexploitation. The consequences of this situation have been analysed elsewhere (Le Houérou, 1979, 1980; Le Houérou & Gillet, 1985; Le Houérou & Grenot, 1986).

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

The integrated approach combining orbital, SRF and ground-sampling data has proved to be an efficient method of continuous evaluation of pastoral resources in the Ferlo. This method was perfected through the close cooperation of various organizations within the IMRES project: FAO (EMASAR), UNEP (GEMS), NASA (LTP), and LNERV, and also because the scientists involved had complementary experience and competence.

The perfection by NASA and the project of the method of determining green herbaceous biomass at the end of the rainy season has been recognized as a technological breakthrough by the international scientific community. It enabled the evaluation, with the appropriate accuracy, of the amount of forage available at the end of each rainy season. This made possible the comparison of primary production with the forage needs deduced from stock numbers censused via SRFs.

Maps of herbaceous biomass available at a scale of 1/500 000 were established and circulated to the users in October 1980, 1981, 1982, 1983 and at the end of 1984 (cf. Figures 65-69).

Thus, by comparing supply and demand, it becomes possible to plan ahead of time the necessary actions needed for the nine months of the dry season, October to June, to bridge the feed gap in case of drought, to initiate appropriate incentives for destocking, making concentrate feed available, organizing rescue operations for the pastoralists, etc.

The information collected in the monitoring activities thus became an essential part of the overall strategy for reducing the effects of drought in the Sahel, as part of the 'Early Warning System'.

Regarding the long-term management of pastoral resources, the method tested by the project resulted in the conclusion that the Ferlo is already overstocked and that a reduction in stock numbers is advisable in the short term in order to rehabilitate the range resources, particularly the woody layer, the most seriously threatened.

These conclusions are supported by other studies using different techniques: a combination of aerial photography, Landsat images and ground surveys, particularly within the DGRST/LAT/GRIZA and LNERV programmes, the conclusions of which have already been published elsewhere (Justice, edit., 1986).

The method also showed the disastrous impact of bush fires, particularly in good years and in the southern half of the Ferlo. As a consequence, it is advisable to dedicate more efforts in expanding firebreak networks and improving their efficiency by vigilant maintenance.

SRF showed the havoc of wind erosion as a consequence of overgrazing and wildfires.

It would seem that the method perfected in the Ferlo should be applicable to the Sahel zone as a whole (3 million km^2 from the Atlantic to the Red Sea). Several attempts in this direction are under way, notably in Mali and the Niger, the preliminary results of which seem to support the Ferlo experience.

However, it should be mentioned that utilizing AVHRR orbital data is also subject to limitations and constraints: vegetation indices become unreliable wherever green biomass is below 250-300 kg DM/ha or wherever woody canopy exceeds 10% of ground cover. It follows that the method is less accurate in years of drought and in the Saharo-Sahelian ecoclimatic zone where mean annual rainfall is below 200 mm, except in rainy years. Vegetation indices are equally unreliable at the present stage of technology in the Sudanian savannahs, where ligneous canopy cover is usually above 10%. It is therefore not likely that, in its present form, orbital remote sensing of green herbaceous biomass could be applied to the whole Sudanian ecoclimatic zone, in contrast to the Sahel. But it is also possible, and probable, that the method could be improved by the use of new satellites equipped with higher-resolution sensors (TM, Spot) and having the appropriate orbital period to overcome the cloud-cover problem in the rainy season.

Low-altitude Systematic Reconnaissance Flights have made it possible to compare data from the aerial census of livestock with the classical ground estimates based on vaccination campaigns and/or surveys such as count samples at boreholes. The degree of agreement between SRF and official estimates in 1981 was 98.5%. The 1981 aerial census, however, produced aberrant figures, which could not be clearly explained (perhaps a sampling error); but these data could be corrected in a satisfactory manner, probably with a small margin of error. The agreement between SRF data and count samples at 13 boreholes is also satisfactory since it falls within a 15% bracket.

Comparison between SRF and official data on livestock numbers would be easier and more reliable if the analysis of SRF data was organized in such a way that administrative limits cold be integrated with the data processing and interpretation. SRFs could be undertaken by specialized private firms, as was often the case in Kenya, Somalia, Ethiopia and Sudan among others. But whenever regularly repeated VSRs are planned, it may be cheaper to set up a national organization as happened in Kenya (KREMU) 1/ and as envisaged in Senegal.

SRFs have also proved useful in other respects in the Ferlo: evaluation of bush fires; of standing hay at the end of the dry season which allows the degree of over-grazing to be determined; of bare ground; of wind and water erosion; and of human settlements.

Nevertheless, SRFs are complex to organize and require a critical analysis and must therefore be entrusted to senior professionals with a strong statistical background.

1/ KREMU = Kenya Rangelands Monitoring Unit

The experience gained in the Ferlo of Senegal in the inventory and monitoring of Sahelian rangelands ecosystems led to recommending to the Government that a permanent operational organization for continuing the activities perfected and tested by the project be established. Such an organization was, in fact, established at the end of the project period, under the name of Centre for the Ecological Monitoring of Sahelian Pastoral Ecosystems (CEMSPE). The funding of CEMSPE was provided by DANIDA and UNSO for an initial period of four years,. The Centre will reinforce national expertise in the field of ecological monitoring while producing the required ecological information for the improved management of the Ferlo rangelands, which, it should be remembered, harbour 50% of the livestock of Senegal and a population of some 100 000 pastoralists. One former expert from the project is at present involved in the centre which uses the methods initiated by GEMS and perfected by the project.

It is furthermore suggested that the governments of other Sahelian countries establish similar centres, which would allow them to base their pastoral policies on sound and accurate information. In order to reduce the costs, several countries could perhaps join efforts in the enterprise.

Moreover, it is recommended that a joint Sahelian satellite-receiving centre be established, in order to collect and process the data required for the evaluation of green herbaceous biomass of the Sahelian rangelands and also to better coordinate satellite data processing with ground sampling. The satellite-receiving station could be part of the above suggested Ecological Monitoring Centre serving both the Sahelian and Sudanian eco-climatic zones.

From a purely technical viewpoint, it is recommended that measurements of vegetation indices be taken from light aircraft at an altitude of 300-500 m above the ground in order to better integrate satellite, aerial and terrestrial data. This would warrant the integration of the leaf biomass of woody species which, in the present system, is poorly integrated since it is included in the satellite data but not in the ground sampling. It is expected that this procedure would permit a refinement and improvement of the presently used methodology.

When SRFs are concerned, it is suggested that flights be organized in such a way that administrative limits could be integrated in data processing and interpretation in order to secure a mutual control between SRF figures and routinely collected data at ground level, which are usually gathered on the basis of administrative units (vaccination, administrative surveys, and in some countries, taxes).

It is finally suggested that the aerial photography step be integrated in the global approach; this was unduly neglected in the project methodology. Indeed, aerial coverage constitutes a rich baseline information source, which is extremely useful, if not mandatory, for any ecological monitoring of rangeland ecosystems.

Table 1

FORAGE VALUE OF THE MAIN HERBACEOUS SPECIES IN THE FERLO 1/

Good grasses (G3)

Medium size, medium to good tillering, good consumption when green or dry (except at the fructification stage for some species):

Andropogon gayanus
Andropogon penguipes
Brachiaria lata
Brachiaria xantholeuca
Cenchrus biflorus
Cenchrus prieurii
Chloris pilosa
Chloris prieurii
Diheteropogon hagerupii
Echinochloa colona
Eragrostis cilianensis
Eragrostis lingulata
Eragrostis pilosa
Eragrostis tremula
Hackelochloa granularis
Panicum laetum
Pennisetum pedicellatum
Schoenefeldia gracilis
Setaria pallidefusca

Medium-value grasses (G2)

Medium to small size, fine but fairly hard stems, good consumption when green but less so when dry:

Andropogon pseudapricus
Aristida adscensionis
Aristida funiculata
Aristida mutabilis
Brachiaria distichophylla
Dactyloctenium aegyptium

Medium-value grasses (Cont.)

Digitaria horizontalis
Eragrostis aegyptiaca
Tetrapogon cenchriformis
Trichoneura mollis

Poor-quality grasses (G1)

Small size, hard stem, few leaves:

Aristida sieberana
Aristida stipoides
Ctenium elegans
Eragrostis ciliaris
Elionurus elegans
Loudetia topoensis
Schizachyrium exile
Sporobolus pectinellus
Tragus berteronianus

Medium-value legumes (L2)

Medium to small size, palatable when dry and often when green:

Aeschynomene indica
Alysicarpus ovalifolius
Cassia mimosoides
Indigofera aspera
Indigofera pilosa
Tephrosia purpurea
Zornia glochidiata (bloating)

Poor-value legumes (L1)

Small size, prostrate habit or hardly consumed:

Cassia obtusifolia
Indigofera astragalina
Indigofera senegalensis

1/ Boudet, 1983.

Miscellaneous forbs of medium value (M2)

Fairly good consumption either green or in fruits:

Blepharis leariifolia
Citrullus lanatus
Commelina forskhalaei
Cyperus esculentus
Ipomaea coscinosperma
Merremia pinnata
Merremia tridentata
Tribulus terrestris

Miscellaneous forbs of poor value (M1)

Small size, hard stem, hardly palatable, except fruits in some:

Achyranthes aspera
Boerhavia repens
Borreria stachydea
Cyperus iria
Fimbristylis hispidula
Gisekia pharnaceoides
Hibiscus diversifolius
Jacquemontia tamnifolia
Cleome tenella
Corchorus tridens
Limeum diffusum
Limeum pterocarpum
Sida cordifolia

Unpalatable species (U)

No forage value:

Borreria chaetocephala
Borreria radiata
Ceratotheca sesamoides
Cleome viscosa
Corchorus depressus
Euphorbia aegyptiaca
Heliotropium strigosum
Hygrophila senegalensis
Limeum viscosum
Mollugo cerviana
Mollugo nudicaulis
Monsonia senegalensis
Polycarpea linearifolia
Polygala erioptera
Portulaca foliosa
Pycreus macrostachyos
Tripogon minimus
Urginea indica
Waltheria indica

Table 2

HERBACEOUS PRIMARY PRODUCTION IN THE FERLO (1979-81) 1/

Range types	1	2	3	4	5	6	7	8	Xa	Xp
No. of sites	5	9	24	21	20	20	7	6	-	-
MSC kg DM/ha/yr	369	1 026	682	755	1 259	769	1 112	1 666	955	908
G3%MSC	50	54	53	39	47	35	53	45	47	46
G2	16	18	25	25	18	29	25	19	22	21
G1	2	3	4	5	2	8	3	1	3.5	4
Tot G	68	75	82	69	67	72	81	65	72	71
L2	27	21	11	22	24	16	11	27	20	20
L1	0.3	1.7	0.5	2	1	1	1	1	1.2	1
Tot L	27	23	12	24	25	17	12	28	21	21
M2	0.4	0.3	2	3	3	2	2	3	2	2
M1	0.3	1	4	2	4	4	4	3	3	3
Tot M	1	1	6	5	7	6	6	6	5	5
U	4	1	1	2	3	5	1	1	2	2
Bare ground %	55	19	28	25	5	30	24	14	25	27
Forage value index %	77	83	73	74	76	69	81	80	77	75
Rainfall	-----330 mm-----									
Rain-Use Efficiency kg DM/ha/yr/mm	1.1	3.1	2.1	2.3	3.8	2.3	3.4	5.0	2.9	2.8
Average RUE: 2.9										

Explanatory notes are given on following page.

1/ Mean values computed from the data published by Boudet, 1983.

Table 2 (cont)

Explanatory notes

Range types

1 = Low potential on iron hardpan

2 = Low potential on downslope

3 = Low potential on upslope

4 = Medium potential on more or less flat ground

5 = Medium potential on downslope

6 = Medium potential on upslope

7 = High potential on interdunal depressions

8 = High potential on downslope

Forage value: cf. Table 1.

Xa = Arithmetic mean; Xp = Weighted mean

MSC = Maximum Standing Crop, end of rainy season

$$\text{RUE} = \text{Rain-Use Efficiency} = \frac{\text{MSC Kg DM / ha / yr}}{\text{rainfall mm}}$$

Table 3

ESTIMATES OF LIVESTOCK NUMBERS IN THE FERLO 1/

Administrative units	Cattle	Smallstock	Equines	Camels	TLU 2/
Region of Louga					
Dept of Linguère (x0.4)	90 000	120 000	18 000	400	105 800
Region of the River					
Dept of Podor (x1.0)	171 000	263 000	9 000	200	191 000
Dept of Matam (x0.3)	53 000	119 000	14 000	40	71 000
Dept of Dagana (x0.3)	36 000	53 000	500	60	39 000
Total	350 000	555 000	41 500	700	406 800
Conversion rates	0.81	0.18	0.53	1.16	-------
TLUs	284 000	100 000	22 000	800	406 800
%	69.8	24.6	5.4	0.2	100

1/ Source: DSPA, 1981.

2/ Conversion factors used are based on the ratio between mean population metabolic weight and metabolic weight of TLU.

Table 4

LIVESTOCK NUMBERS RECORDED FROM SRF 1/

Years / Species	1980	1981	1982	1983	Corrected mean	TLU	%
	---------numbers in 10^3---------						
Smallstock	726	1 231	683	700	708	106.2	25.7
Cattle	367	602	325	385	358	286.4	69.4
Donkeys	25.6	27	12.5	23	19.2	10.2	2.5
Horses	9.7	10	6	8	7.4	7.4	1.8
Camels	1	2	2.5	6	2.7	2.7	0.6
Total	-	-	-	-	-	412.9	100.0
Density Ha/TLU	-	-	-	-	-	7.3	-

1/ Sharman, 1983 (a).

Table 5

VARIABILITY OF ANNUAL RAINFALL IN THE FERLO 1/

Periods	1920-69			1970-81			1920-81		
	Number of years	x mm	C V %	Number	x	C V	Number	x	C V
Podor	44	318	39	12	191	33	56	287	42
Dagana	48	318	35	12	218	34	60	298	37
Matam	42	520	29	11	302	42	53	474	35
Linguère	36	517	24	12	339	18	48	473	29
Dahra	33	526	24	12	342	35	45	477	30

1/ Barral et al, 1983.

Table 6

RAINFALL PROBABILITIES IN THE FERLO 1/

Mean annual rainfall	Probabilities								
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
300	430	385	350	315	287	260	232	205	170
400	550	500	460	420	390	360	325	290	250
500	665	610	567	525	492	460	422	385	335
600	780	720	675	630	595	560	520	480	420

1/ Le Houérou, 1986.

Table 7

MAIN SOIL CATEGORIES IN THE FERLO 1/

Item No. in soil map caption	Soils categories (French taxonomy)	Area km^2	Area %
1 & 2	Raw mineral soils and iron pan duricrust	1 900	6.0
3, 4, 5, 6, 14	Isohumic brown-red soils on sand or sandstone	14 300	45.1
7, 8, 9, 10	Tropical ferrugineous soils slightly leached on sand or sandstone	11 200	35.4
11, 12	Hydromorphic soils	3 900	12.4
13	Halomorphic soils	200	0.6

1/ Maignien, ORSTOM, 1965.

Table 8

LIVESTOCK CONVERSION RATES INTO TLU USED BY VARIOUS AUTHORS IN THE SAHEL

Species	IEMVT 1968/80	Boudet 1983	Meyer 1980	Planche-nault 1983	Barral *et al*, 1983	Sharman 1983	Le Houérou & Grenot 1986
Cattle	0.70 to 0.73	0.75	0.80	0.80	0.80	0.80	0.81
Sheep	0.10 to 0.12	0.15	0.15	0.15	0.15	0.15	0.18
Goats	0.08 to 0.10	0.15	0.15	0.15	0.15	0.15	0.15
Horses	1.00	1.00	1.00	1.00	1.00	1.00	0.80
Donkeys	0.50	0.50	0.50	0.50	0.50	0.53	0.53
Camels	1.00	1.00	1.00	1.00	1.00	1.00	1.16

Table 9

THEORETICAL WATER REQUIREMENTS IN THE PILOT AREA
(mean figures, outside the area of dependency of the Senegal River and of Lake of Guiers)

Consumers	Number	Daily requirements (in kg)	Annual needs (in m^3) 1/
People	92 000	25	840 000
Cattle	360 000	40	3 900 000
Smallstock	750 000	7	1 420 000
Horses	7 500	20	41 000
Donkeys	20 000	15	81 000
Camels	2 500	10	7 000
Total	-------	--	6 289 000

1/ On the basis of 270 days a year; water consumption is ensured by ponds for an annual average of 90 days in the rainy season.

Table 10

MAIN CHARACTERISTICS OF SATELLITE IMAGERY USED IN THE INVENTORY OF TERRESTRIAL RESOURCES OPERATIONAL IN 1985 1/

Types of satellites	Scene (km)	Resolution (m)	Practical scale of enlargement and use	Minimum land surface identified (ha)	Orbital period (days)	Approximate cost of acquisition of colour composites	Channels/ spectra
Meteosat	12 500	5 000	1/5 000 000	15 625	30	?	4 channels: VIS,TIR
NOAA 7/ AVHRR	2 400	1 100	1/1 000 000	6 250	LAC 9 GAC 3	?	5 channels: VIS,NIR, MIR, TIR
LANDSAT/ MSS	185	80	1/250 000	40	16	0.02–0.03 \$ per km^2	4 channels: VIS, PT
LANDSAT/ TM	185	30	1/100 000	6.25	16	500–800 \$ per 1/4 Scene = 0.06–0.09 \$ per km^2	7 channels: VIS,NIR, MIR, TIR
SPOT Sensor a	60	20	1/75 000	3.5	9	0.33 \$/km^2 (1 200 \$/Sc)	3 channels: VIS,NIR
Sensor b	60	10	1/50 000	1.6	9		1 channel: VIS

MSS Channels
- 4 500 – 600 nm green
- 5 600 – 700 nm orange-red
- 6 700 – 800 nm red, near infrared
- 7 800 – 1 100 nm near infrared

SPOT a
- 1 500 – 590 nm green
- 2 610 – 680 nm red
- 3 790 – 890 nm near infrared

SPOT b
- 1 Panchromatic, visible

Thematic Mapper
- 1 450 – 520 nm blue-green
- 2 520 – 600 nm green
- 3 630 – 690 nm red
- 4 760 – 900 nm near infrared
- 5 1 550 – 1 750 nm medium infrared
- 6 2 080 – 2 350 nm medium infrared
- 7 10.3 – 12.5 µm thermic infrared

1/ Le Houérou, 1985; Tucker, Hielkema and Roffrey, 1985.

Table 11

WAVELENGTHS USED IN THE RADIOMETER SENSORS FOR THE EVALUATION OF GREEN HERBACEOUS PHYTOMASS

C1 = 0.55 - 0.68 μm = visible red

C2 = 0.725 - 1.10 μm = near infrared

C3 = 3.55 - 3.93 μm = infrared

C4 = 10.5 - 11.5 μm = thermic infrared

C5 = 11.5 - 12.5 μm = thermic infrared

Table 12

COEFFICIENTS OF CORRELATION BETWEEN GROUND-MEASURED AND SATELLITE-SENSED INDVI AND MNDVI 1/

Years	1980	1981	1982	1983	1981-83	1980-83
No. of observations	68	42	66	96	204	272
INDVI	0.46	0.58	0.78	0.82	0.83	0.79
MNDVI	0.33	0.52	0.77	0.73	0.80	0.76

1/ Tucker *et al*, 1985.

Table 13

NORMALIZED DIFFERENCES OF VEGETATION INDEX IN THE FERLO 1/

Years	Mean INDVI	Standard deviation	Mean INDVI	Prediction of accumulated phytomass in kg DM/ha
1980	560.7	23.6	0.094	643
1981	590.9	24.5	0.153	1 093
1982	553.3	23.0	0.080	536
1983	528.4	11.2	0.033	178
1984	520.7	11.9	0.017	55

Overall regression equation: Y = 74.3 + 7 631.5 INDVI.

1/ Tucker *et al*, 1985.

Table 14

NORMALIZED DIFFERENCE VALUES FROM GAC AND LAC IMAGES
FOR 13 FERLO AREAS IN 1981 1/

Areas	25 August		21 September		30 September		8 October	
	LAC	GAC	LAC	GAC	LAC	GAC	LAC	GAC
Podor	0.019	0.017	0.053	0.052	0.053	0.049	0.042	0.043
Tatki	0.100	0.103	0.115	0.114	0.092	0.096	0.074	0.077
Mbidi	0.090	0.086	0.116	0.119	0.094	0.095	0.072	0.074
Ganine Erogne	0.087	0.084	0.160	0.162	0.135	0.138	0.100	0.101
Namarel	0.076	0.078	0.131	0.134	0.118	0.116	0.083	0.086
Tessekre	0.108	0.106	0.153	0.153	0.143	0.143	0.098	0.098
Labgar	0.086	0.084	0.154	0.140	0.137	0.133	0.092	0.088
Mbeulekhe	0.095	0.099	0.167	0.165	0.143	0.144	0.099	0.101
Lougere Tioli	0.076	0.068	0.113	0.122	0.093	0.093	0.066	0.065
Linguère	0.089	0.092	0.161	0.159	0.145	0.143	0.091	0.091
Salde	0.064	0.045	0.105	0.105	0.090	0.057	0.065	0.049
Matam	0.102	0.097	0.122	0.103	0.106	0.098	0.070	0.065
Dagana	0.059	0.063	0.097	0.099	0.084	0.085	0.068	0.068

1/ Vanpraet *et al*, 1983.

Table 15

MEDIAN RAW VALUES OF THE NORMALIZED DIFFERENCE
FOR GIVEN GREEN PHYTOMASSES 1/

Median phytomass	1980		1981		1982		1983		All years	
	N D	n	N D	n	N D	n	N D	n	N D	n
100 kg/ha	0.06	5			0.04	4	0.03	49	0.03	58
300 kg/ha	0.09	22	0.14	2	0.05	19	0.04	26	0.06	69
500 kg/ha	0.09	21	0.125	4	0.065	10	0.035	2	0.09	37
700 kg/ha	0.095	12	0.10	6	0.09	11	0.125	2	0.09	31
900 kg/ha	0.11	4	0.14	8	0.10	9	0.08	1	0.115	22
1100 kg/ha	0.12	2	0.175	6	0.16	5			0.16	13
1300 kg/ha	0.14	1	0.17	5	0.14	3			0.16	9
1500 kg/ha	0.17	1	0.21	3	0.12	1	0.16	1	0.165	6
1700 kg/ha			0.16	1					0.16	1
1900 kg/ha			0.175	2			0.16	2	0.165	4
2100 kg/ha			0.22	3	0.17	1			0.17	4
2300 kg/ha			0.17	1					0.17	1
2500 kg/ha							0.22	1	0.22	1

1/ Vanpraet *et al*, 1983.

Table 16

MATCHING NORMALIZED DIFFERENCE OF VEGETATION INDEX COLOURS WITH BIOMASS CLASSES (kg DM/ha) AS ESTABLISHED WITH IMAGES AT OPTIMUM OF PHOTOSYNTHETIC ACTIVITY 1/

Biomass class / Colour glass of ND	0-200	200-400	400-600	600-800	800-1 000	1 000-1 200	1 200-1 400	over 1 400
GAC 23/9/80	1	2-3	4-5	6-7	8	9-10	11-12	
LAC 21/9/81	1-2	3	4-5	6	7	8	9	10-11
Composite GAC of 26 to 28/8/82	1-2	3-4	5-6	7	8-9	10	11	
Composite LAC of 26 to 27/8 and 1 to 3/9/83	1-2-3	4-5	6	7	8			

1/ Gaston et al, 1983.

Table 17

SAMPLING WITH HAND-HELD RADIOMETER ON THE GROUND 1/

Year	Number of biomass sampling sites	Number of sites used in Mark II calibration	Number of m^2 quadrats sampled per site	Total number of calibration measurements
1981	42	27	13	198
1982	70	48	5	240
1983	112	18	10	180
Total	224	93	--	618

1/ Gaston, 1983.

Table 18

VARIATIONS AROUND THE CORRECTED MEAN OF LIVESTOCK NUMBERS
(rounded figures)

Species	numbers in 10^3				
	mean x 0.8	mean x 0.9	mean	mean x 1.1	mean x 1.2
Smallstock	570	639	710	781	850
Cattle	288	324	360	396	432
Donkeys	15	17	19	20	23
Horses	6	7	8	9	10
Camels	2	2.3	2.5	2.8	3

Table 19

ANNUAL VARIATION IN PRECIPITATION AND HERBACEOUS BIOMASS
PREDICTED FROM SATELLITE NOAA/AVHRR REMOTELY-SENSED DATA
ON SIX 3 X 3 KM SITES CENTRED ON RELIABLE RAINFALL RECORD STATIONS.
RAIN-USE EFFICIENCY (RUE) 1/

Stations	years					
	1980	1981	1982	1983	1984	Average
Mbeuleukhe	349	465	412	79	181	297
Mbidi	210	317	141	139	84	178
Tatki	-	351	278	100	92	205
Tessekré	382	304	300	118	171	255
Vendo-Tiengoli	207	193	196	121	117	167
Mbar Toubab	245	298	193	119	77	186
Mean mm	279	321	236	113	120	214
Predicted Biomass	(700)	1 375	780	285	112	650
RUE	2.51	4.28	3.31	2.52	0.93	3.04

1/ Tucker *et al*, 1985.

Appendix 1

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Figure 1

ADMINISTRATIVE MAP OF THE NORTH FERLO

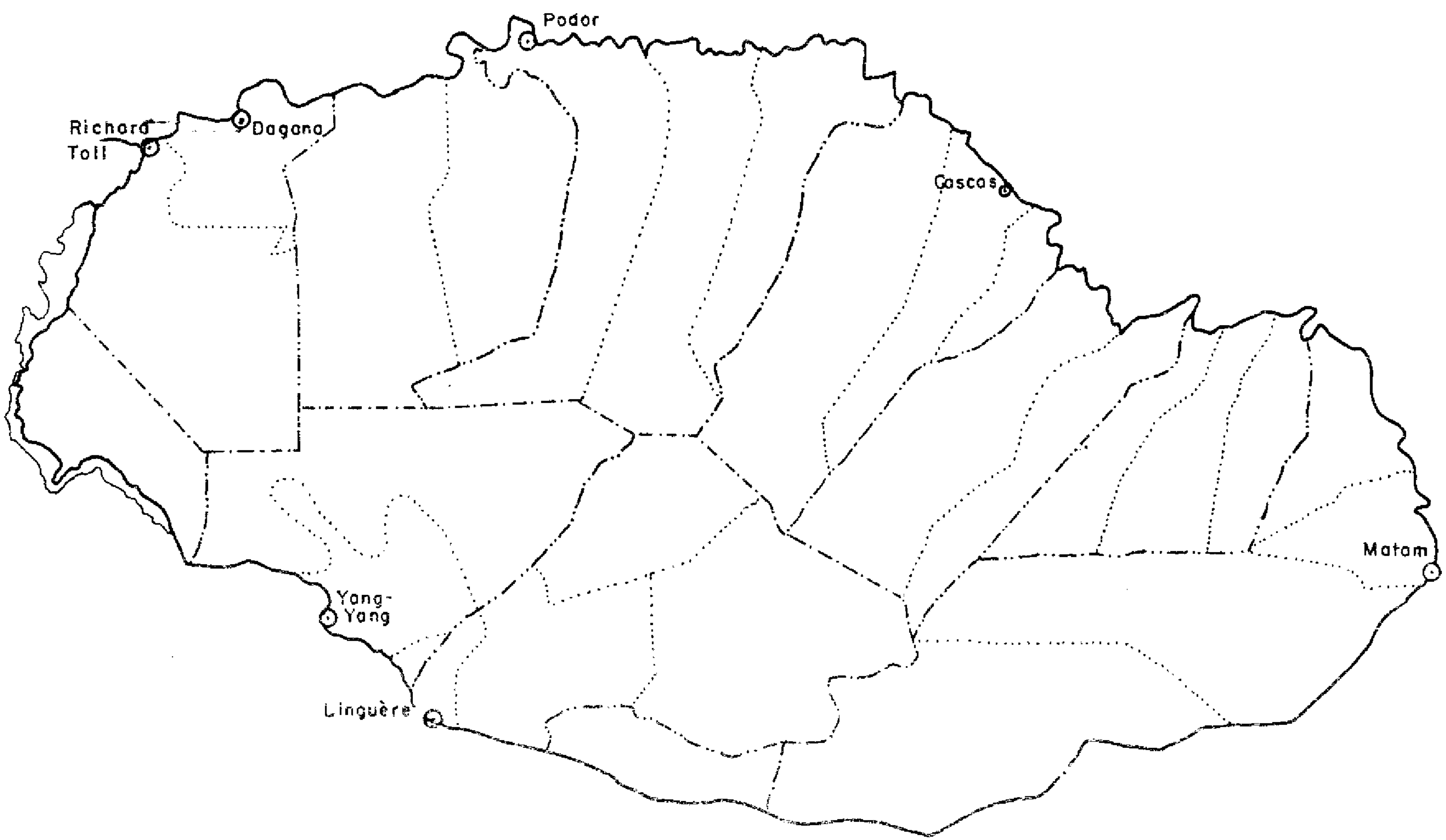


Figure 2

MAP OF HUMAN SETTLEMENTS

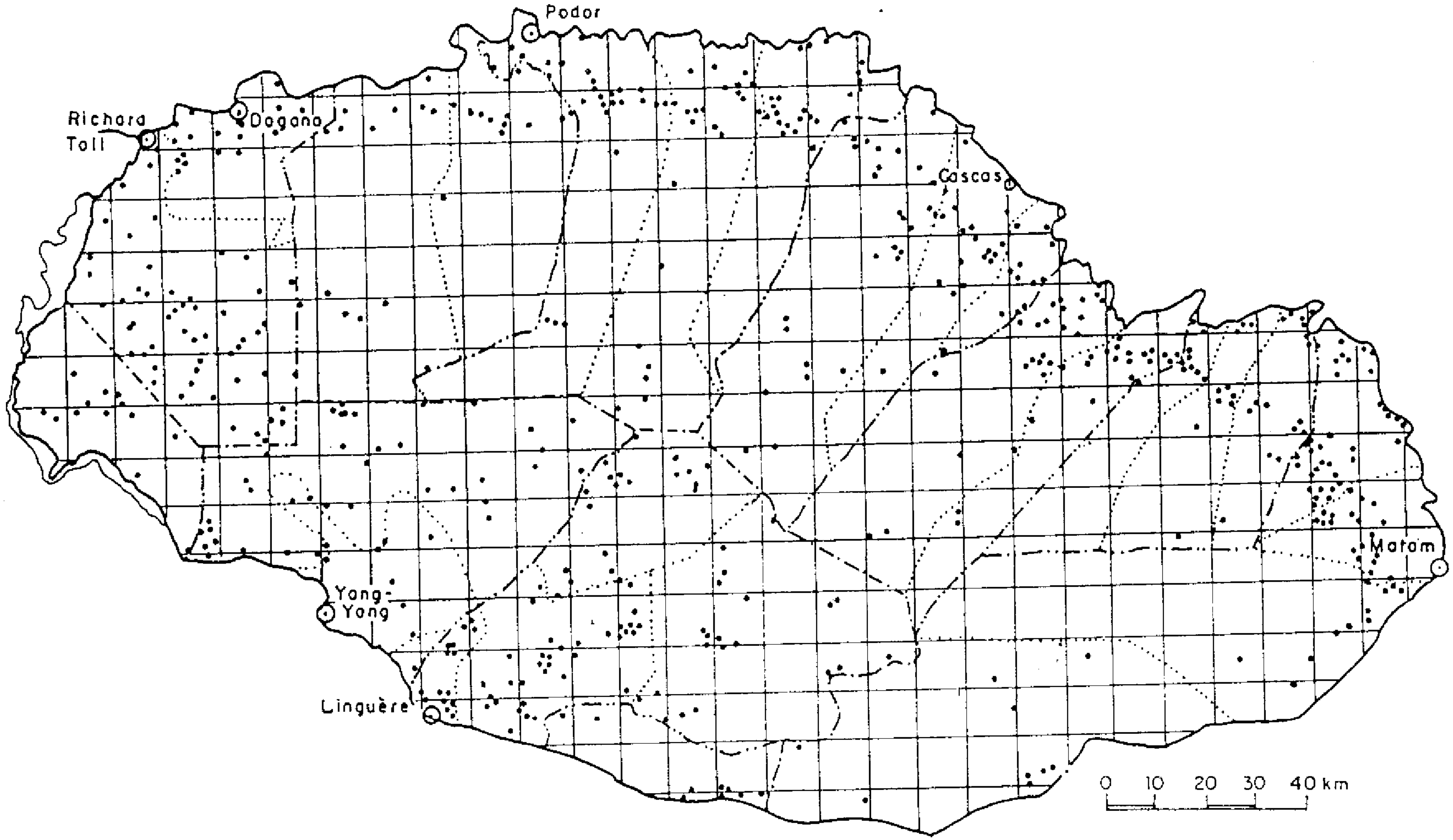


Figure 3

MAP OF MEAN ANNUAL RAINFALL 1929-69 (BELLOCQ 1983)

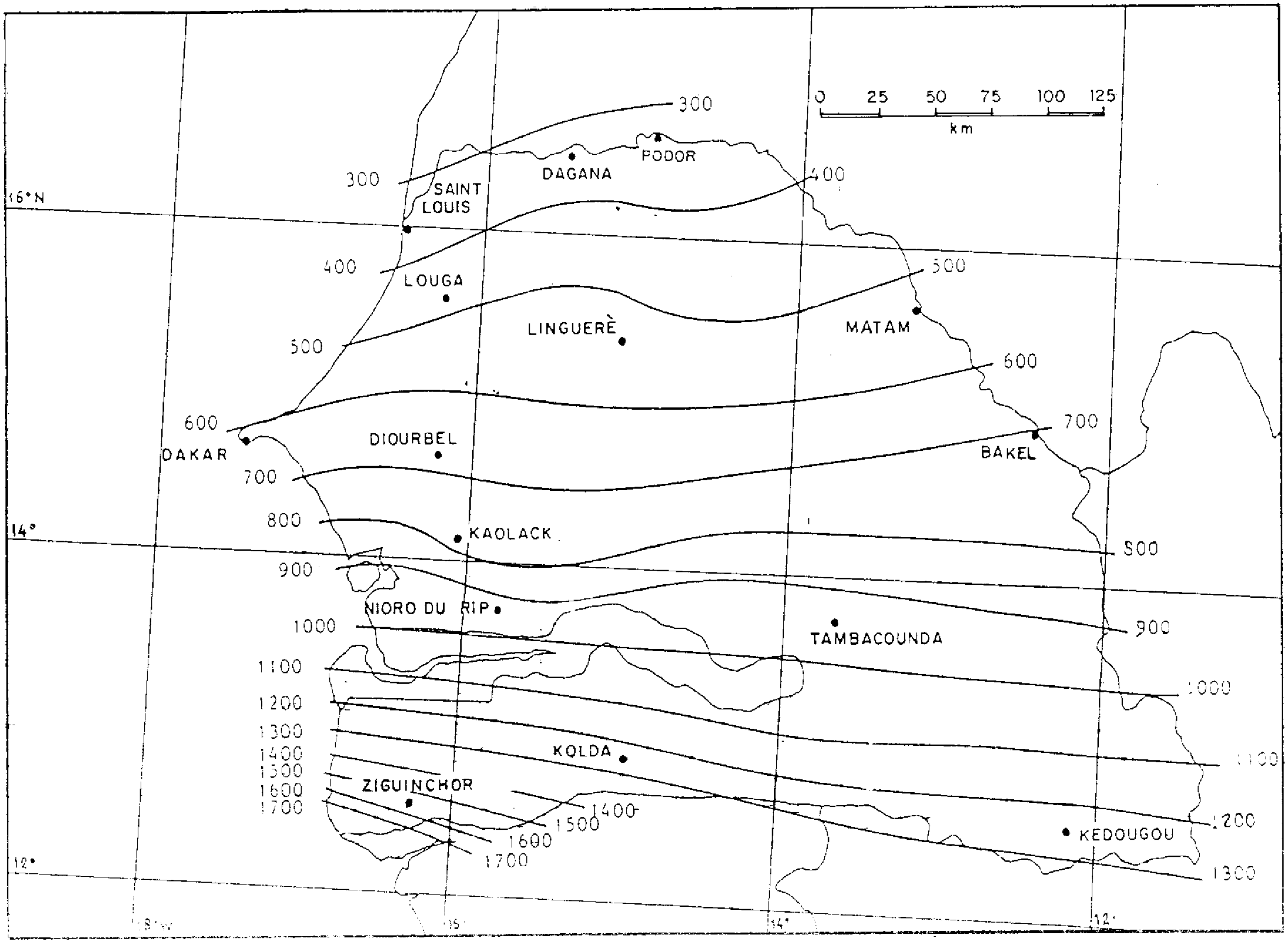


Figure 4

RAINY SEASON PRECIPITATION (JUNE-OCTOBER: MEAN, MEDIAN AND MODE
(ISOHYETS ARE BASED UPON ALL RECORDS AVAILABLE FOR EACH STATION)
(Beilocq, 1983)

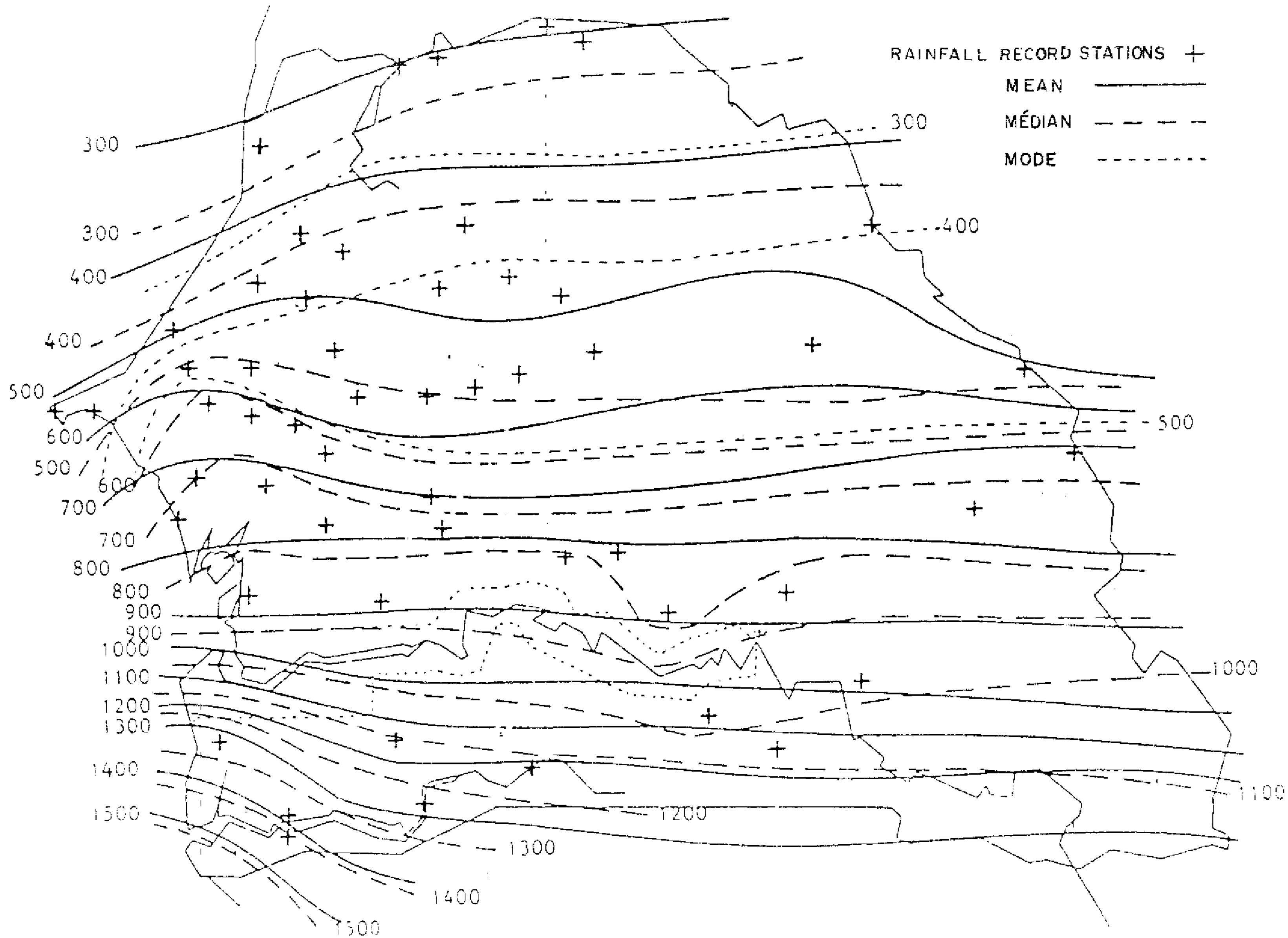


Figure 5

80% PROBABILITY RAINY SEASON PRECIPITATION (BELLOCQ 1983)

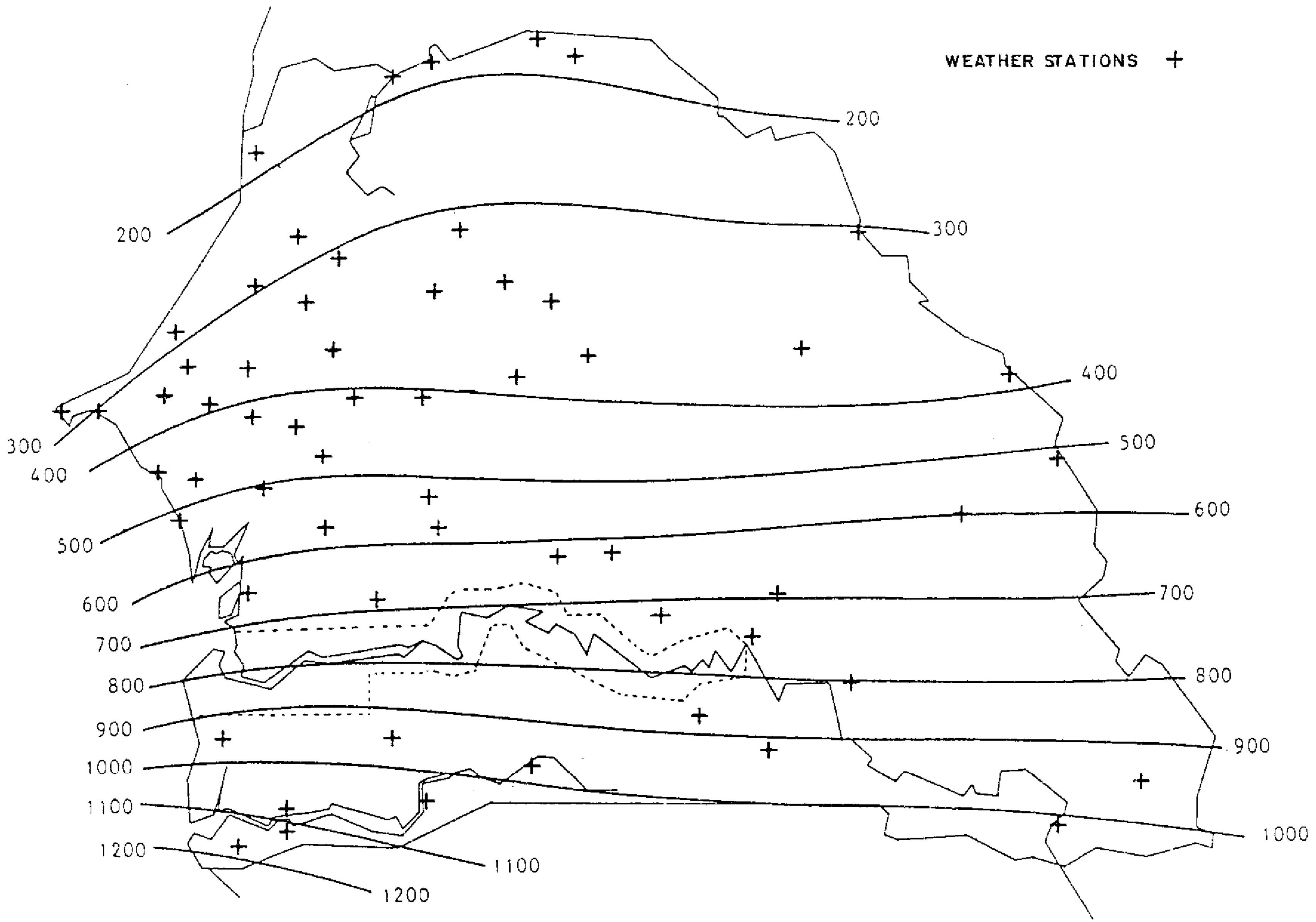


Figure 6

DRY/RAINY SEASON CLIMATIC WATER BUDGET

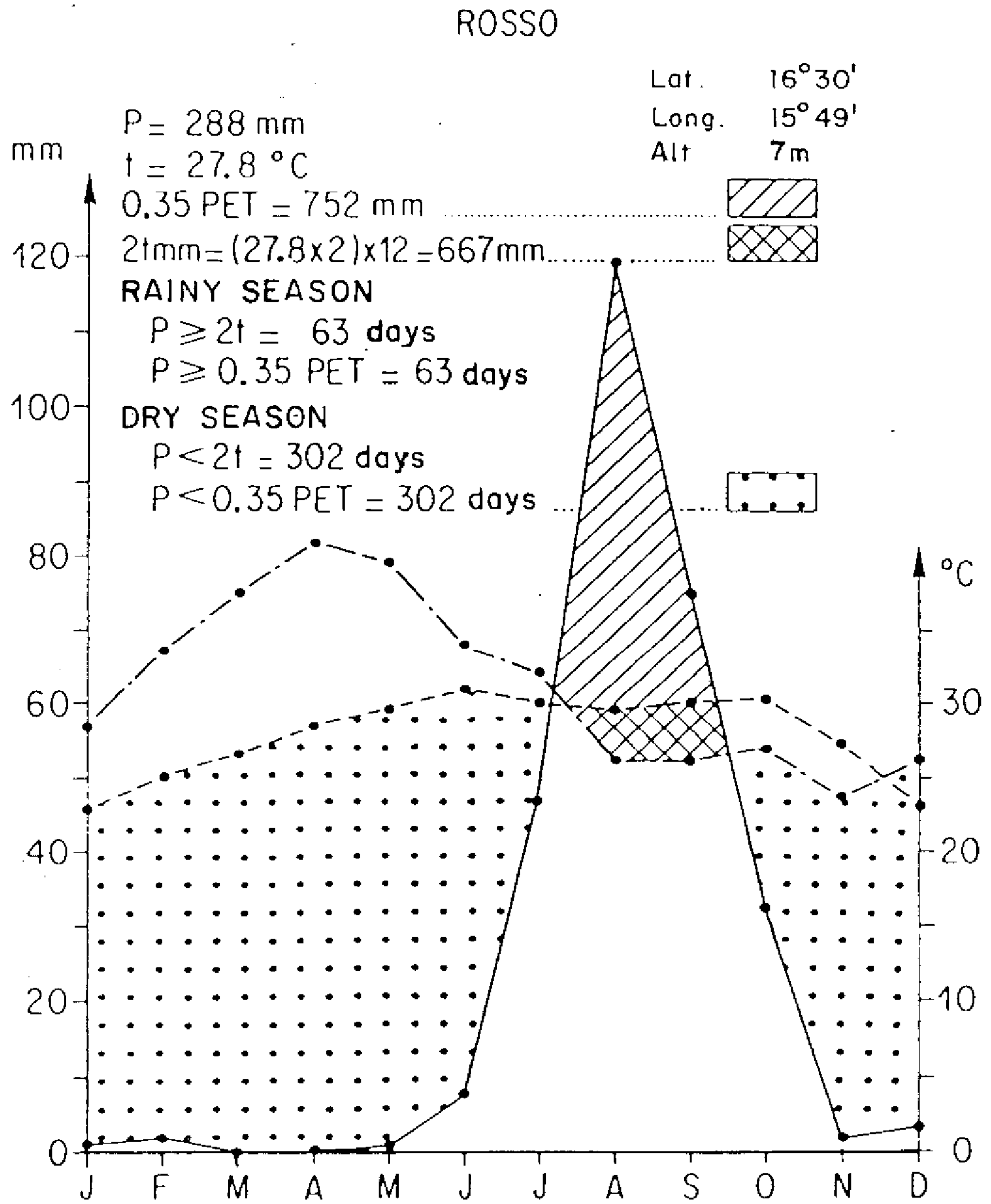


Figure 7

DRY/RAINY SEASON CLIMATIC WATER BUDGET

DAGANA

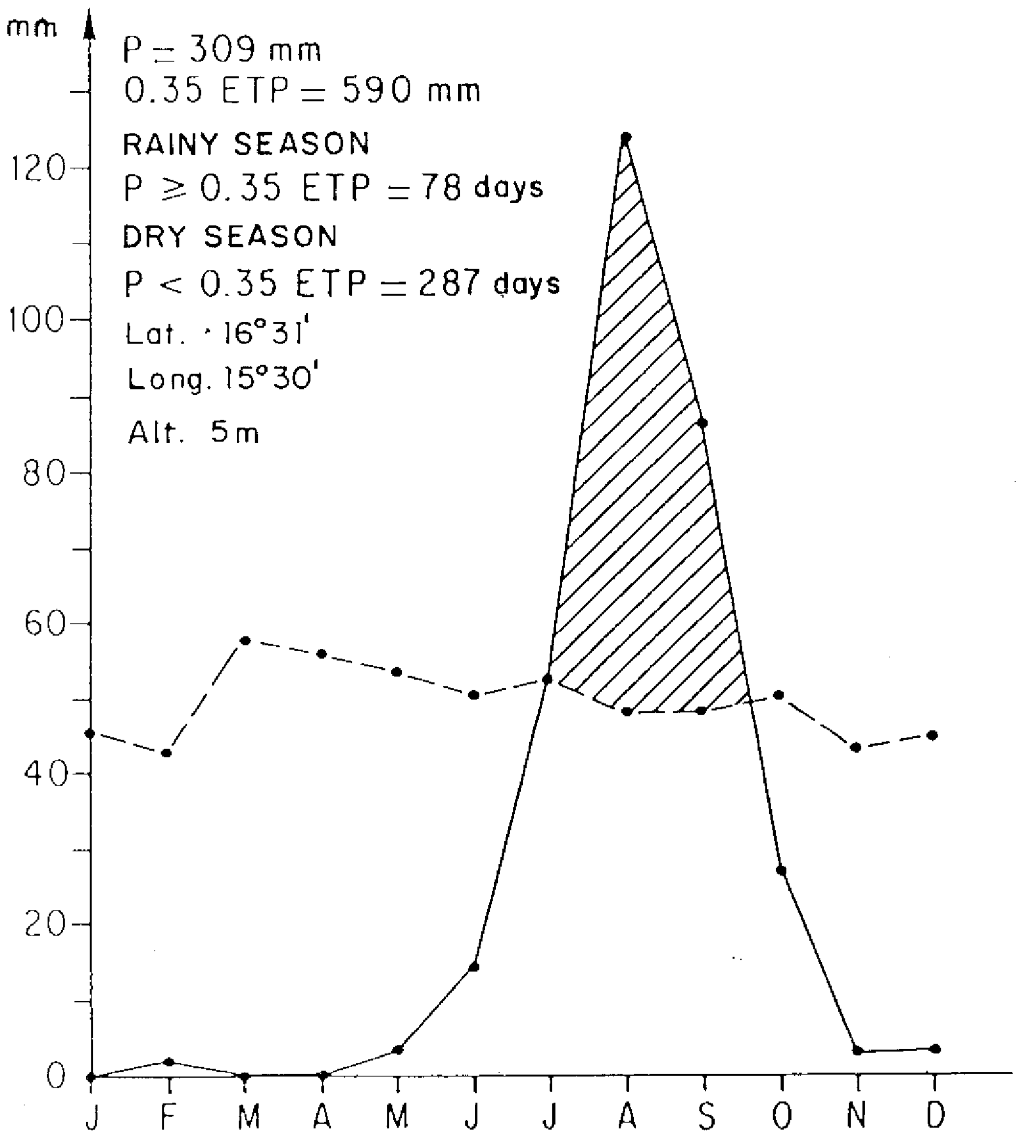


Figure 8

DRY/ RAINY SEASON CLIMATIC WATER BUDGET

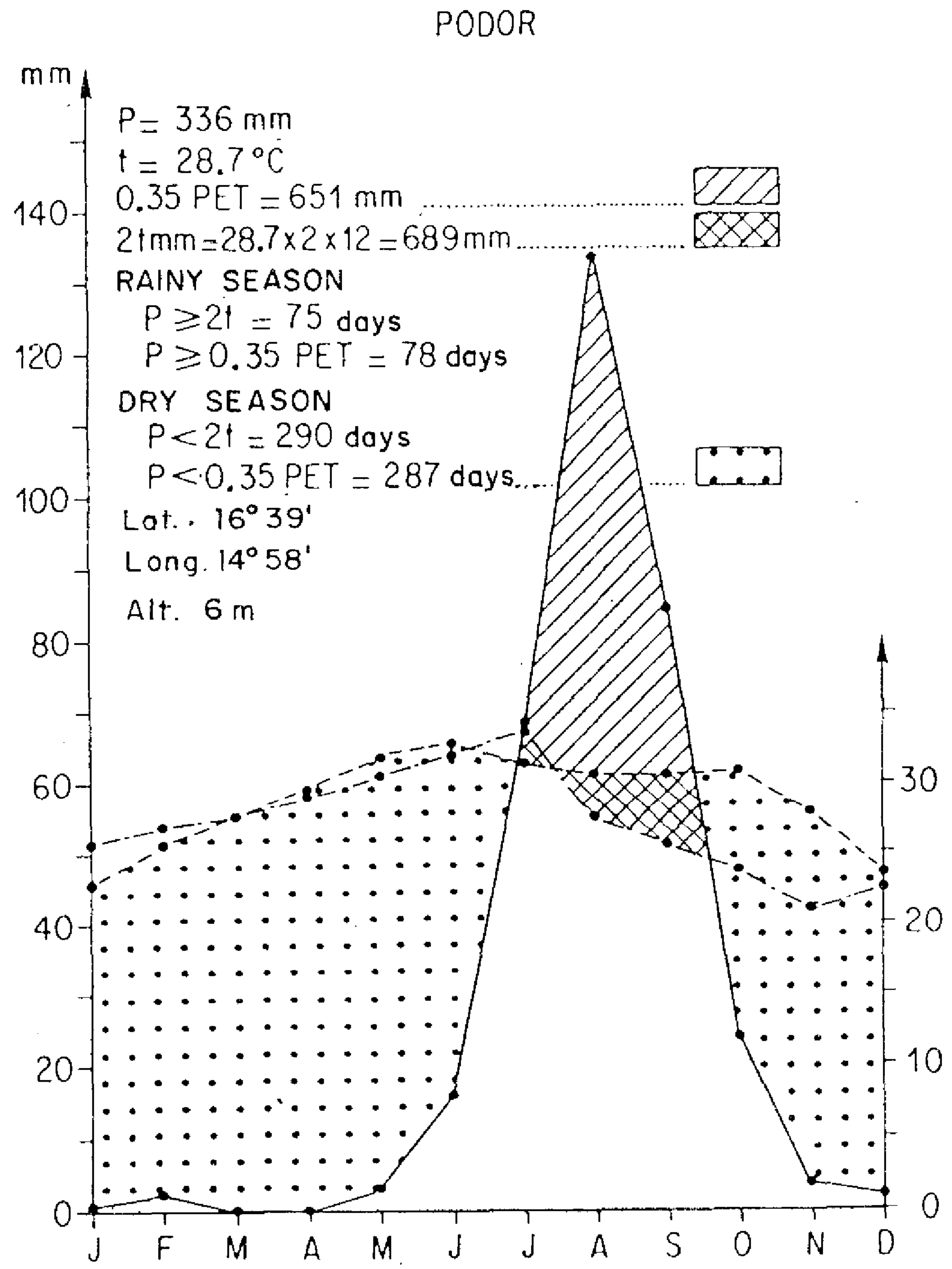


Figure 9

DRY/RAINY SEASON CLIMATIC WATER BUDGET

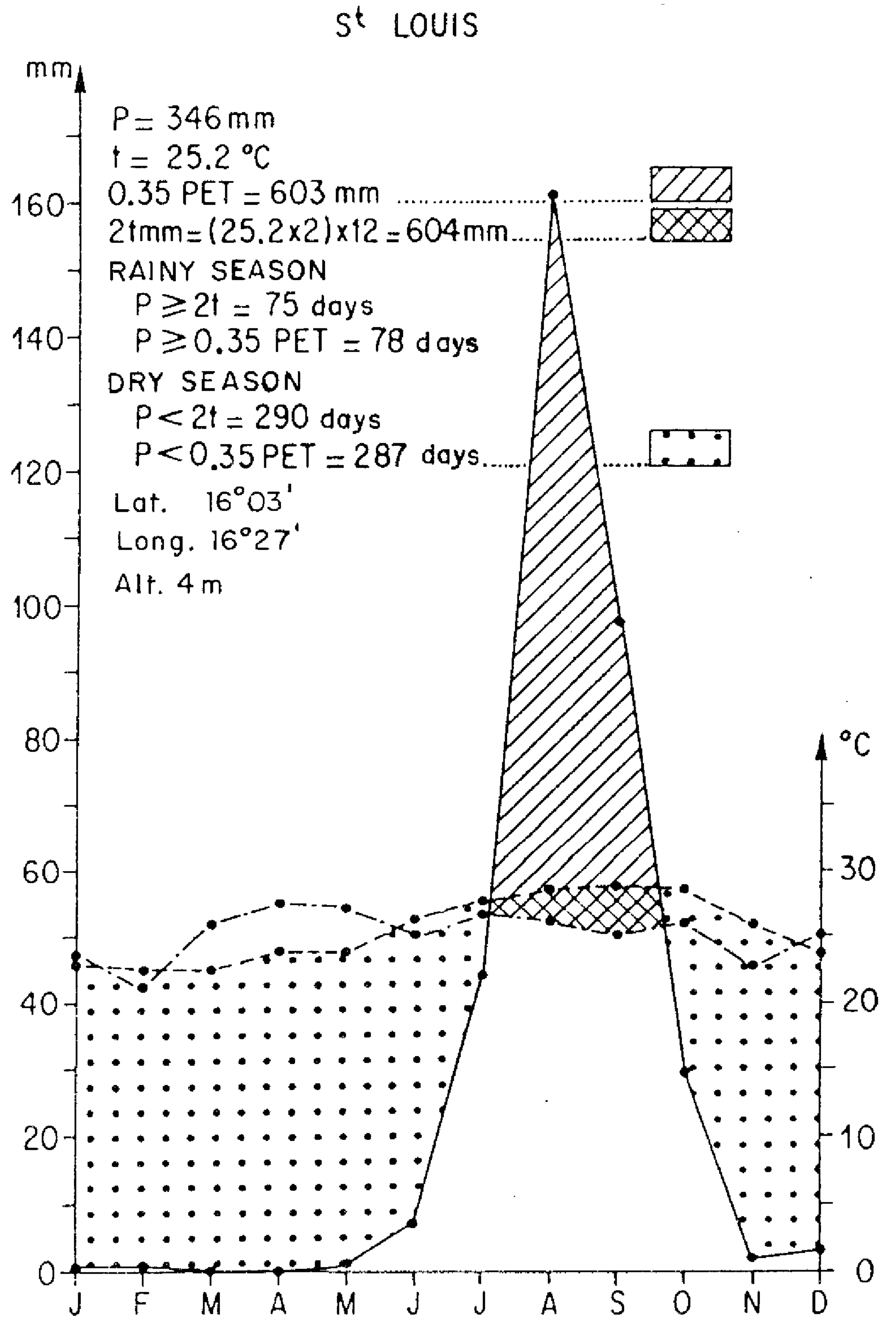


Figure 10

DRY/RAINY SEASON CLIMATIC WATER BUDGET

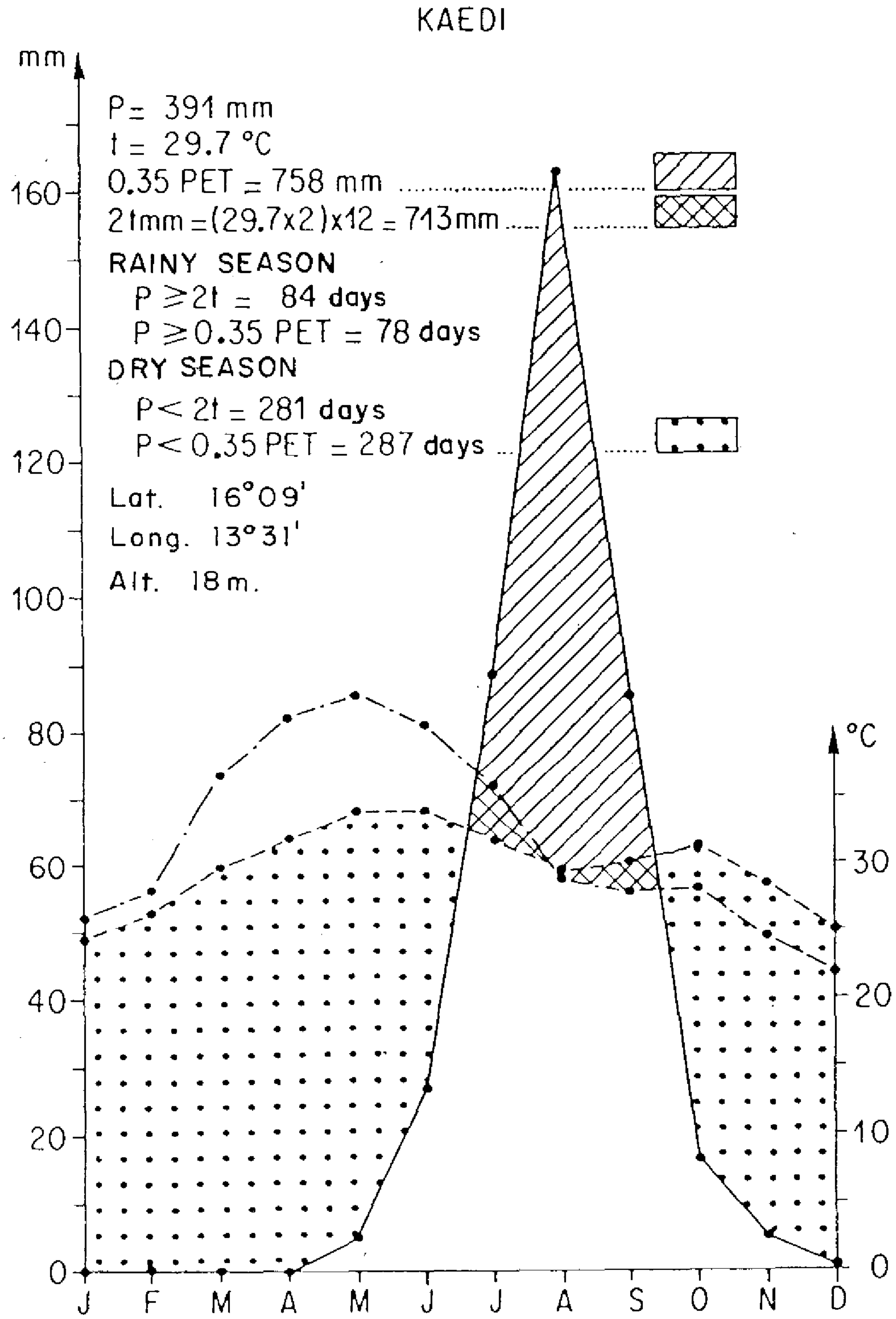


Figure 11

DRY/ RAINY SEASON CLIMATIC WATER BUDGET

KEBEMER

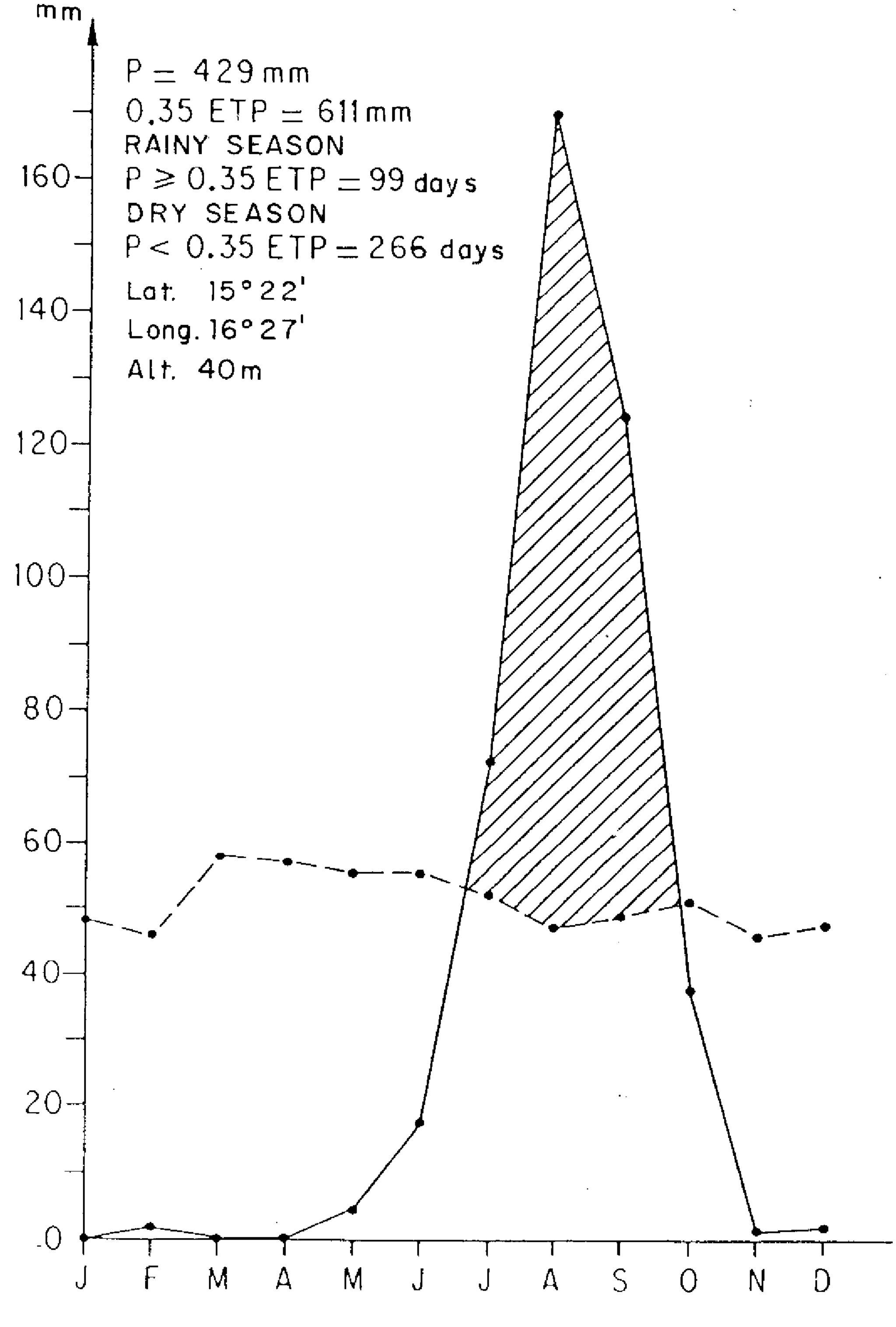


Fig. 12

DRY/RAINY SEASON CLIMATIC WATER BUDGET

LOUGA

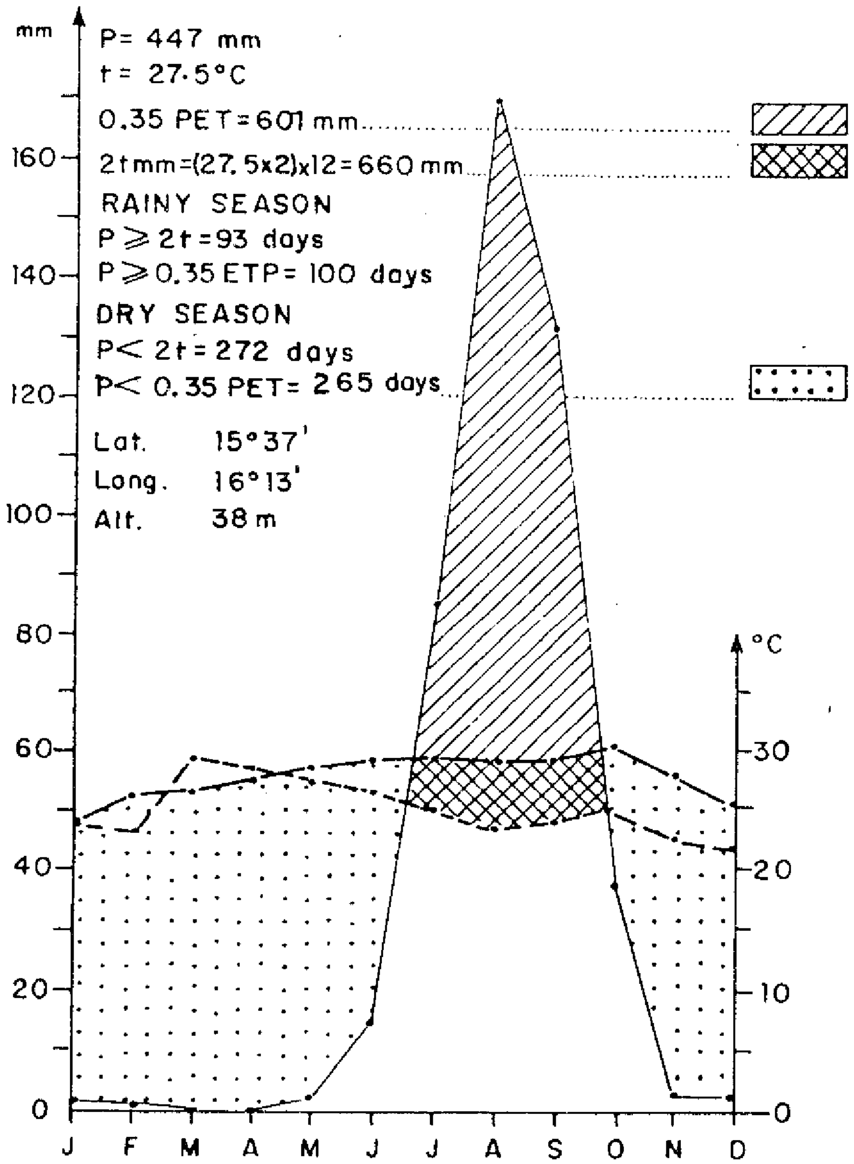


Figure 13

DRY/RAINY SEASON CLIMATIC WATER BUDGET

DAHRA

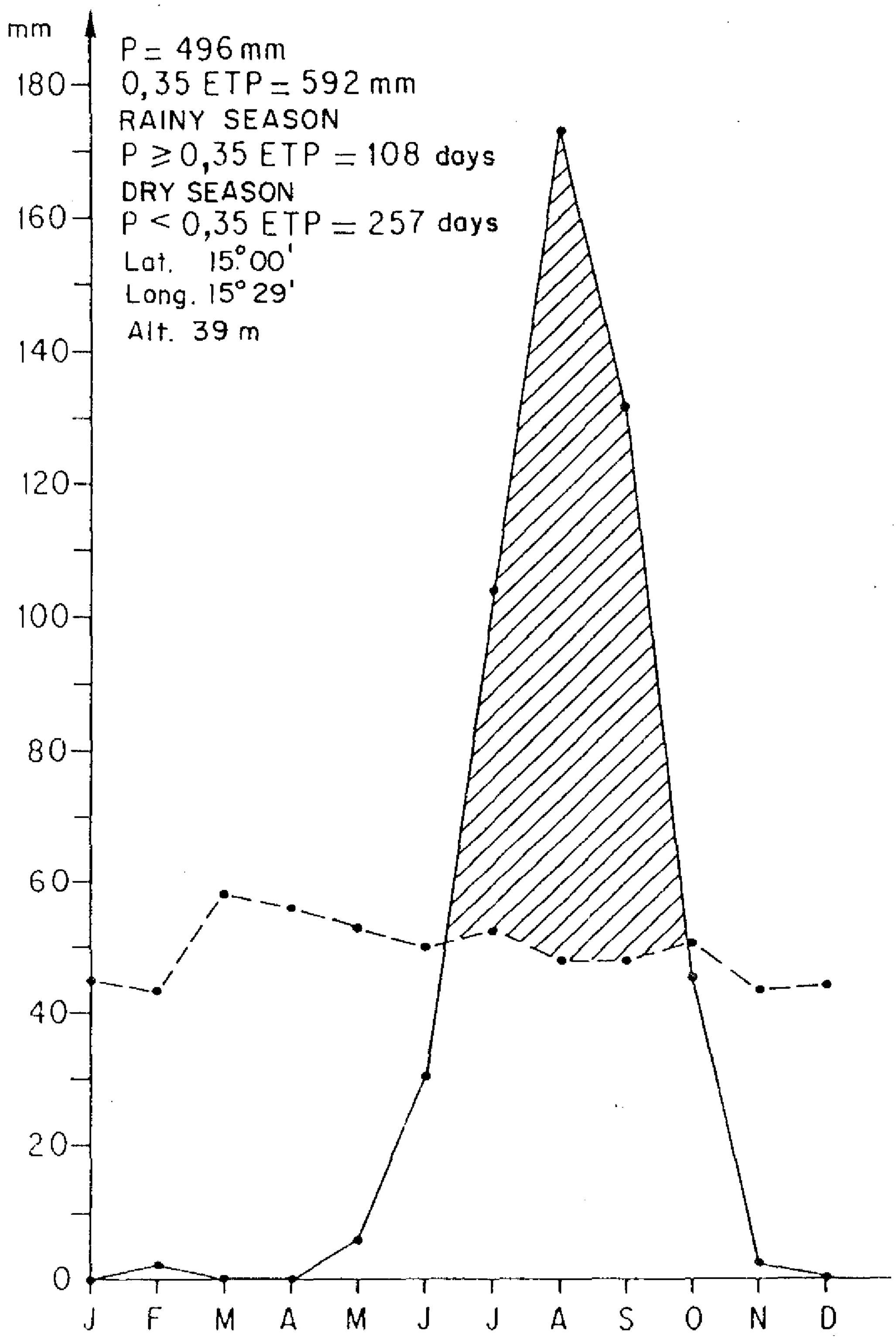


Figure 14

DRY/RAINY SEASON CLIMATIC WATER BUDGET

BAKEL

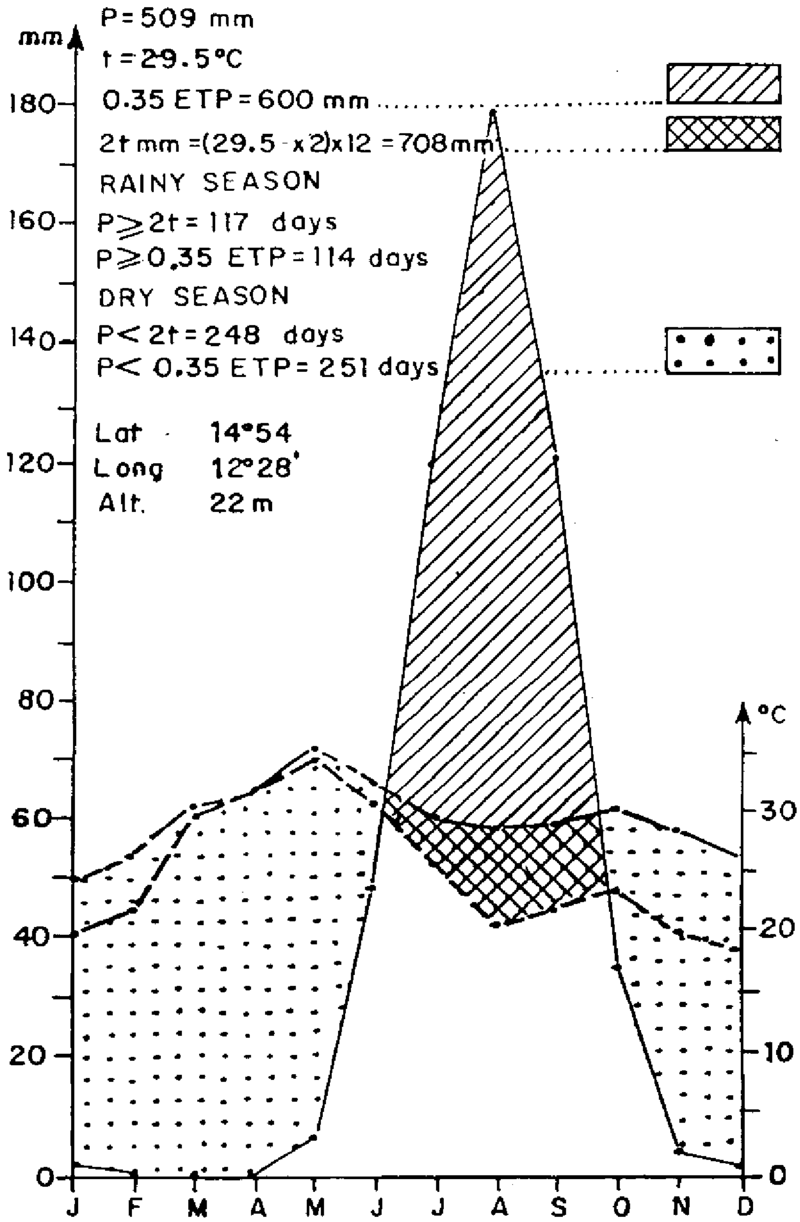


Figure 15

DRY/RAINY SEASON CLIMATIC WATER BUDGET

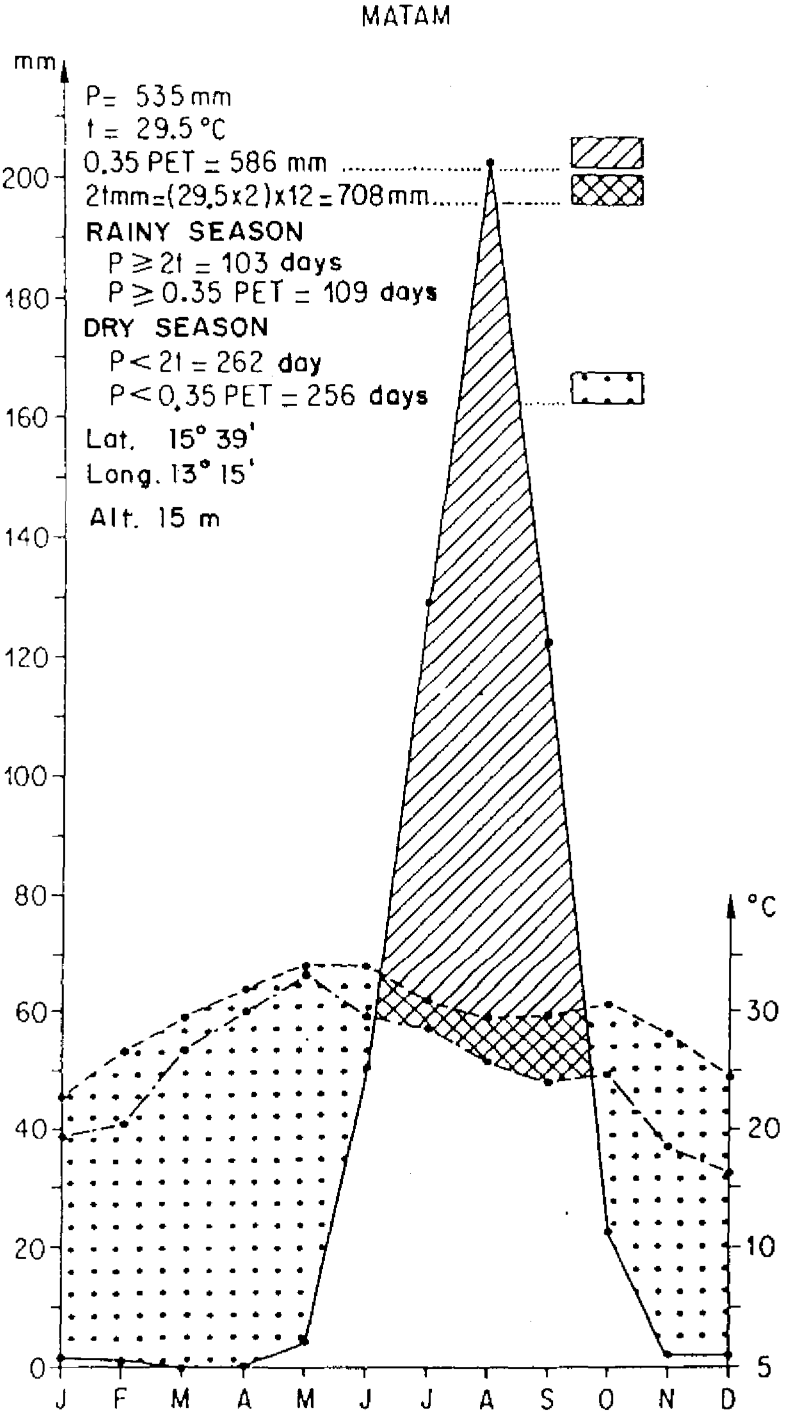


Figure 16

DRY/RAINY SEASON CLIMATIC WATER BUDGET

LINGUÈRE

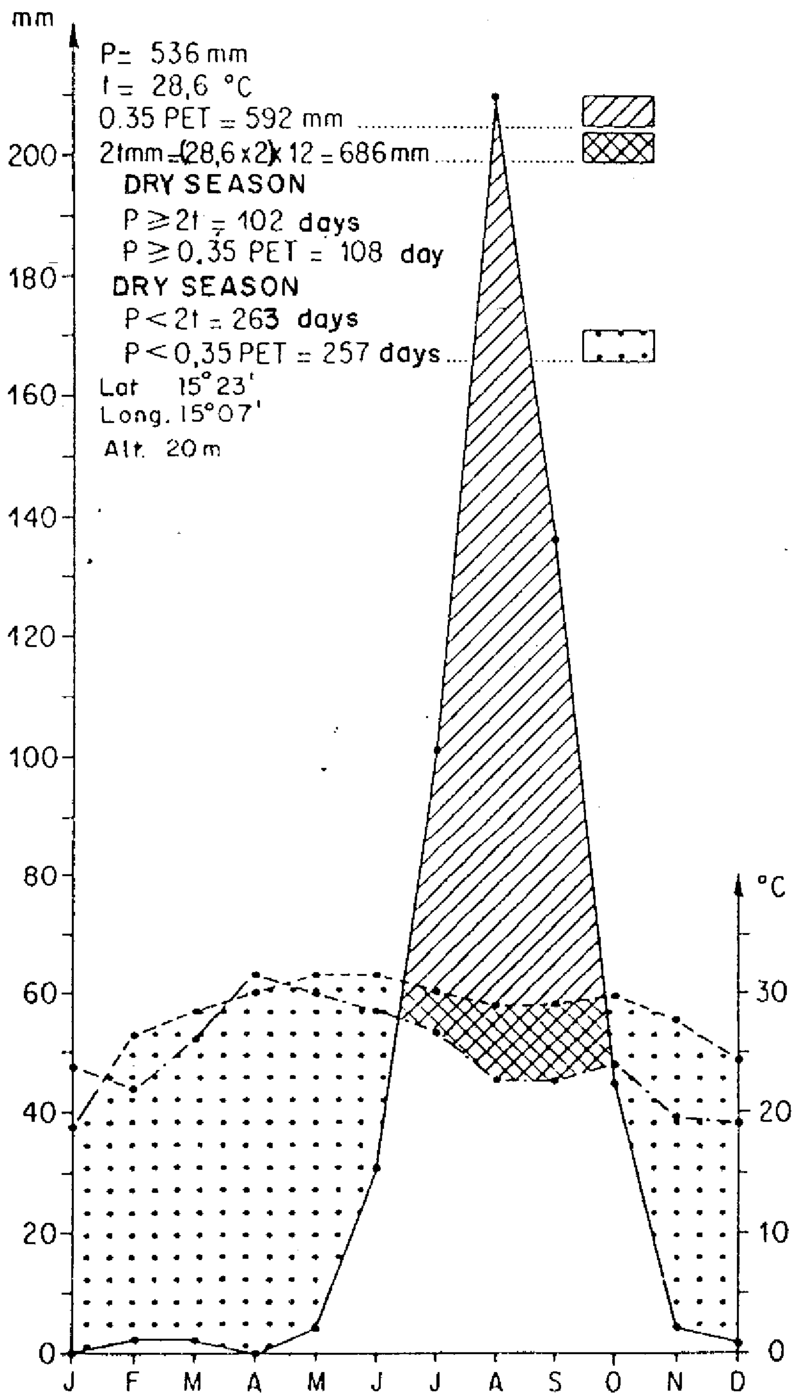


Figure 17

GEOLOGICAL CROSS-SECTION OF THE FERLO FROM NORTHWEST TO SOUTHEAST
(Naegelé 1971)

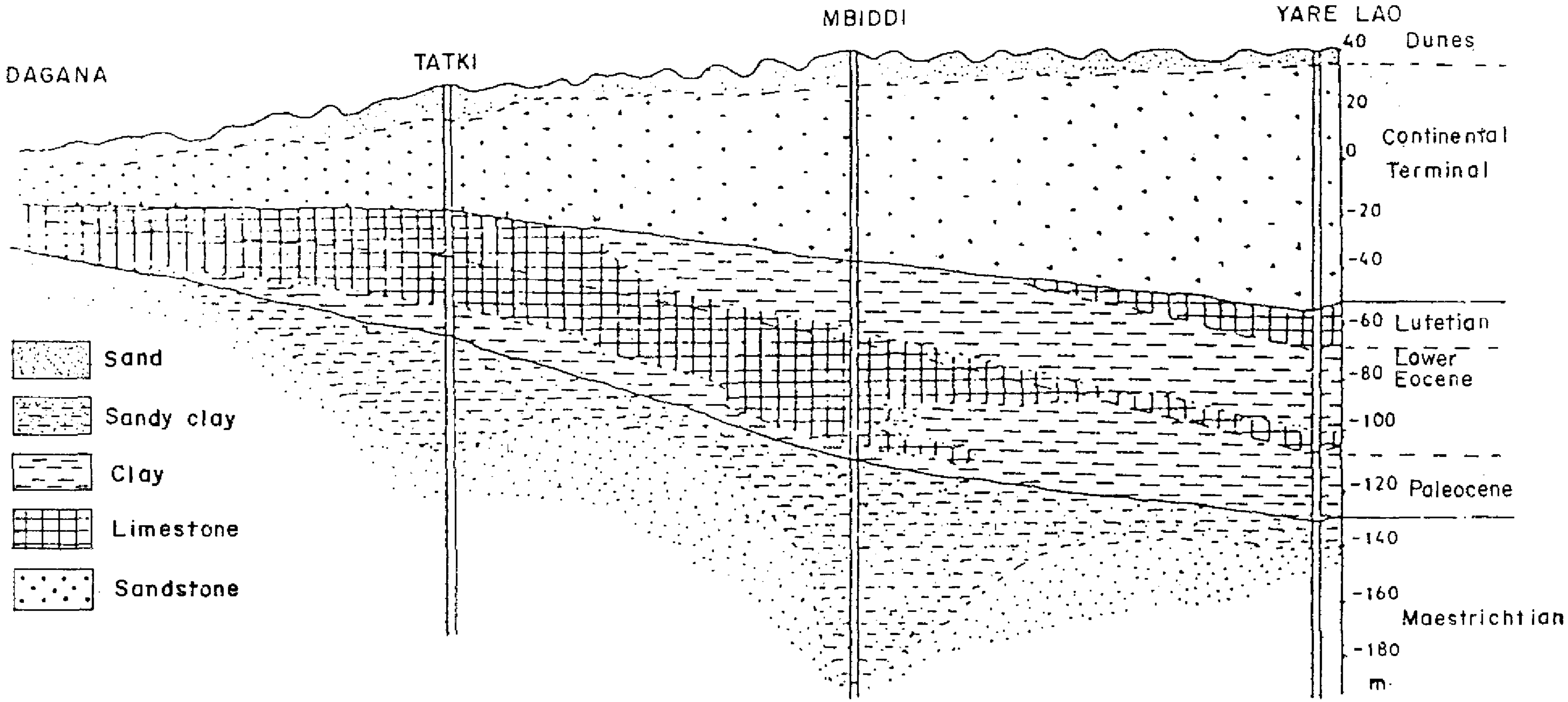


Figure 18

CHANGES IN BOREHOLE NUMBERS IN THE FERLO FROM 1940 TO 1984
(Vanpraet, 1985)

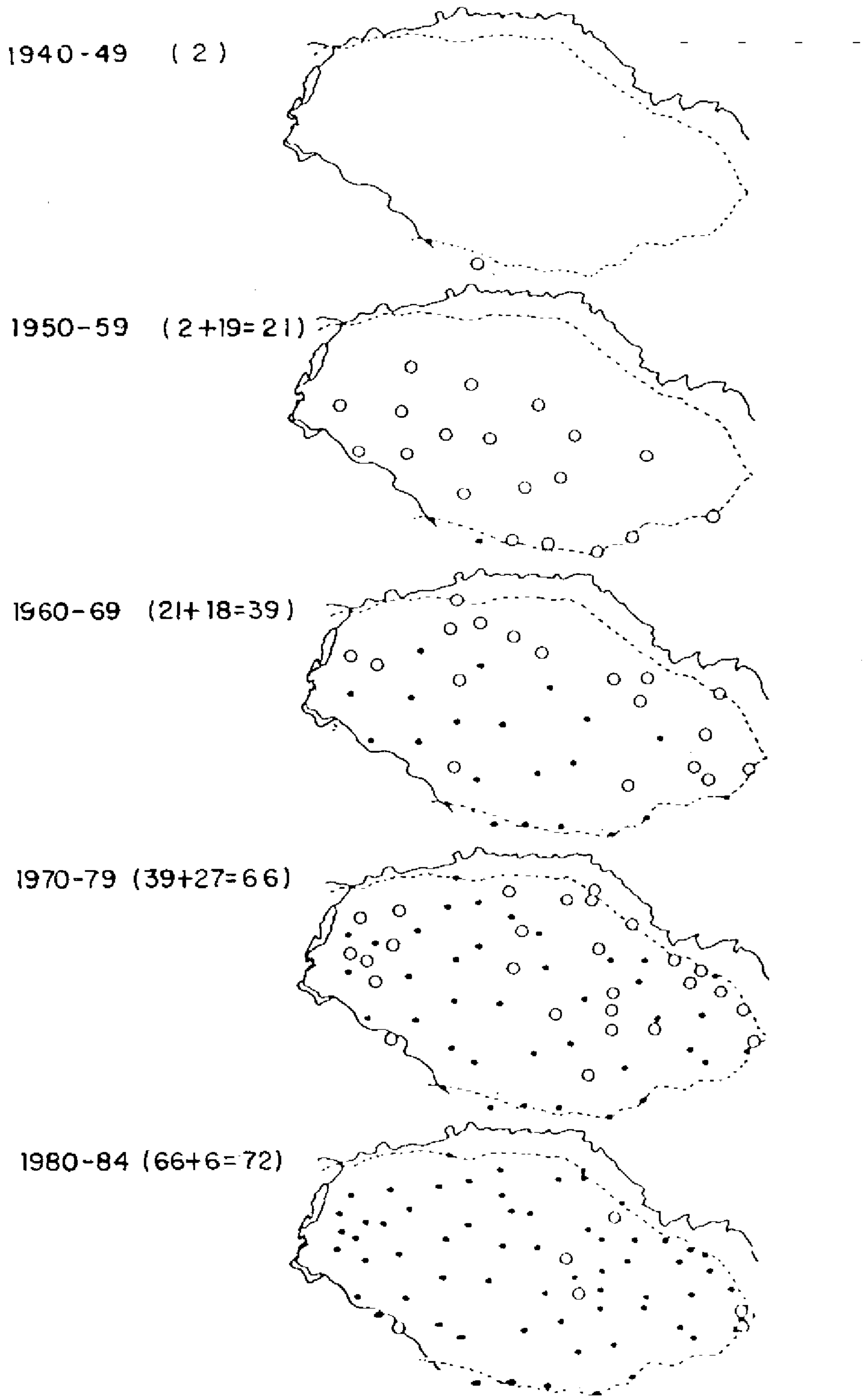


Figure 19

EVOLUTION OF BOREHOLE NUMBERS OVER TIME AS RELATED TO MAJOR EVENTS (VANPRAET, 1985)

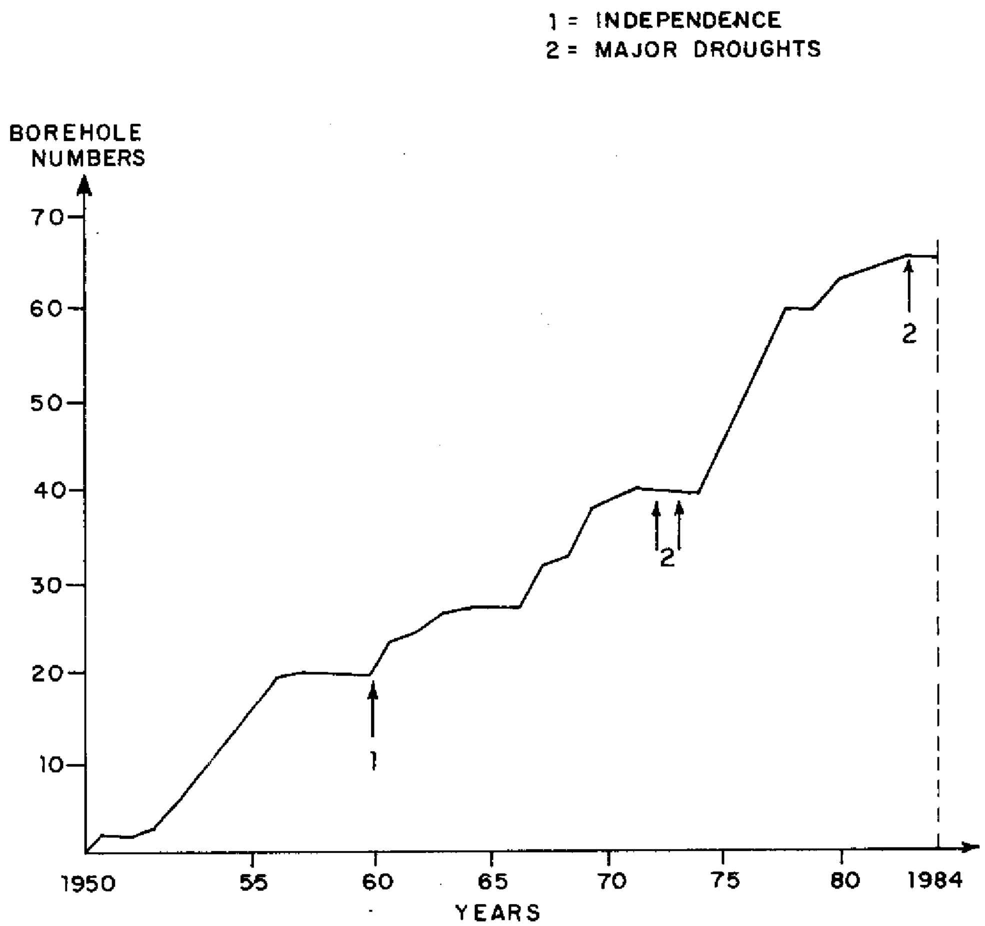


Figure 20

DISTRIBUTION OF BOREHOLES AND OTHER WATER RESOURCES IN THE FERLO (1983)
(Vanpraet, 1985)

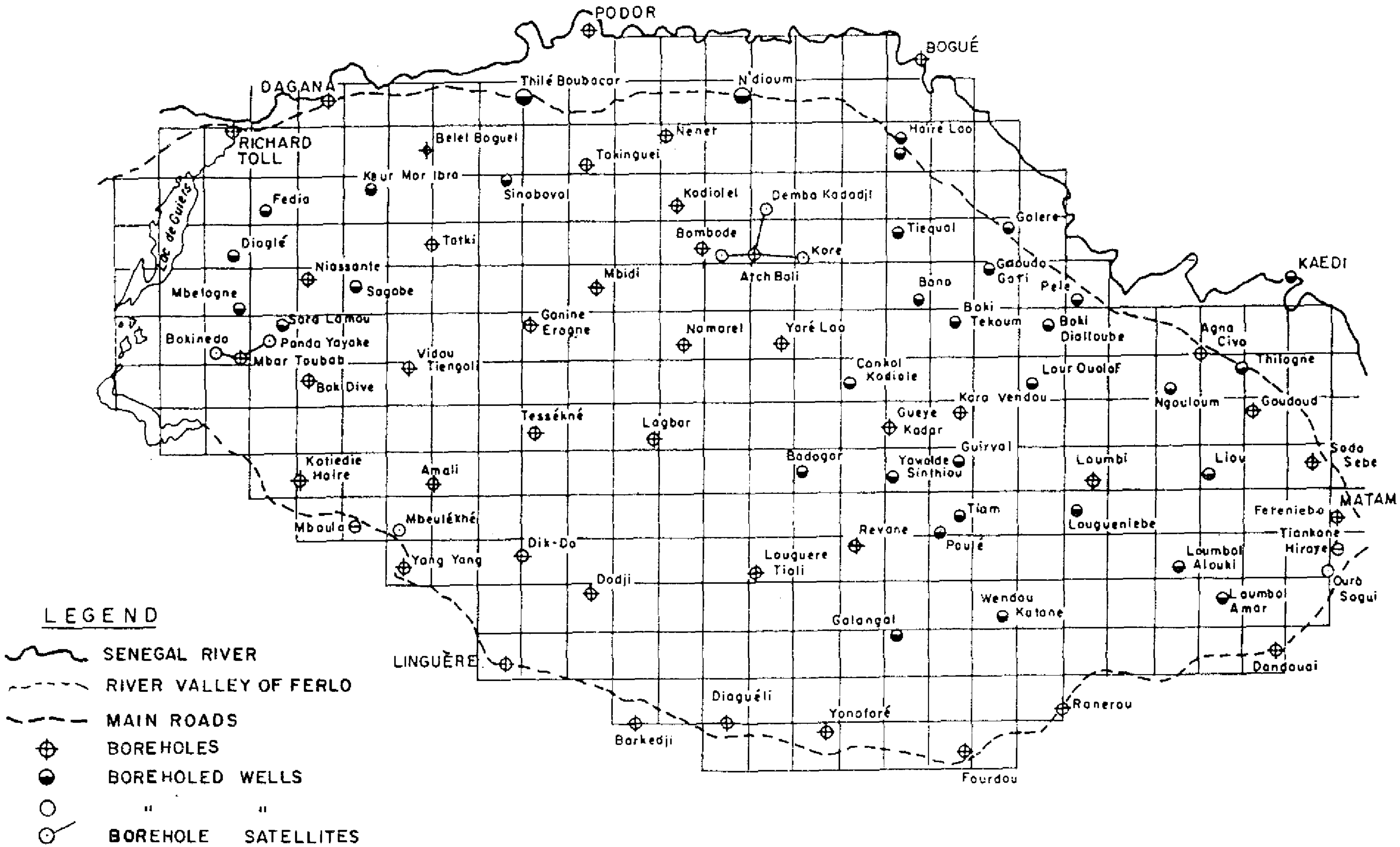


Figure 21

SOIL MAP OF NORTHERN SENEGAL, EXCLUDING WATERLOGGED SOILS

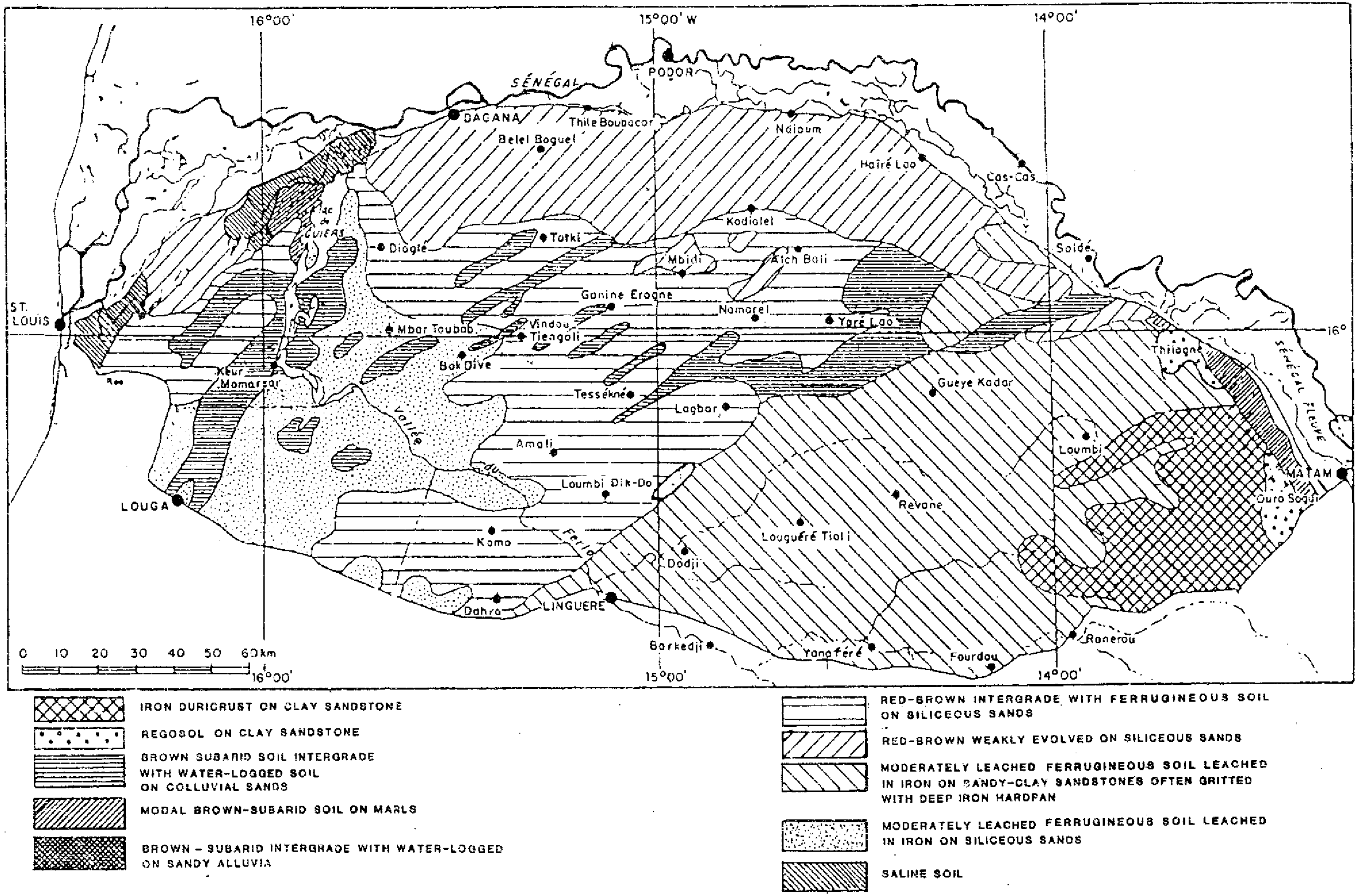
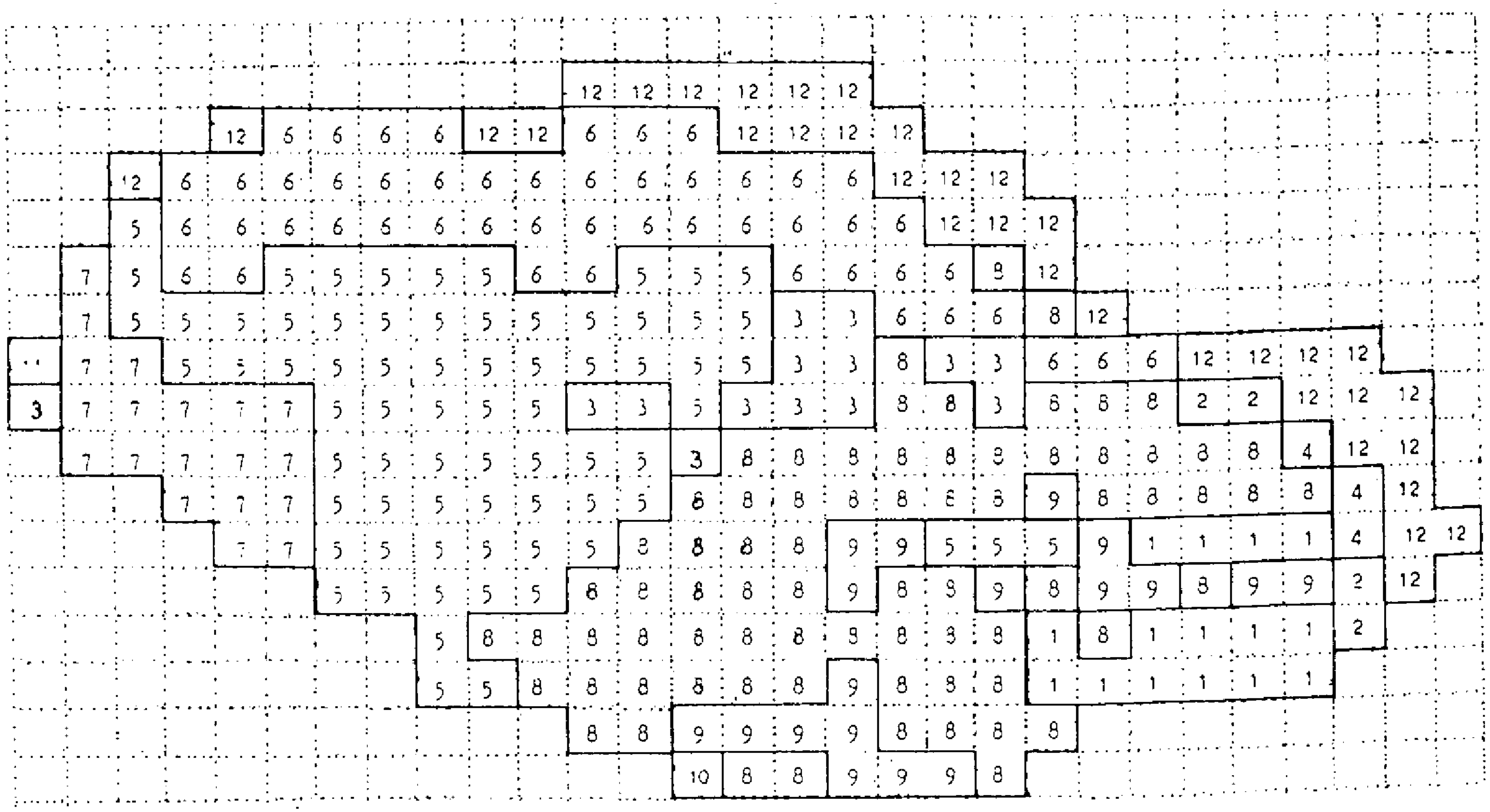


Figure 22

DIGITAL SOIL MAP OF THE NORTH FERLO, SCALE 1/1 000000 (Vanpraet, 1985)



(FROM THE INTERNATIONAL MAP OF SOILS FAO / UNESCO)

Figure 22: Caption

1. Eroded, lithic, raw mineral soil, iron hardpan (duricrust) on lay sandstone.

2. Eroded, regolithic, raw mineral soil on clay sandstone.

3. Isohumic brown-subarid soil, intergrade with waer-logged soils on colluvial sands.

4. Modal isohumic brown-subarid soil on marls.

5. Isohumic brown-red soil intergrade with ferruginous soil on siliceous sands.

6. Isohumic brown-red, slightly leached soil on siliceous sands.

7. Slightly leached ferruginous soil, on siliceous sands.

8. Tropical ferruginous soil, slightly leached in iron, on siliceous sands.

9. Tropical ferruginous soil, leached in iron, on sandy-clay alluvia.

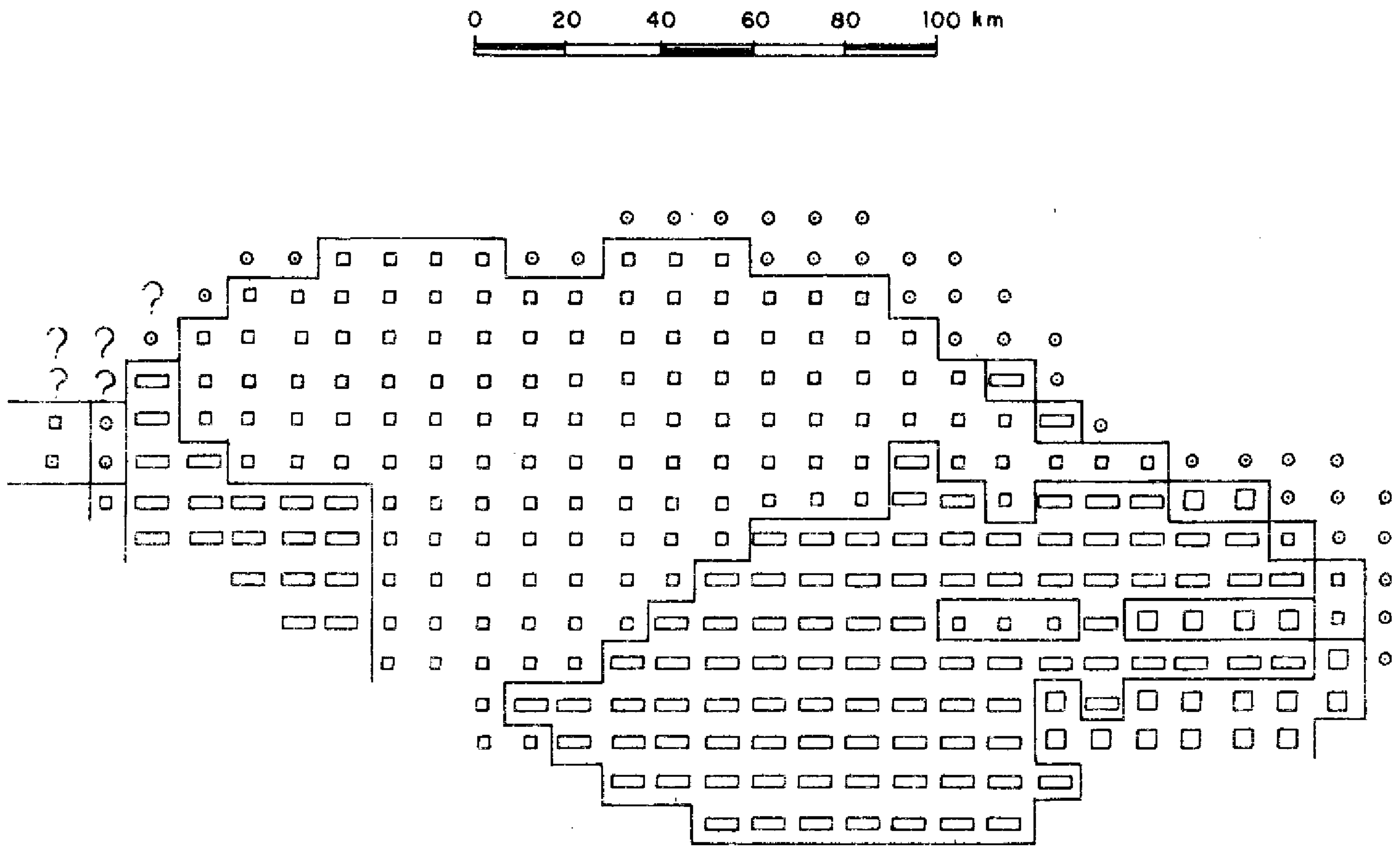
10. Leached tropical ferruginous soil, water-logged, with iron grit (pisolithic limonite).

11. Hydromorphic, fairly organic soil; water-logged with gley in the lower layers.

12. Hydromorphic mineral soil, water-logged with gley from the surface.

Figure 23

SIMPLIFIED DIGITAL SOIL MAP (Vanpraet, 1985)



KEY : ⊙ HYDROMORPHIC SOILS ◻ SANDY SOILS. ▭ IRON-GRIT SOILS

◻ IRON-HARDPANS (DURICRUST).

Figure 24

DGRST / GRIZA/LAT STUDY AREA SHOWING THE DISTRIBUTION OF MAIN BOREHOLES AND TRACKS (Barral, 1982)

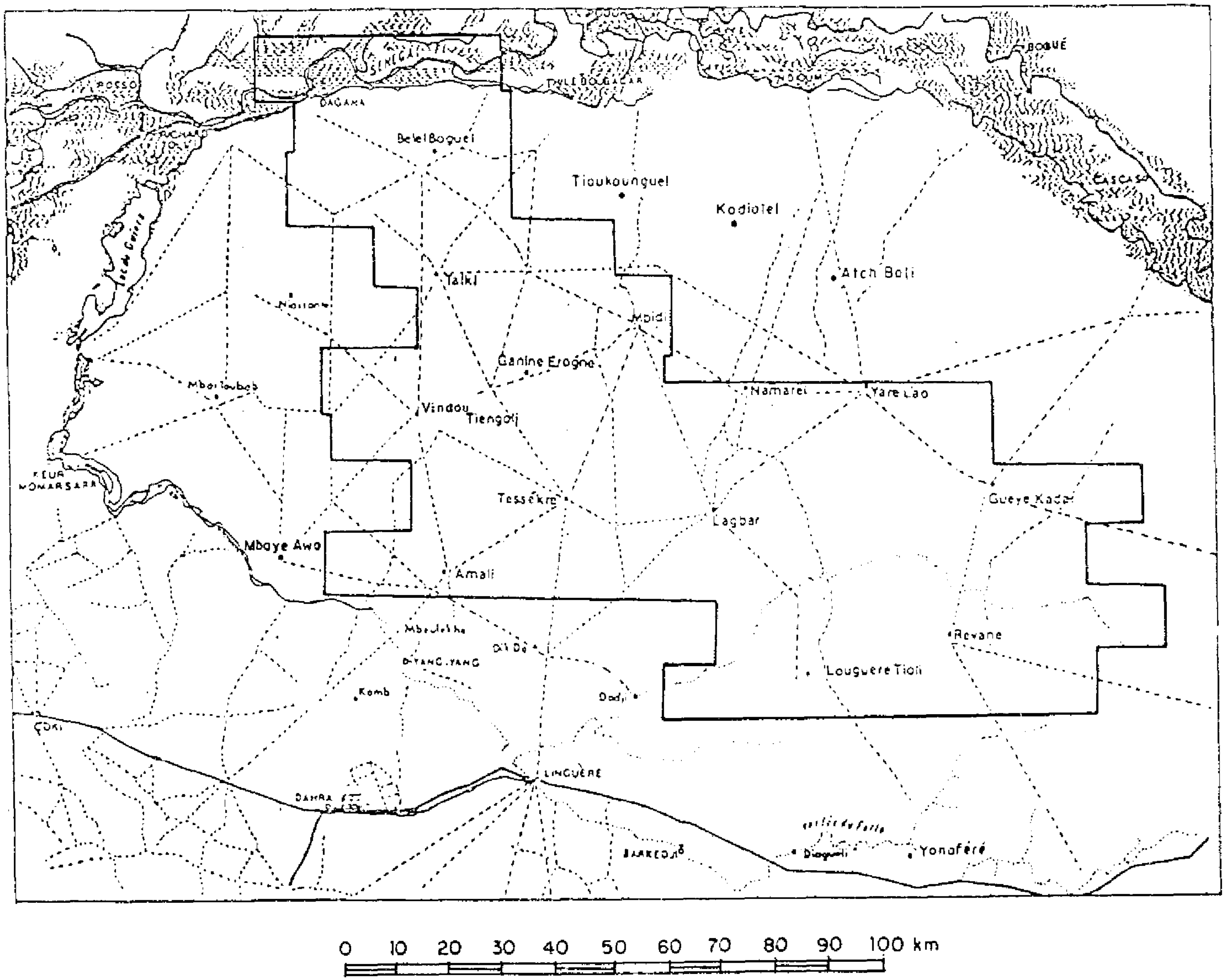


Figure 25

BOREHOLES IN THE NORTH FERLO AND THEIR AREAS OF DEPENDENCY
(Vanpraet, 1985)

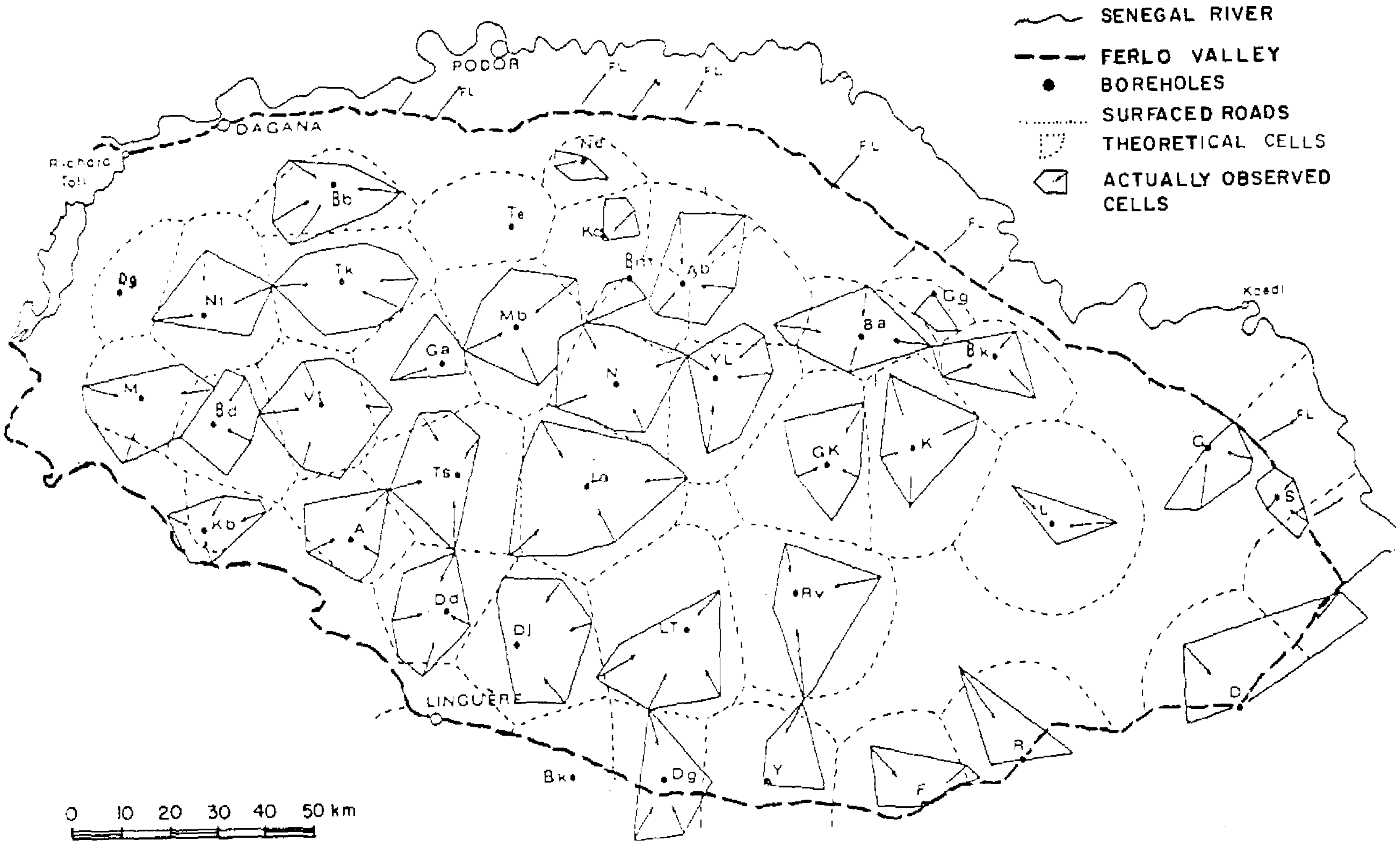


Figure 26

BOREHOLES AND THEIR AREAS OF DEPENDENCY IN THE DGRST /GRIZA/ LAT STUDY AREA (Barral, 1982)

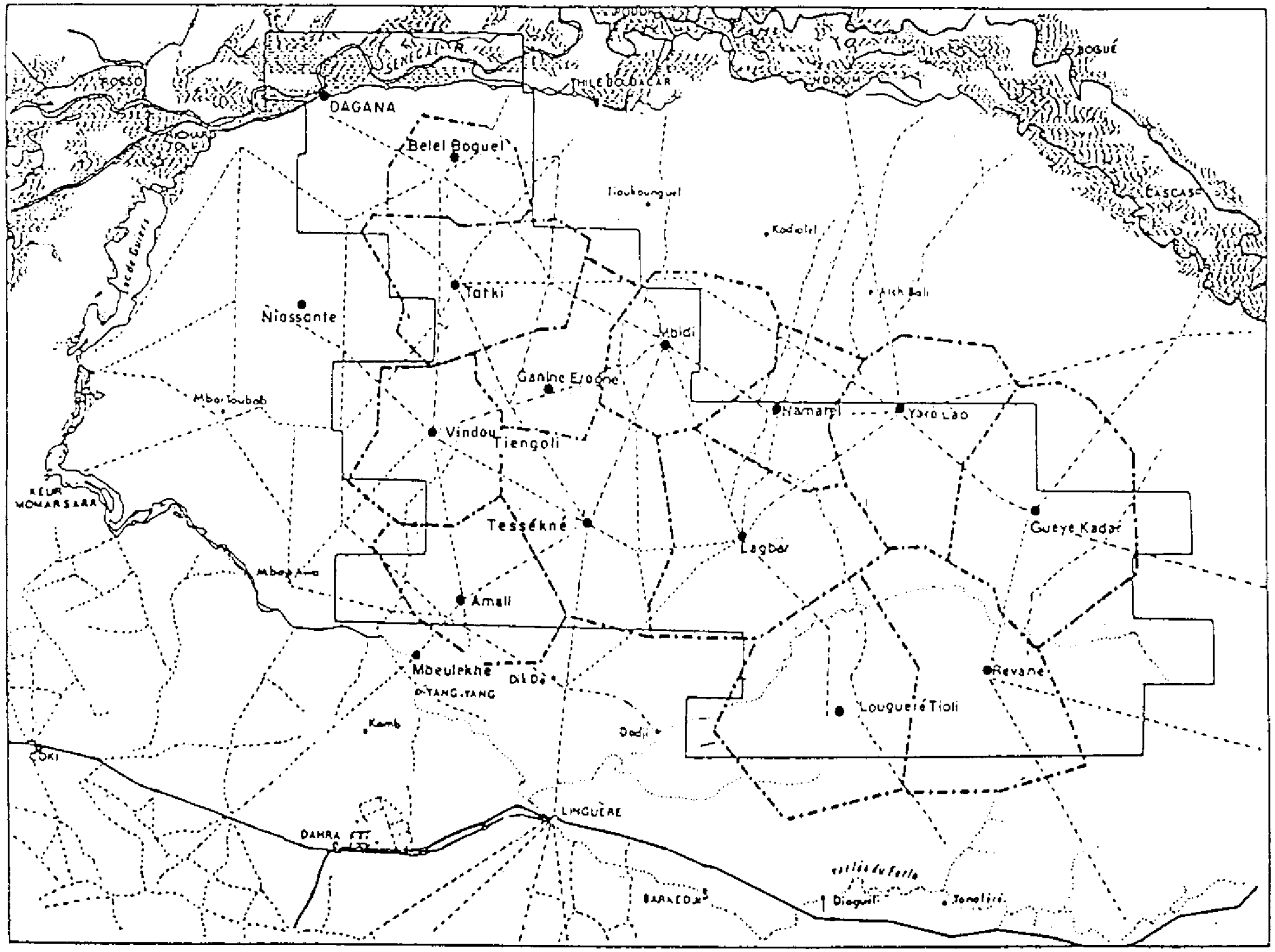


Figure 27

VILLAGES AND CAMPS AND THEIR WATER DEPENDENCY IN THE DGRST/GRIZA/LAT STUDY AREA (BARRAL, 1982)

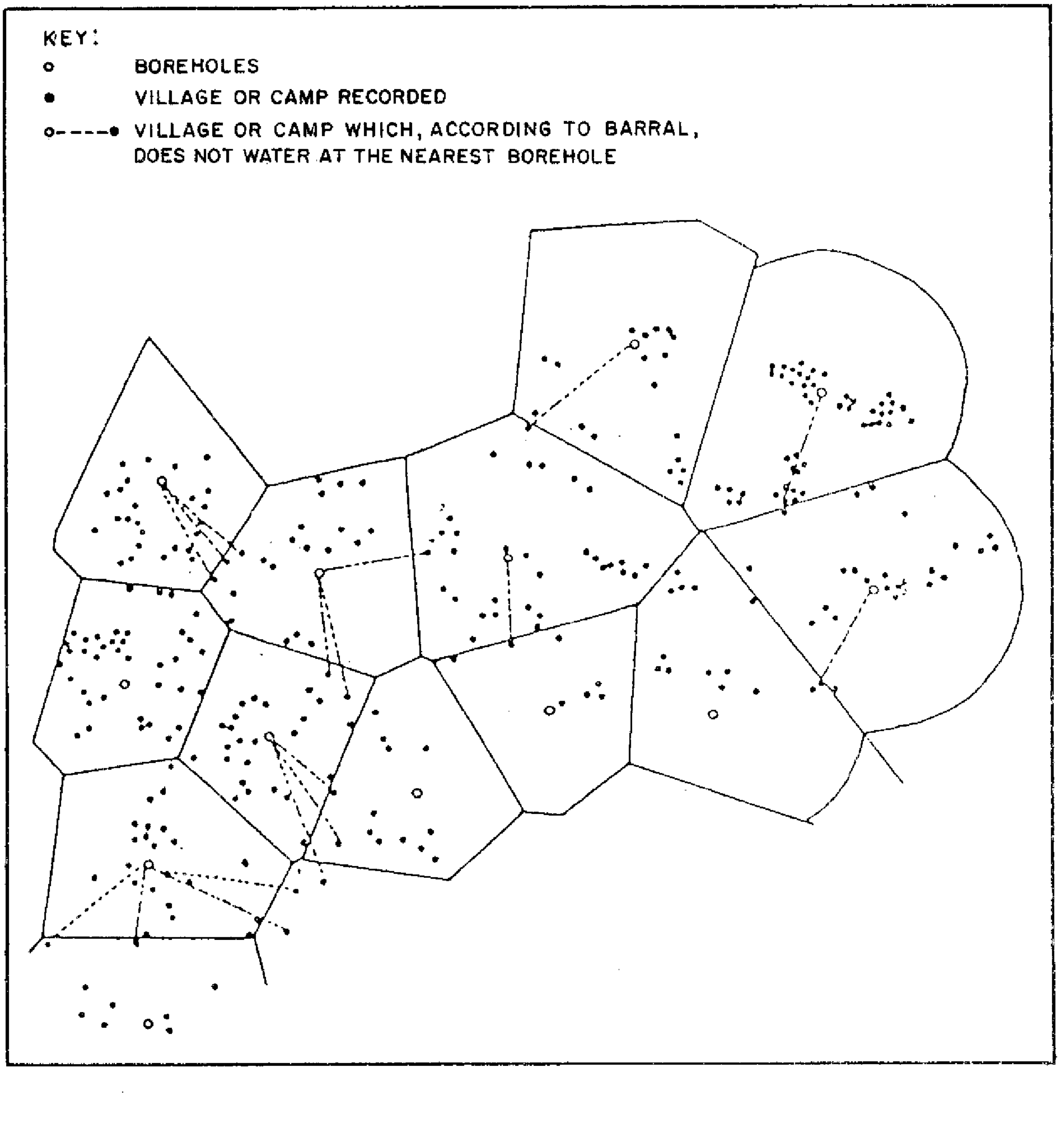


Figure 28

TRANSHUMANCE ROUTES BEFORE THE BOREHOLES
(Bonnet-Dupeyron, 1952; ex Barral, 1982)

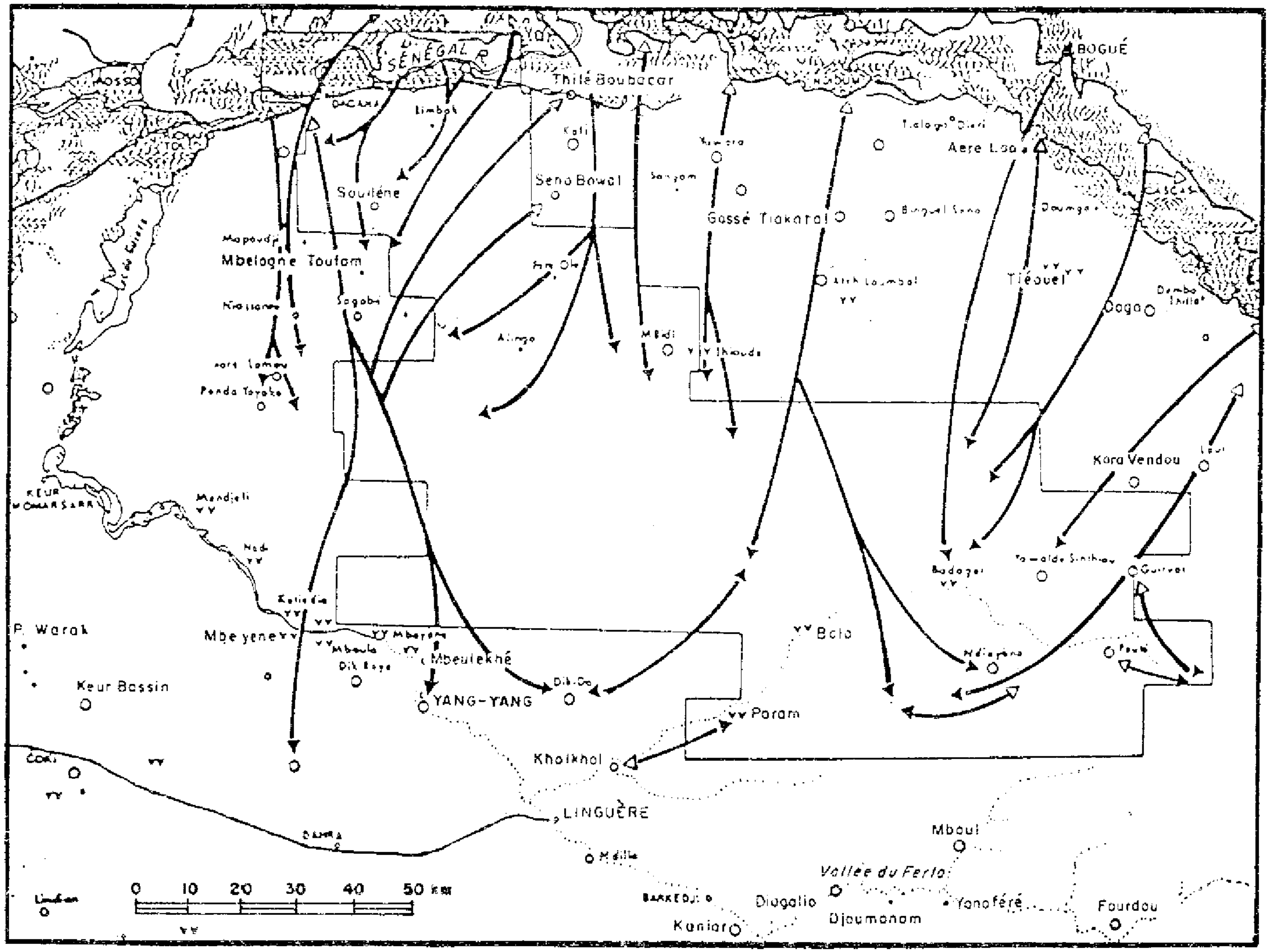


Figure 29

TRANSHUMANCE ROUTES IN 1957 (Granier, 1957; ex Barral, 1982)

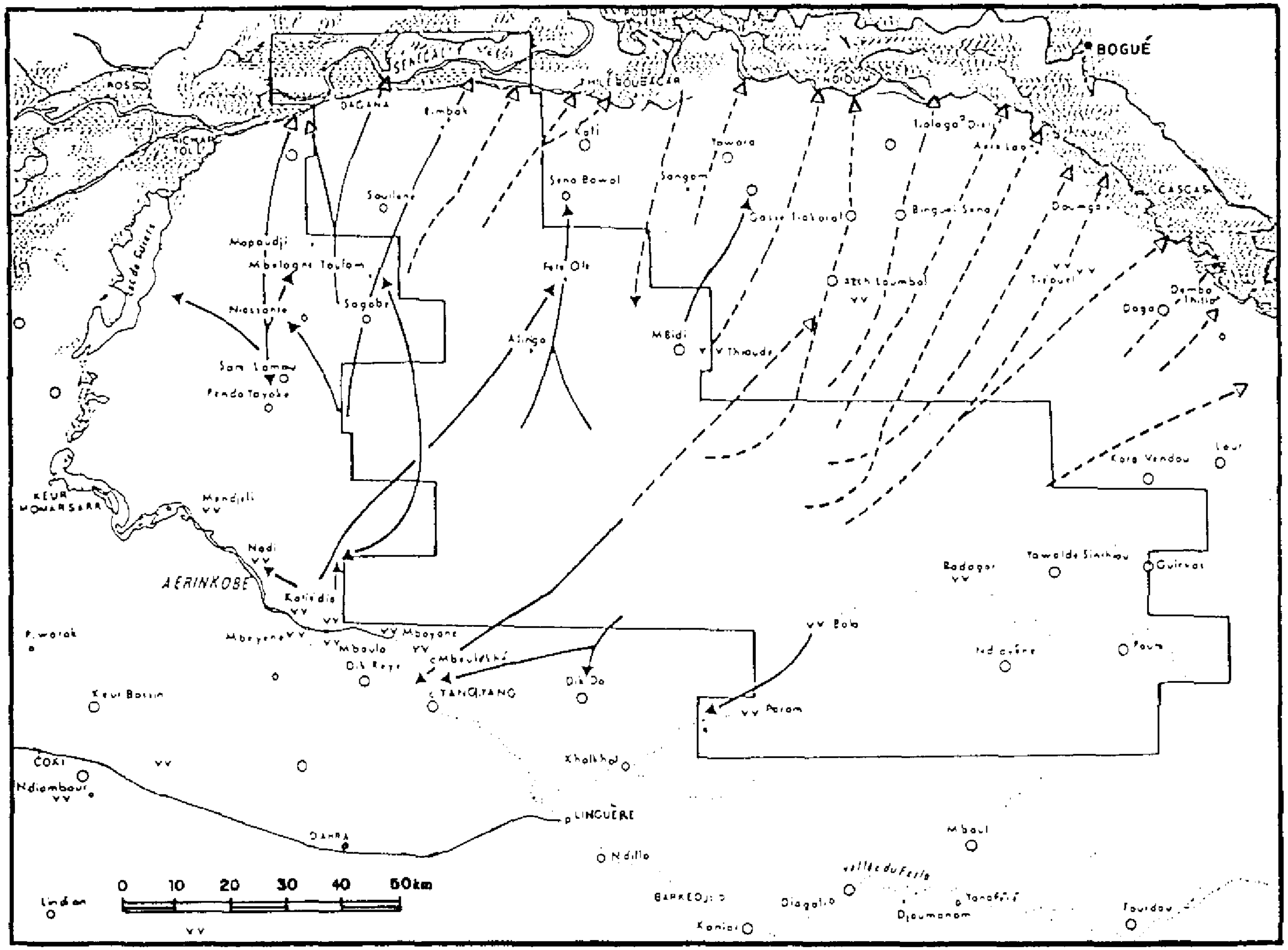


Figure 30

COMPARISON OF WAVELENGTHS BETWEEN VARIOUS ORBITAL SENSORS
(Tucker *et al.*, 1983)

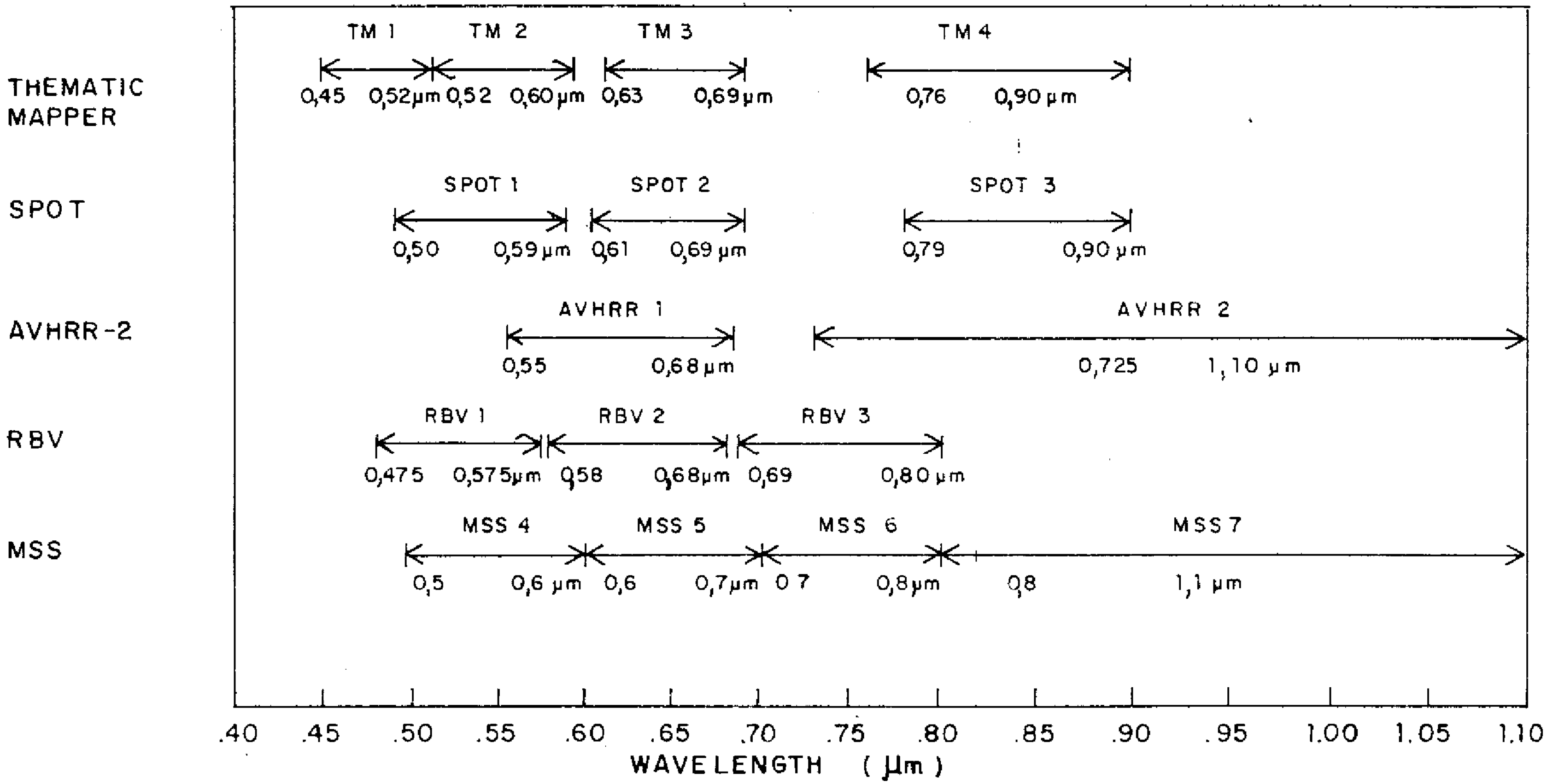


Figure 31

CORRELATIONS BETWEEN GREEN BIOMASS INDVI AND MNDVI
(ex Tucker et al., 1985)

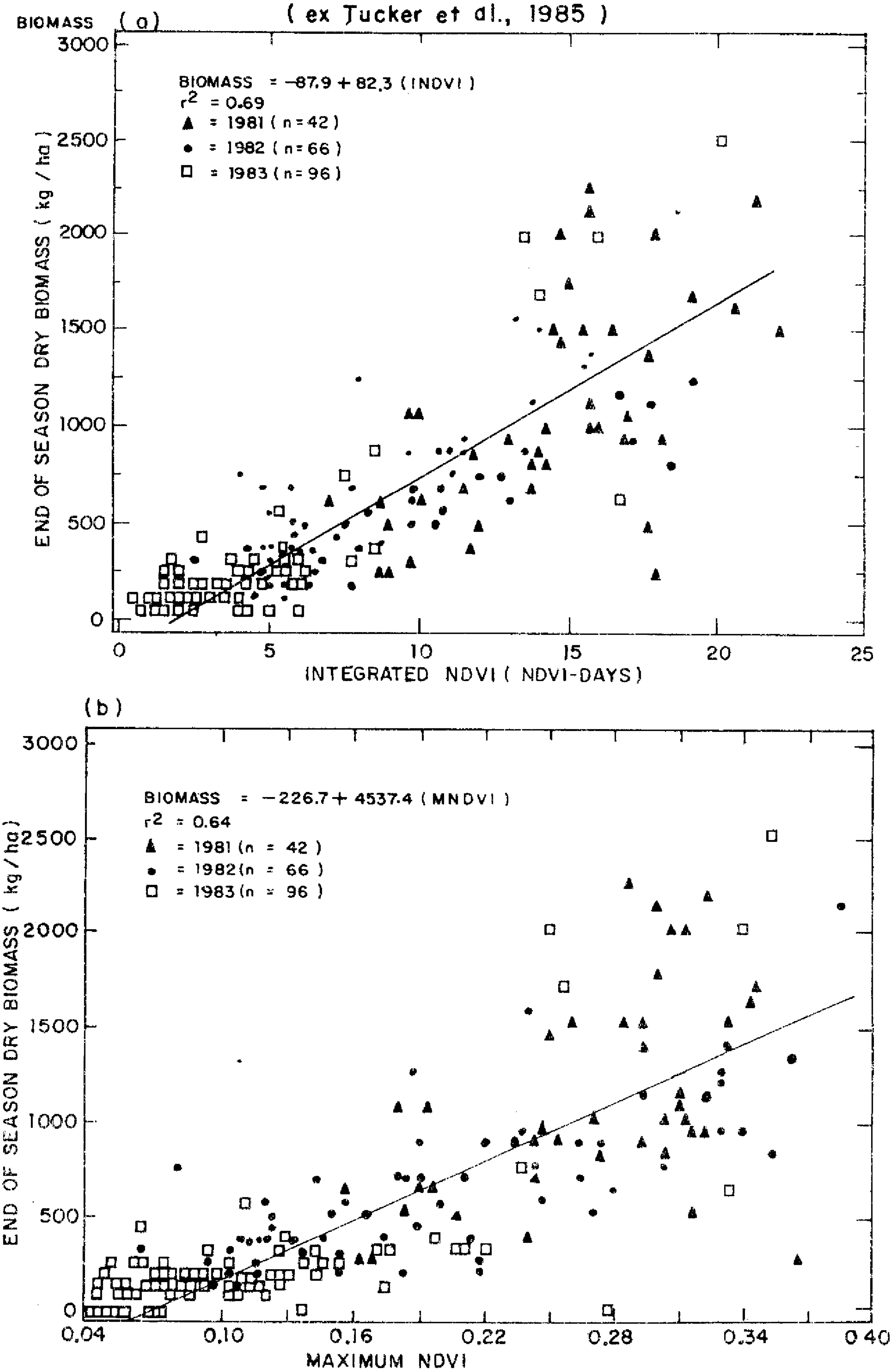
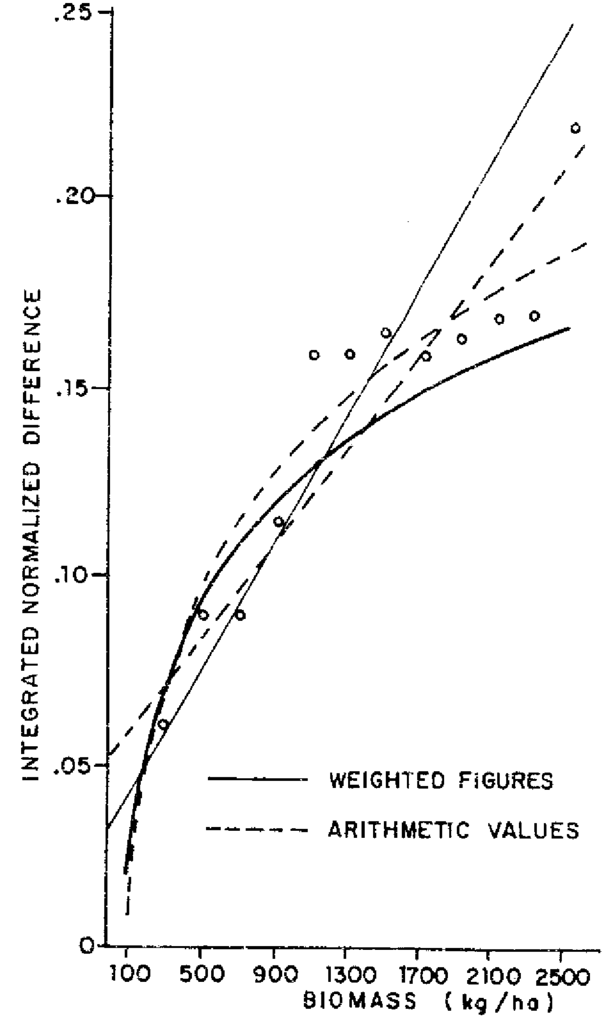


Figure 32

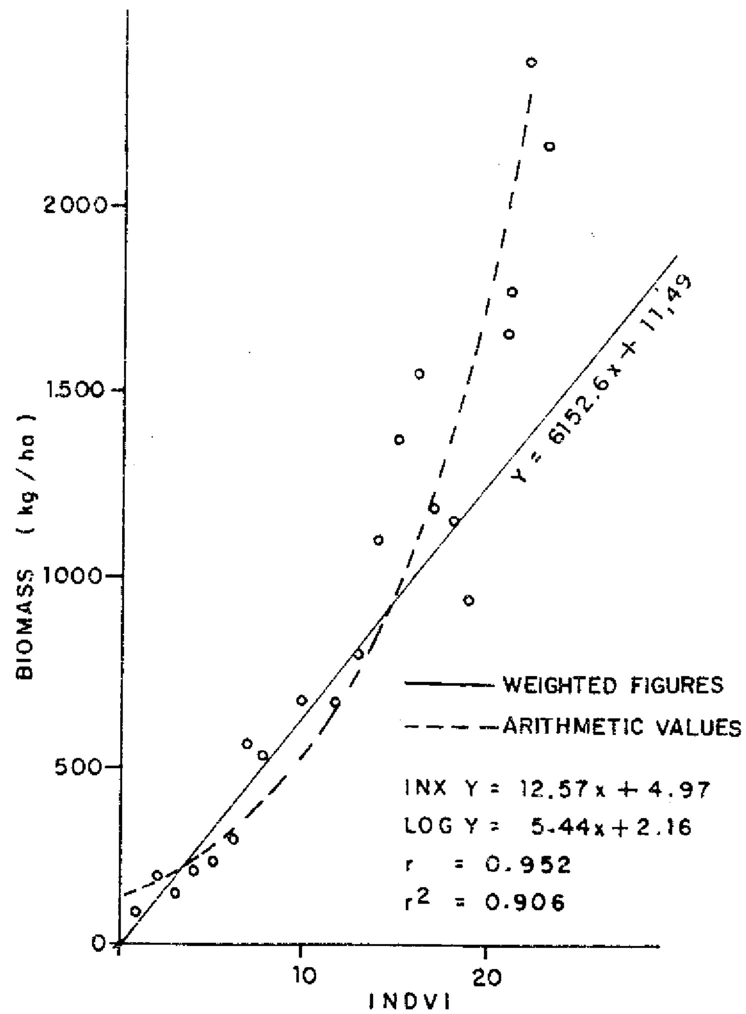
RELATIONSHIP BETWEEN INDVI AND BIOMASS
1980-83 (Vanpraet *et al.*, 1983)



Each dot is the median value of INDVI for a given class of biomass, all years taken together 1980 -83

Figure 33

RELATIONSHIP BETWEEN BIOMASS AND INDVI
1980 - 83 (Vanpraet *et al.*, 1983)



Each dot is the median biomass in a given class of INDVI, all years taken together 1980-83

Figure 34

RELATIONSHIP BETWEEN INDVI AND BIOMASS
OVER FOUR YEARS, NON-WEIGHTED FIGURES

(Vanpraet et al, 1983)

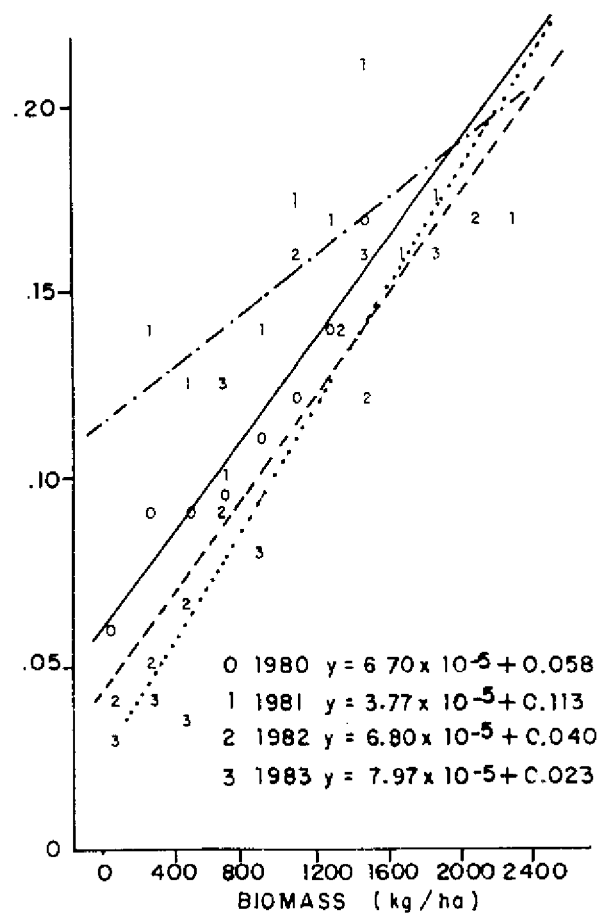
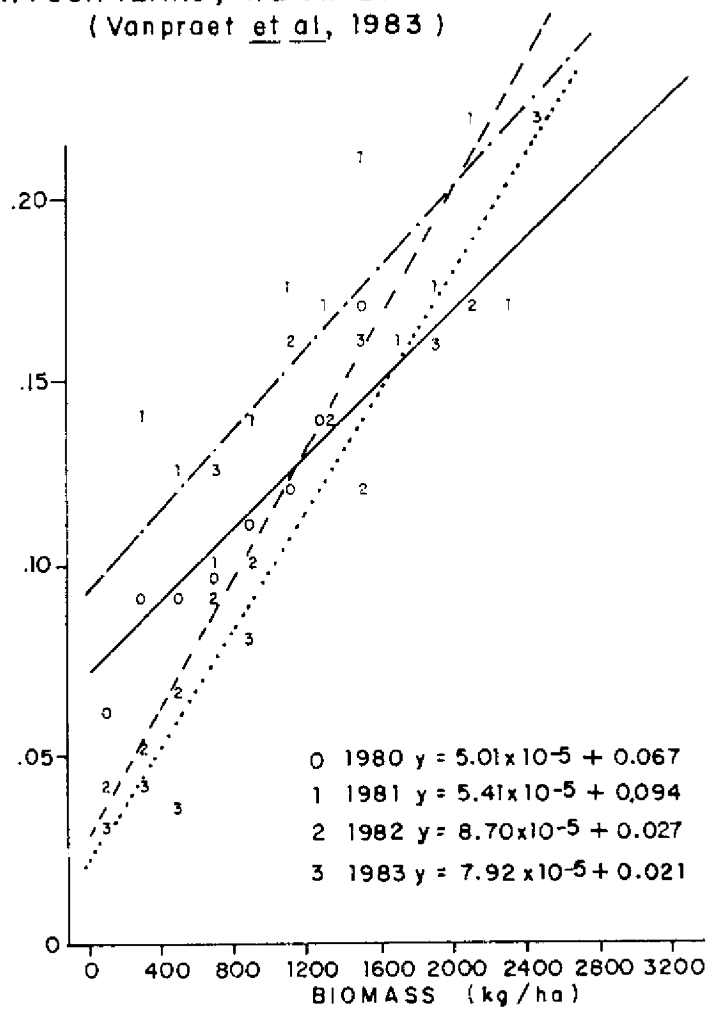


Figure 35

RELATIONSHIP BETWEEN INDVI AND BIOMASS
OVER FOUR YEARS, WEIGHTED FIGURES
(Vanpraet et al, 1983)



——— 1980 —·—·—·— 1981 – – – – – – 1982 1983

EACH DOT IS THE MEDIAN VALUE OF INDVI FOR EACH CLASS OF BIOMASS VALUES PER ANNUM.

Figure 36

THEORETICAL MEAN OF NORMALIZED DIFFERENCE INDICES WITH HAND-HELD RADIOMETER ACCORDING TO LINEAR AND LOGARITHMIC MODELS, FOR GRASSES AND LEGUMES

(VANPRAET *et al.*, 1983)

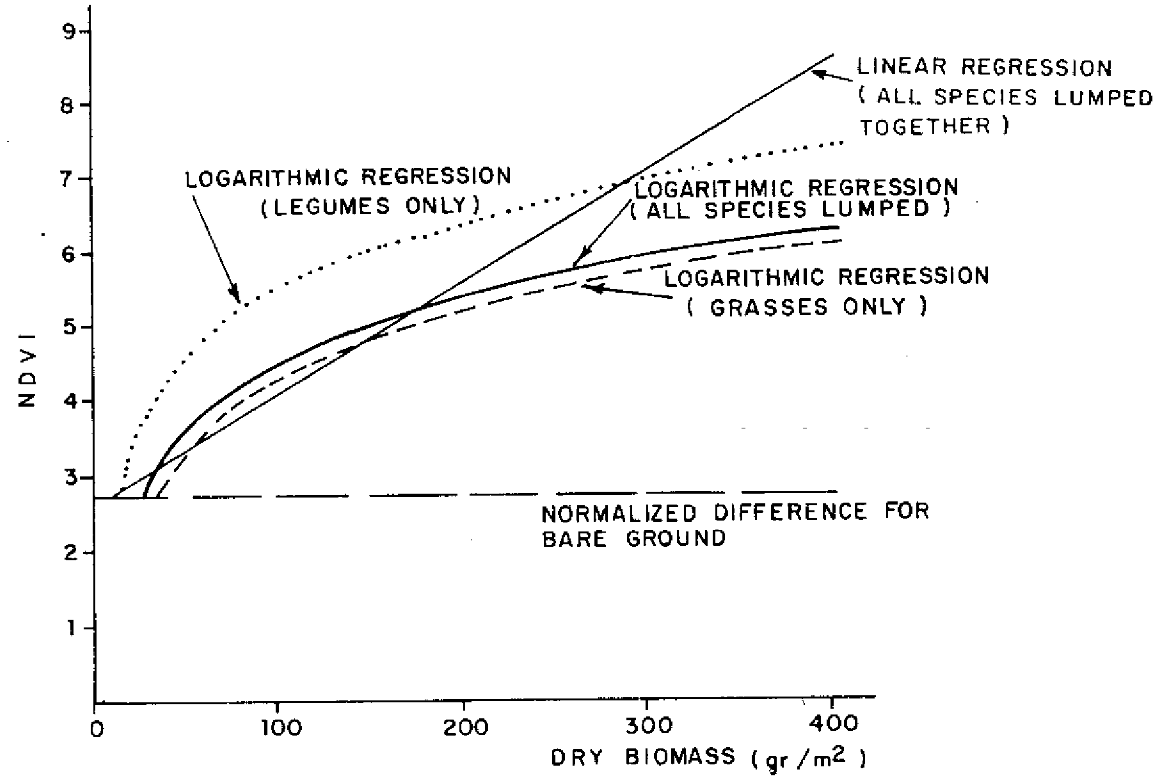


Figure 37

NORTH-SOUTH PROFILE OF NDVI AND BIOMASS BETWEEN THILLÉ BOUBACAR AND LINGUÈRE (112 LAC PIXELS)

(VANPRAET *et al.*, 1983)

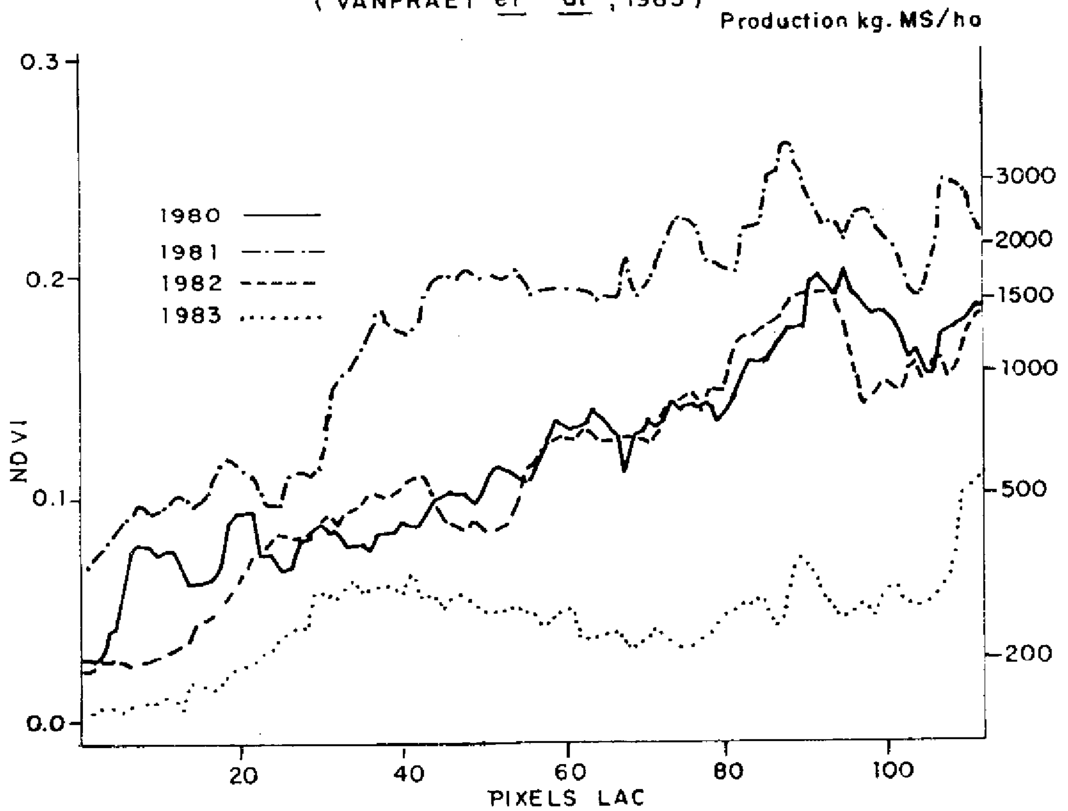


Figure 38

RELATIONSHIP BETWEEN GREEN BIOMASS PRODUCTION AND SEASONAL RAINFALL IN THE PROJECT AREA AS MEASURED IN 22 WEATHER STATIONS (●) FROM 1980 TO 1983
(Tucker *et al.*, 1985; Vanpraet *et al.*, 1983)

SEE ALSO TABLE 19

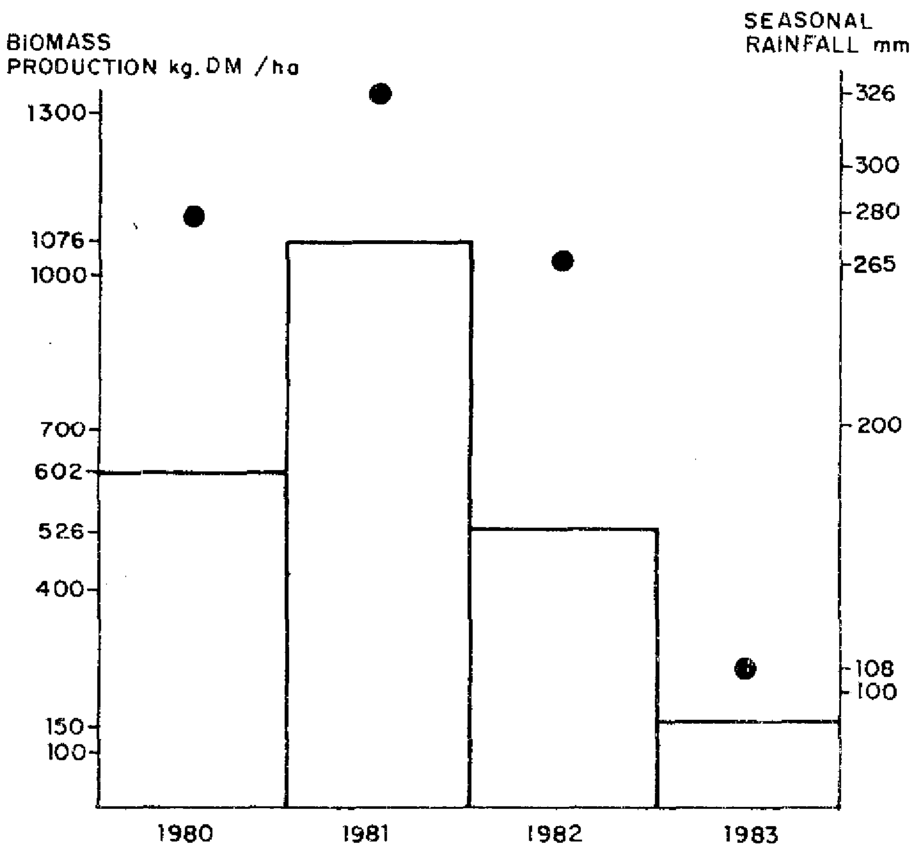


Figure 39

GROUND VALIDATION SITES FOR NOAA/AVHRR 6 AND 7 DATA
(Tucker *et al*, 1983)

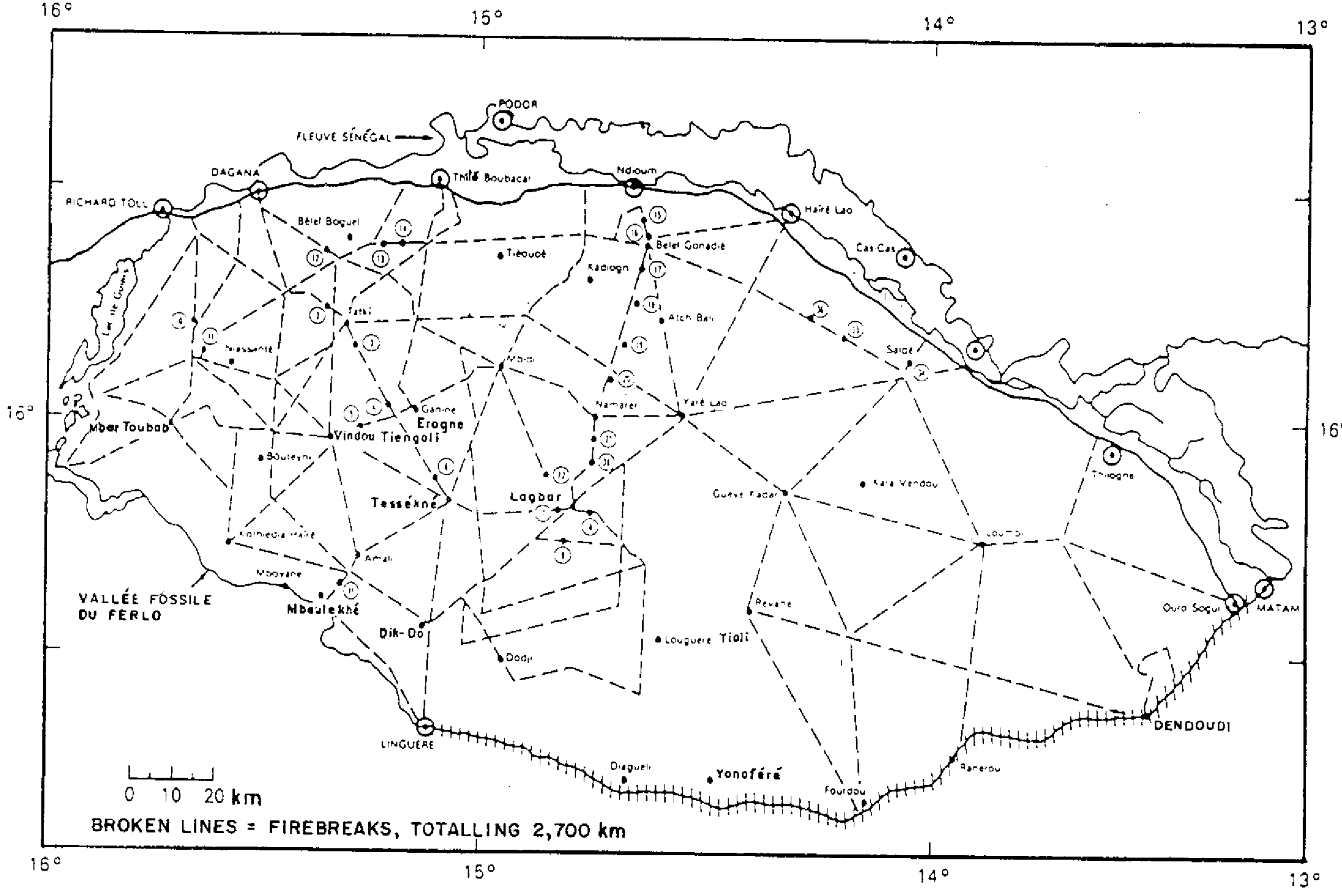


Figure 40

RELATIONSHIP BETWEEN NDVI AND GREEN HERBACEOUS BIOMASS, ALL SPECIES AND ALL YEARS POOLED TOGETHER (*Aristida mutabilis*, *Chloris prieurii*, *Schoenefeldia gracilis* and *Zornia glochidiata*) 1981-83 (Sharman and Vanpraet, 1983)

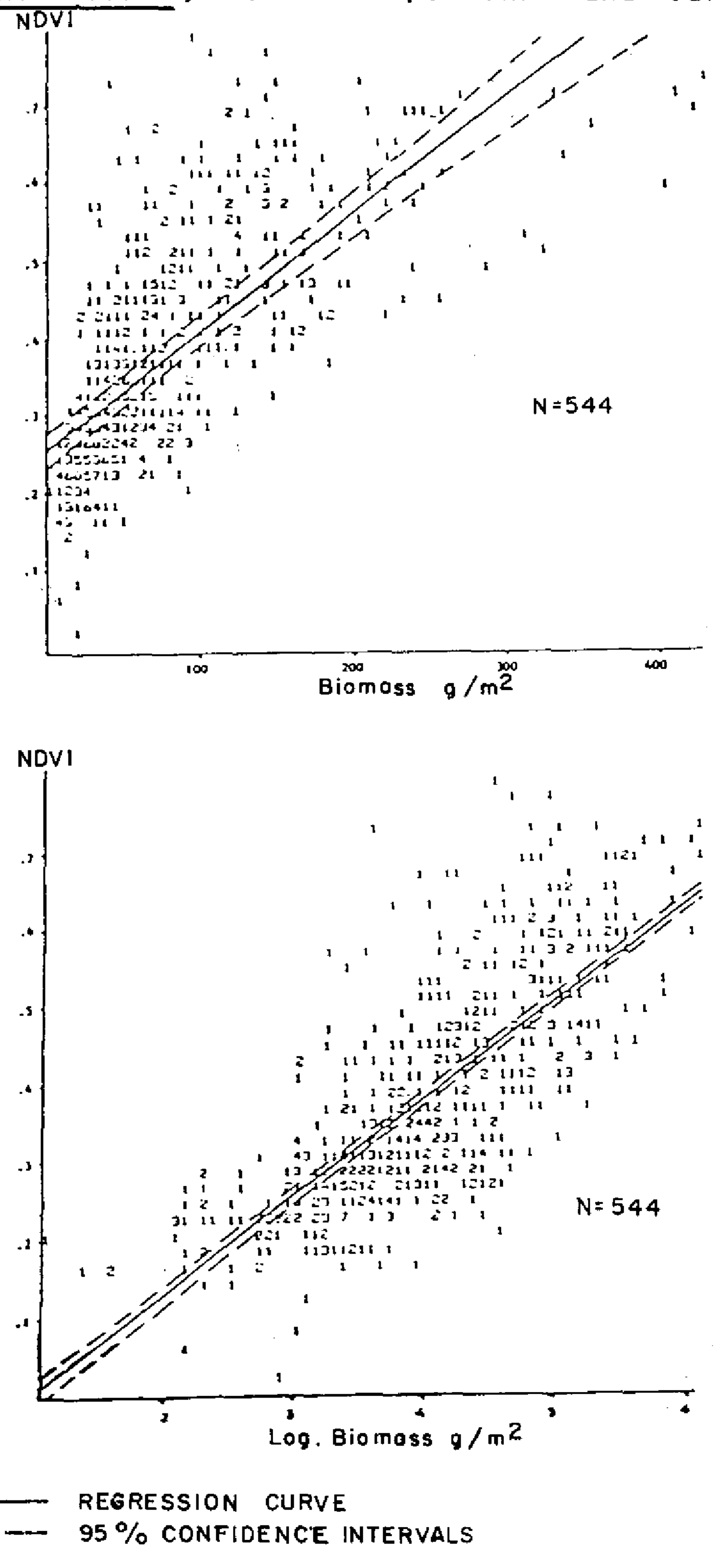


Figure 41

RELATIONSHIP BETWEEN BIOMASS AND NDVI AS MEASURED WITH HAND-HELD RADIOMETER, ALL YEARS POOLED TOGETHER (1981-83) (SHARMAN AND VANPRAET, 1983)

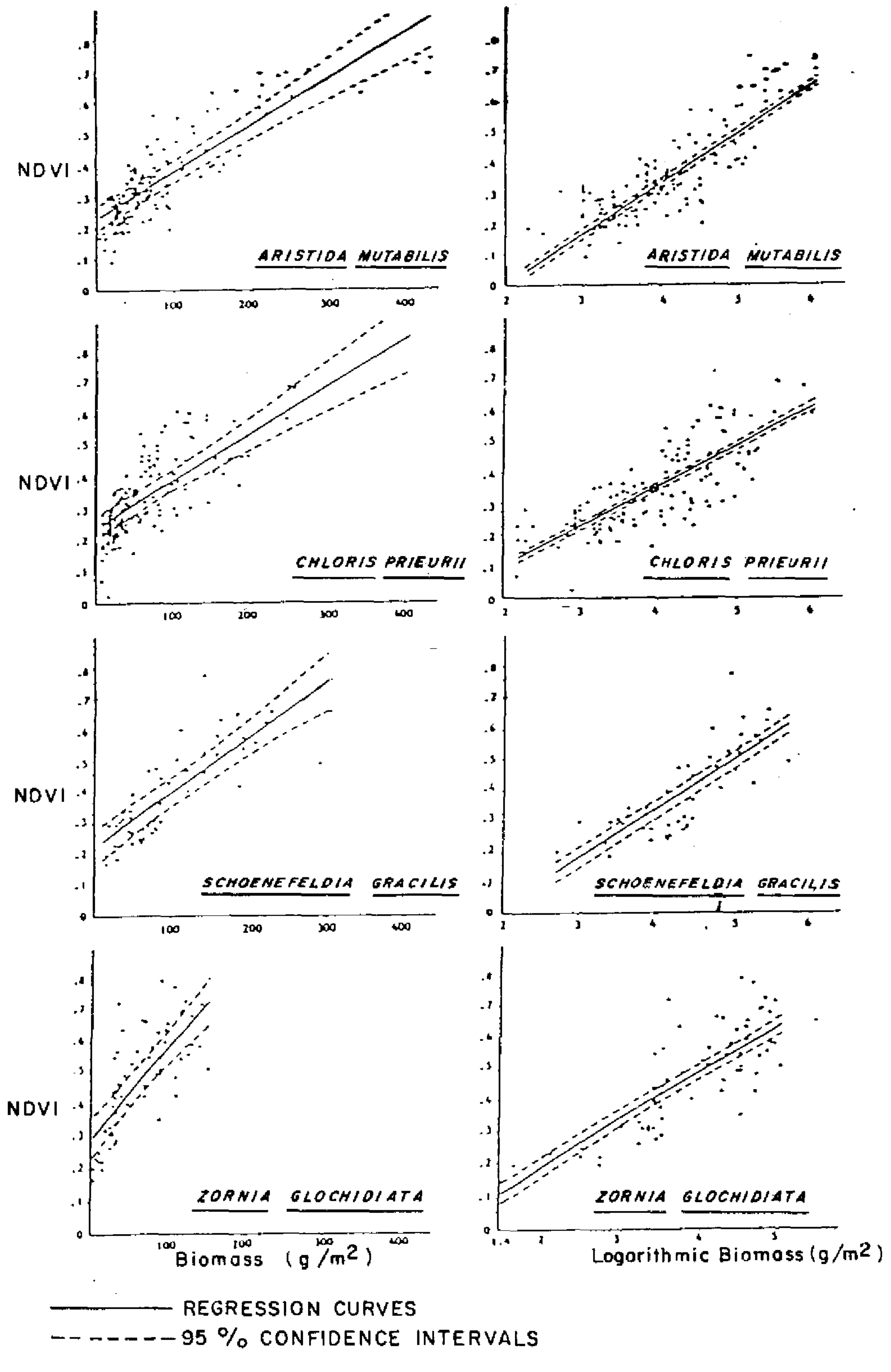


Figure 42

RELATIONSHIPS BETWEEN NDVI AND BIOMASS FOR TWO DOMINANT SPECIES OF ANNUAL GRASSES (1981) (SHARMAN AND VANPRAET, 1983)

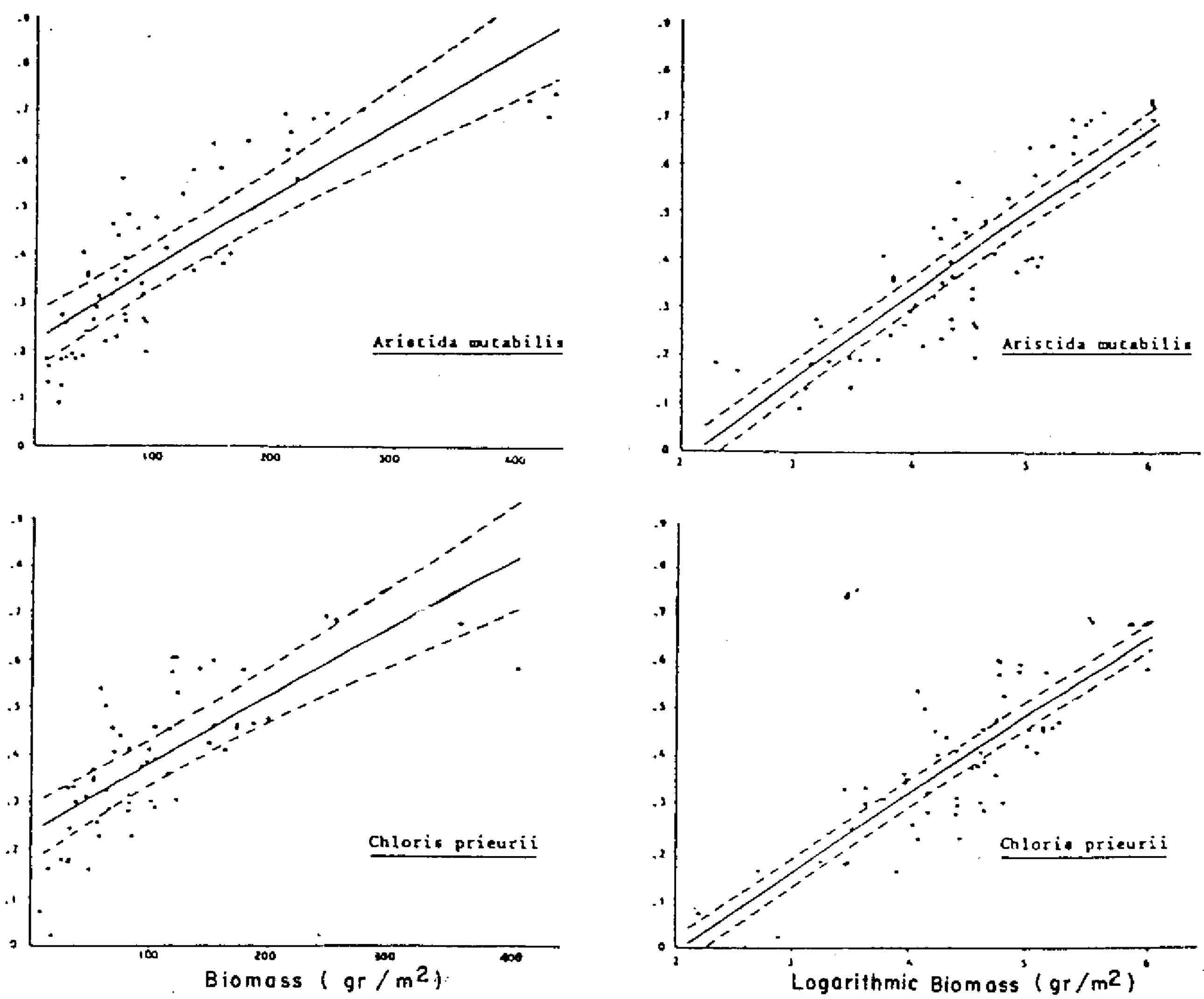


Figure 43

RELATIONSHIP BETWEEN BIOMASS AND CLASS OF NOAA / INDVI COLOURS; MEDIAN VALUES FOR 1980, 1981, 1982 AND 1983 (DASHED PARTS CORRESPOND TO COLOUR CLASSES FOR WHICH THERE WERE NO GROUND VALIDATION DATA) (GASTON et al., 1983)

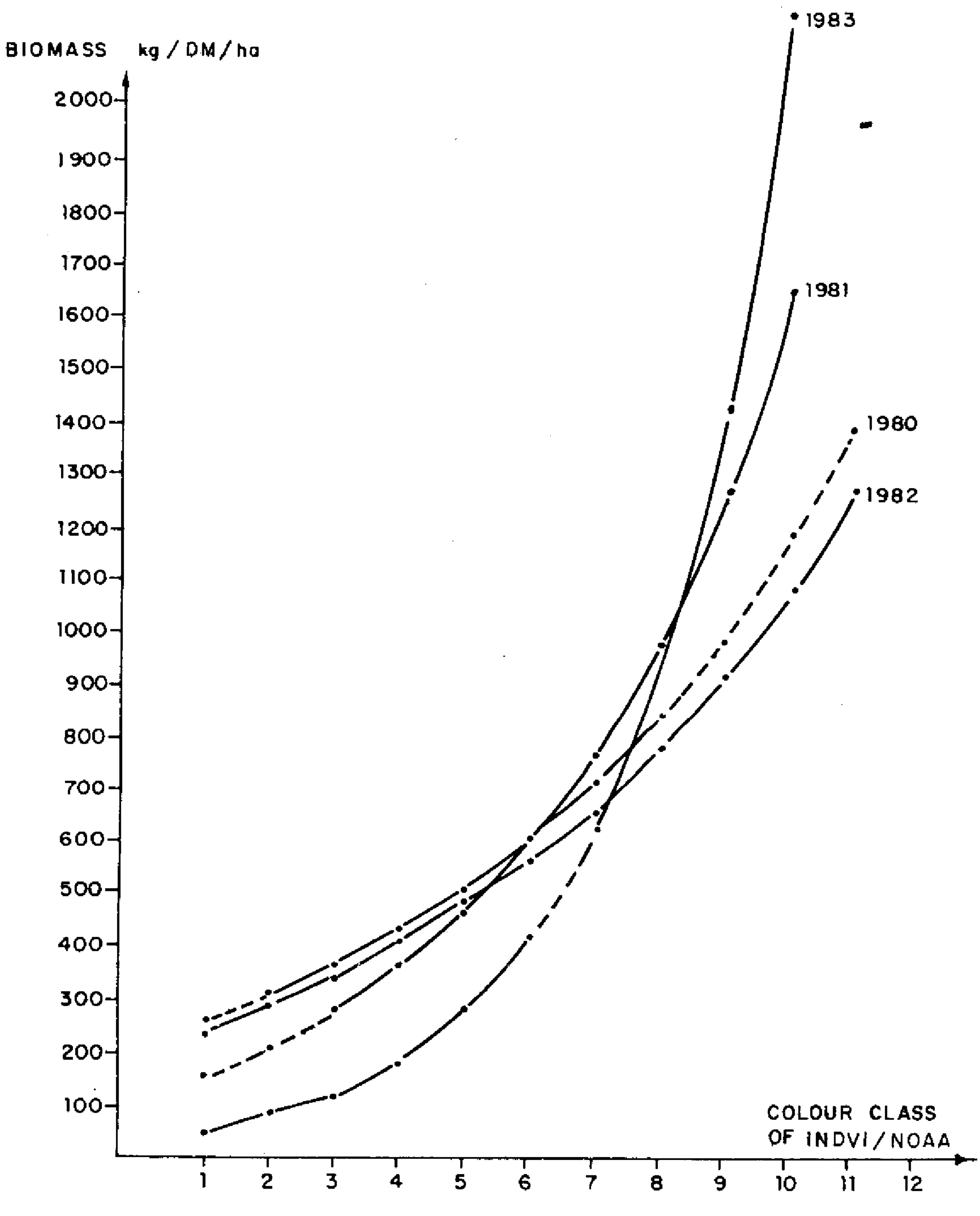


Figure 44

SRF SAMPLING CONTROL DEVICE (SHARMAN, 1982)

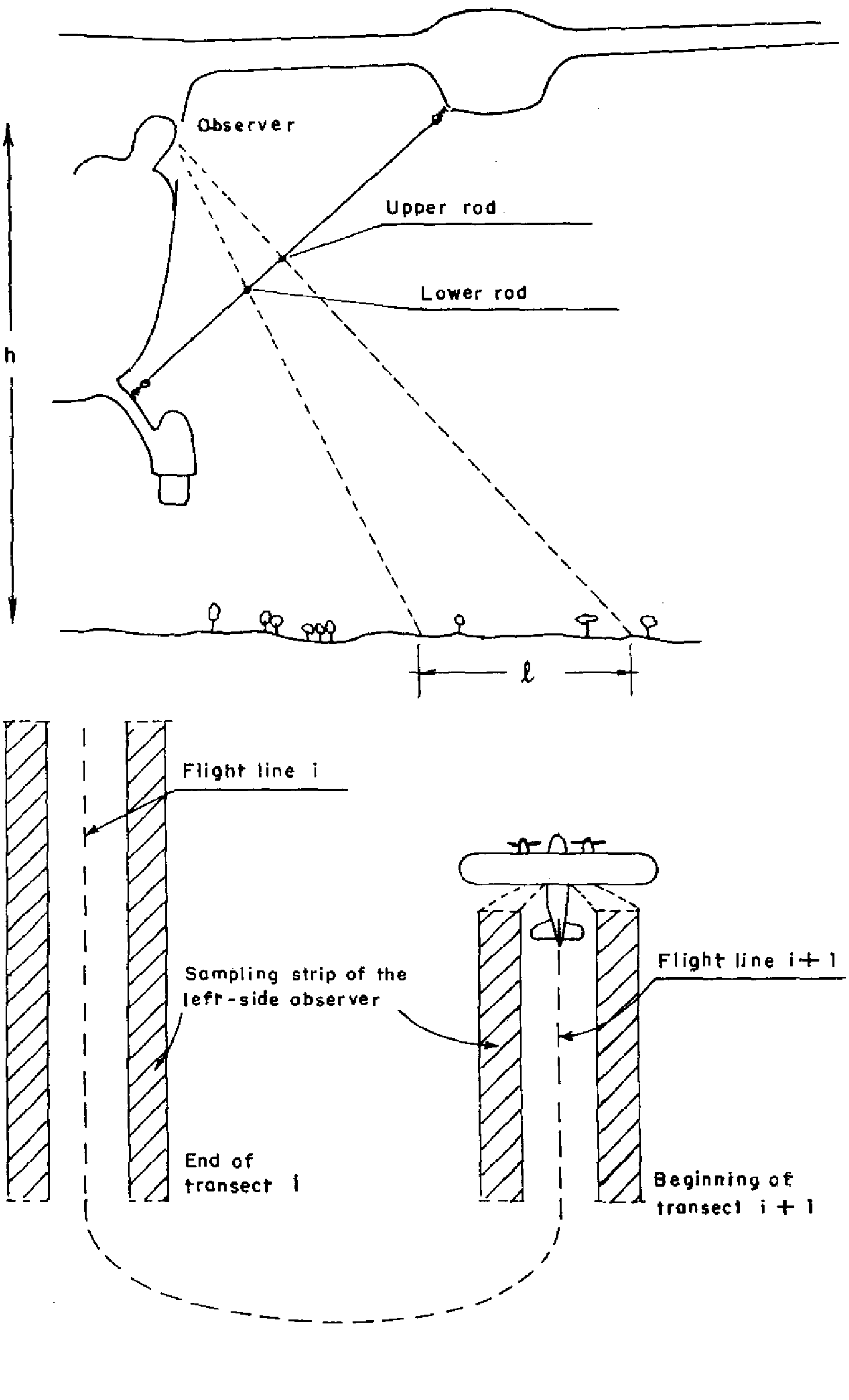


Figure 45

SRF FLIGHT-LINE LAYOUT (SHARMAN, 1982)

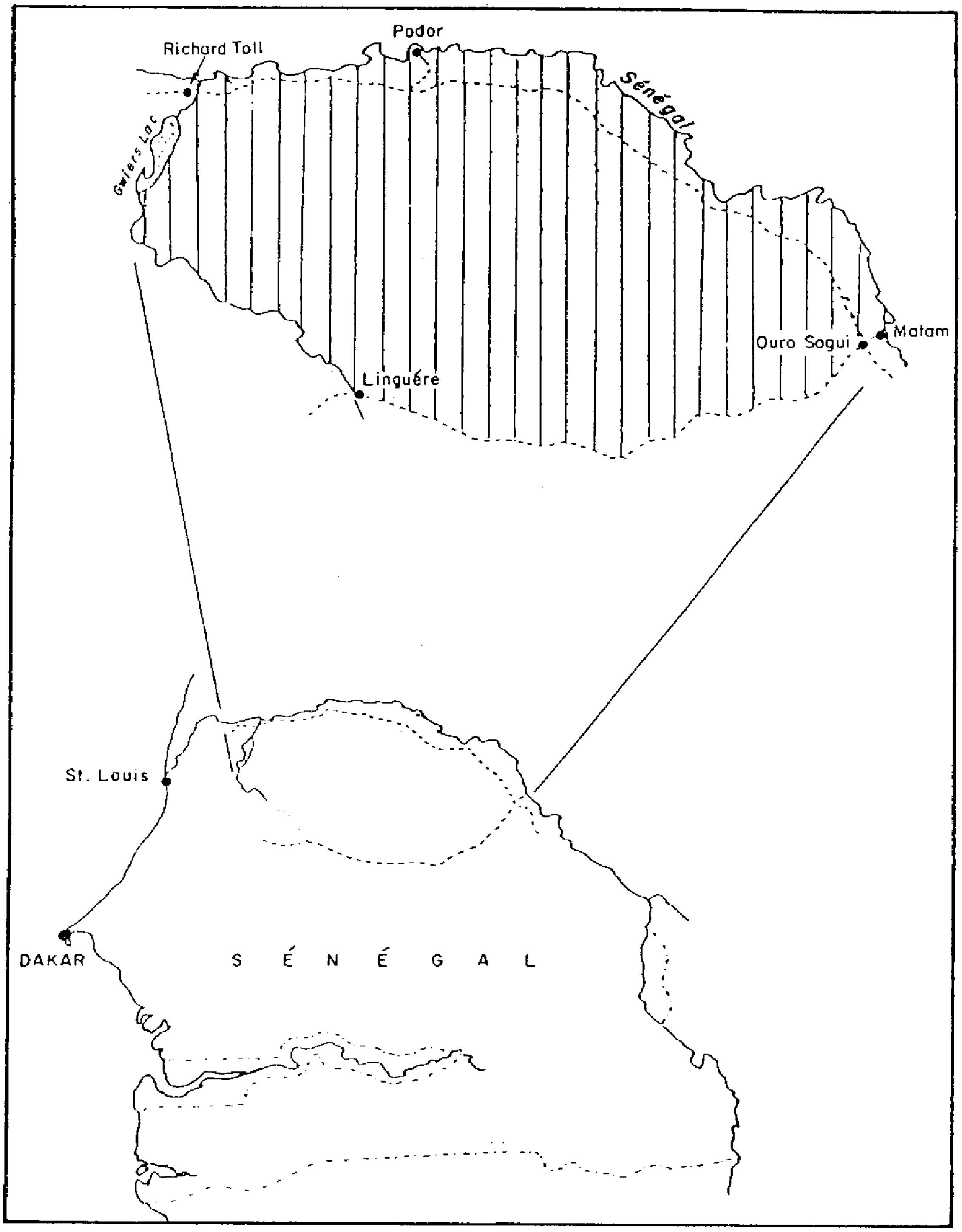


Figure 46

DISTRIBUTION OF CATTLE AND SMALLSTOCK ACCORDING TO SRF DATA, MAY 1983 (SHARMAN, 1983a)

(SHARMAN, 1983a)

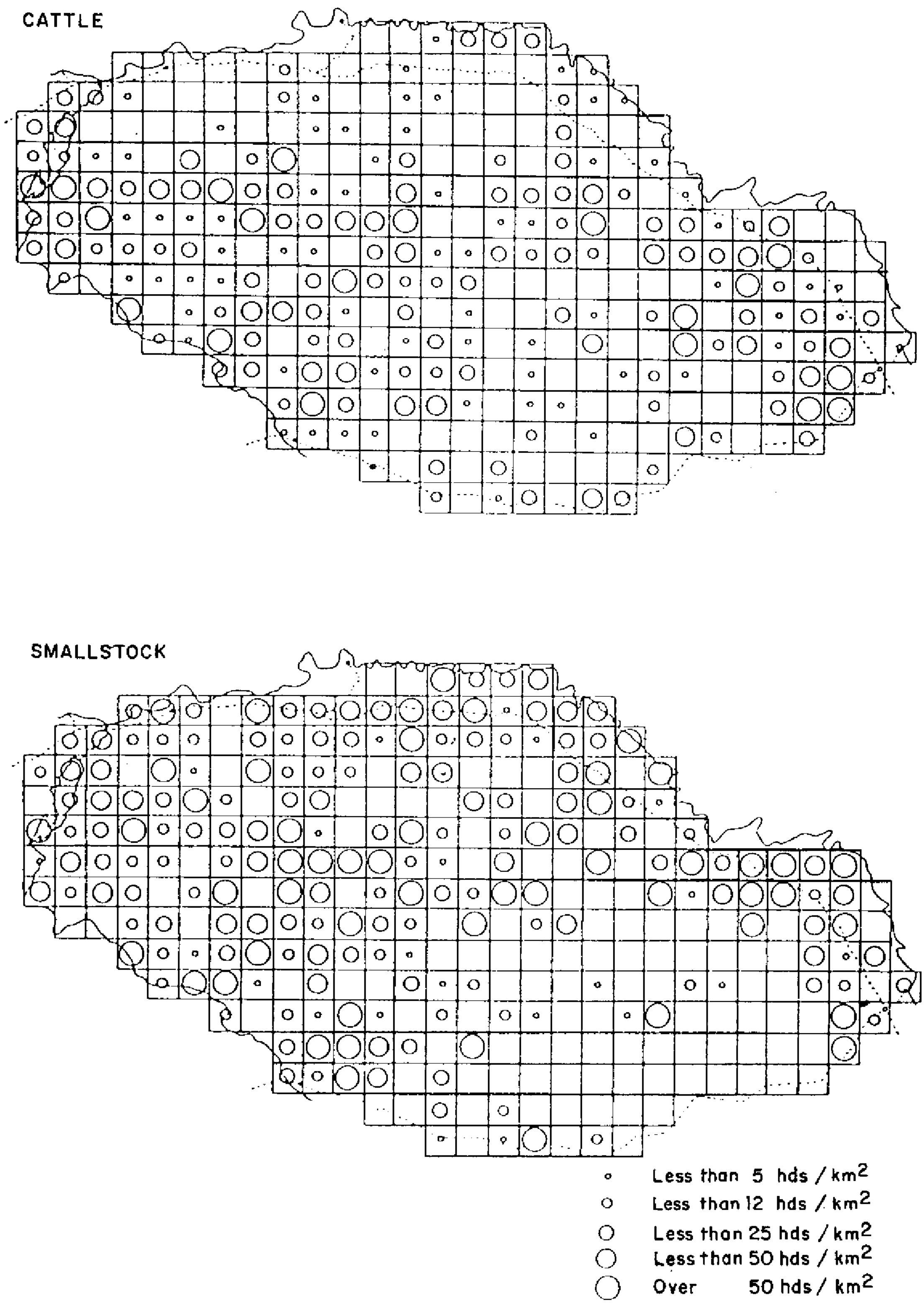


Figure 47

DISTRIBUTION OF CATTLE AND SMALLSTOCK ACCORDING TO SRF DATA, OF MAY 1983
EXPRESSED IN TLU (SHARMAN, 1983 a)

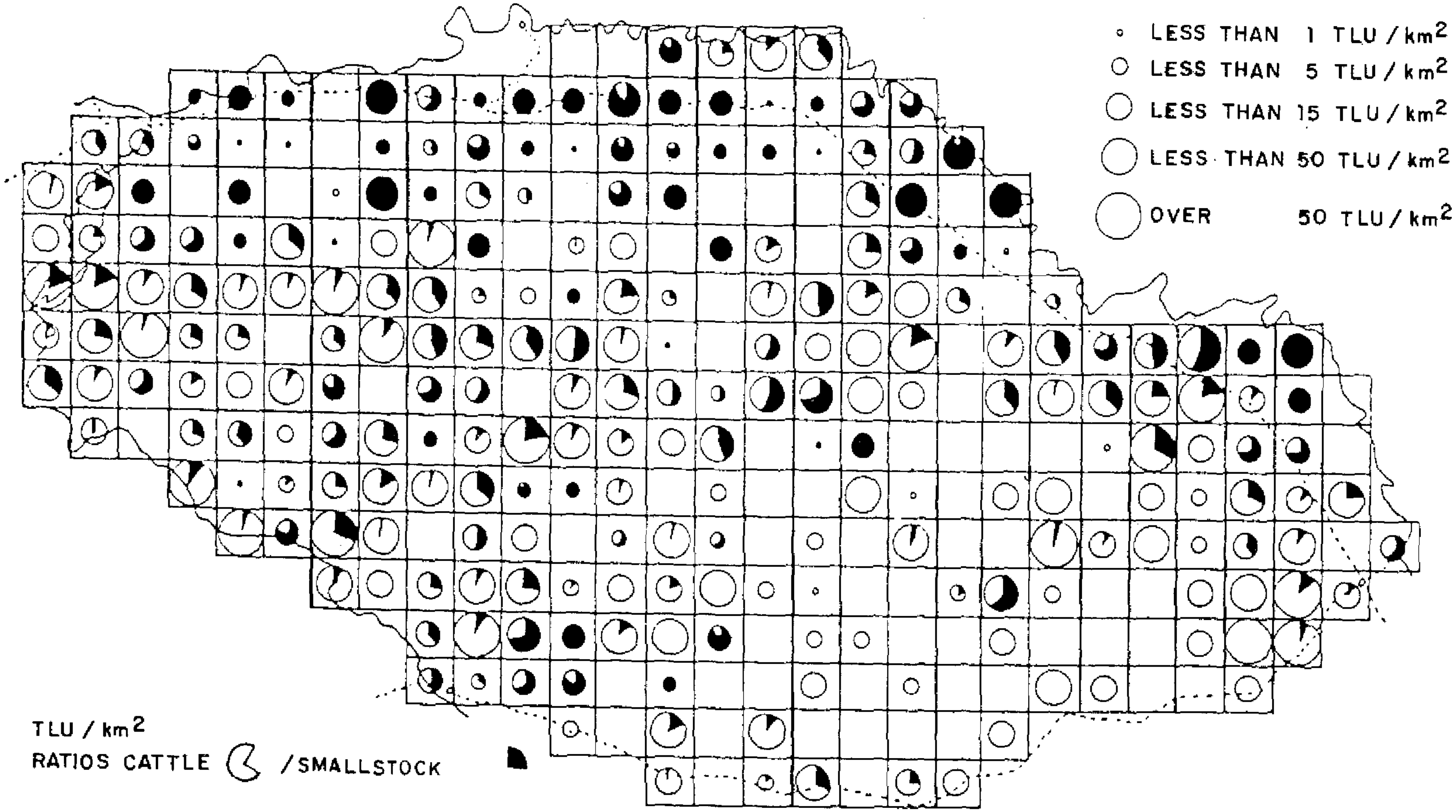


Figure 48

COMPARISON OF DISTRIBUTION OF CATTLE ACCORDING TO THREE SRFs IN 1980, 1981 AND 1982 (SHARMAN, 1983a)

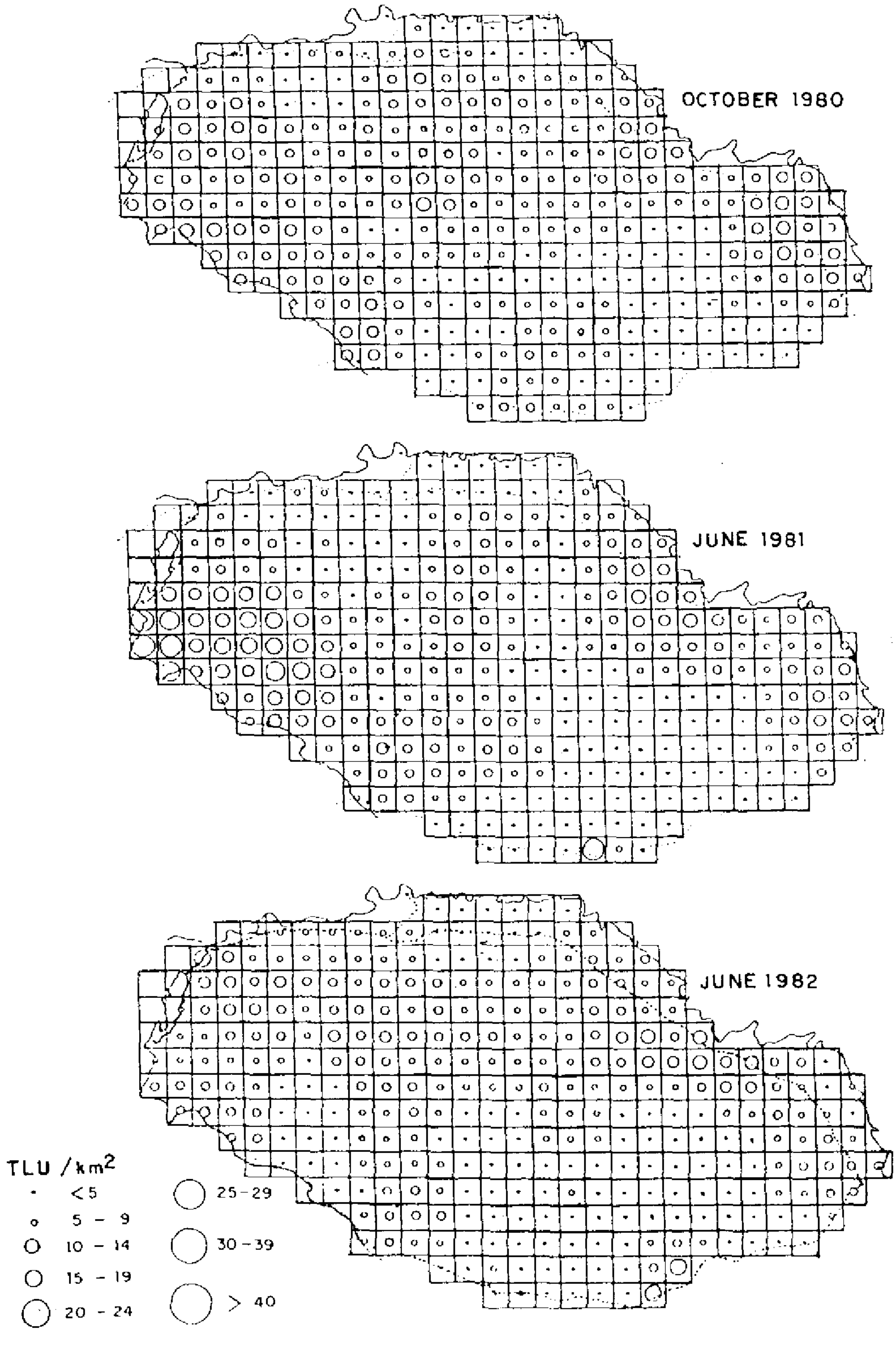


Figure 49

COMPARISON OF DISTRIBUTION OF SMALLSTOCK ACCORDING TO THREE SRFs IN 1980, 1981 AND 1982 (SHARMAN, 1983a)

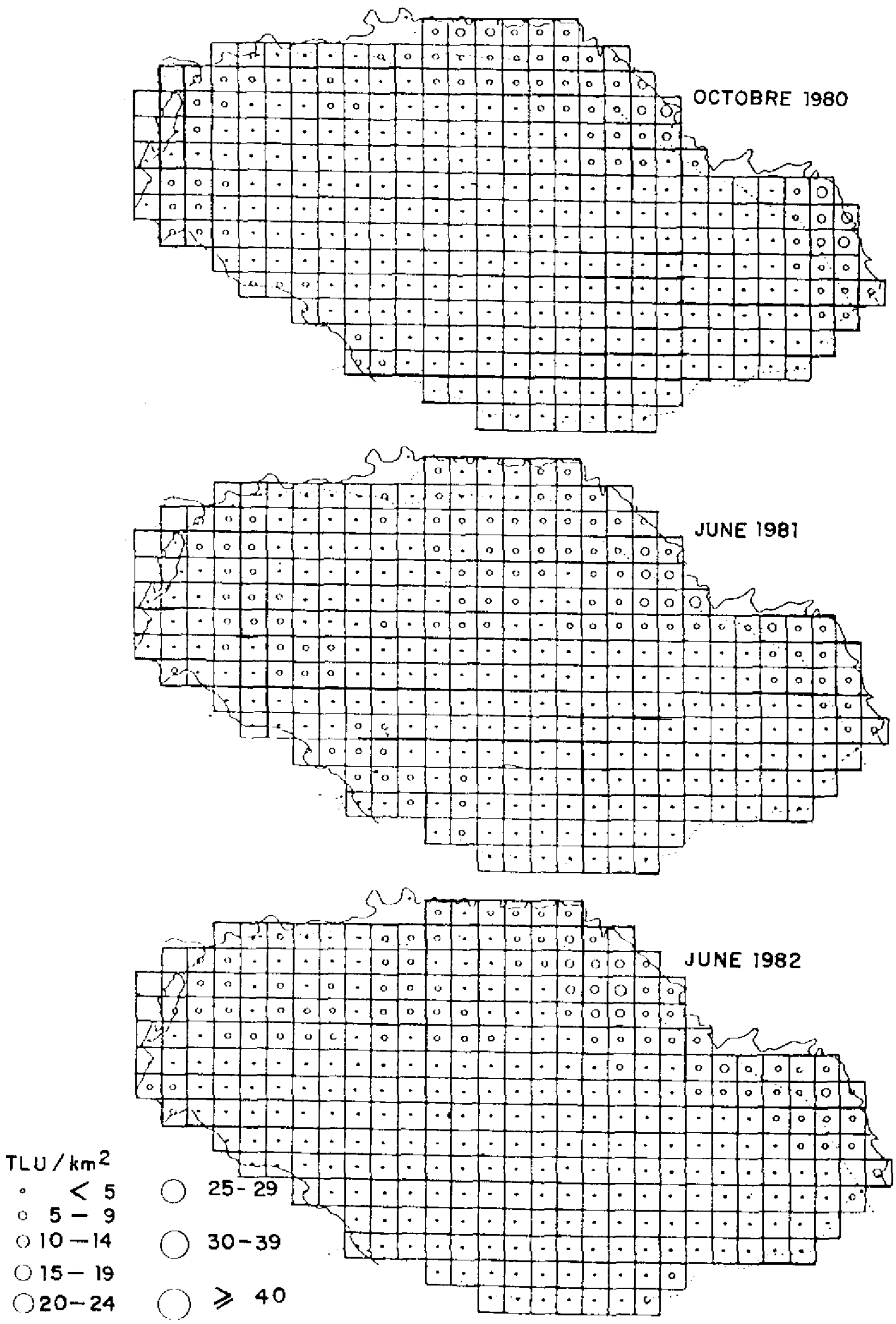
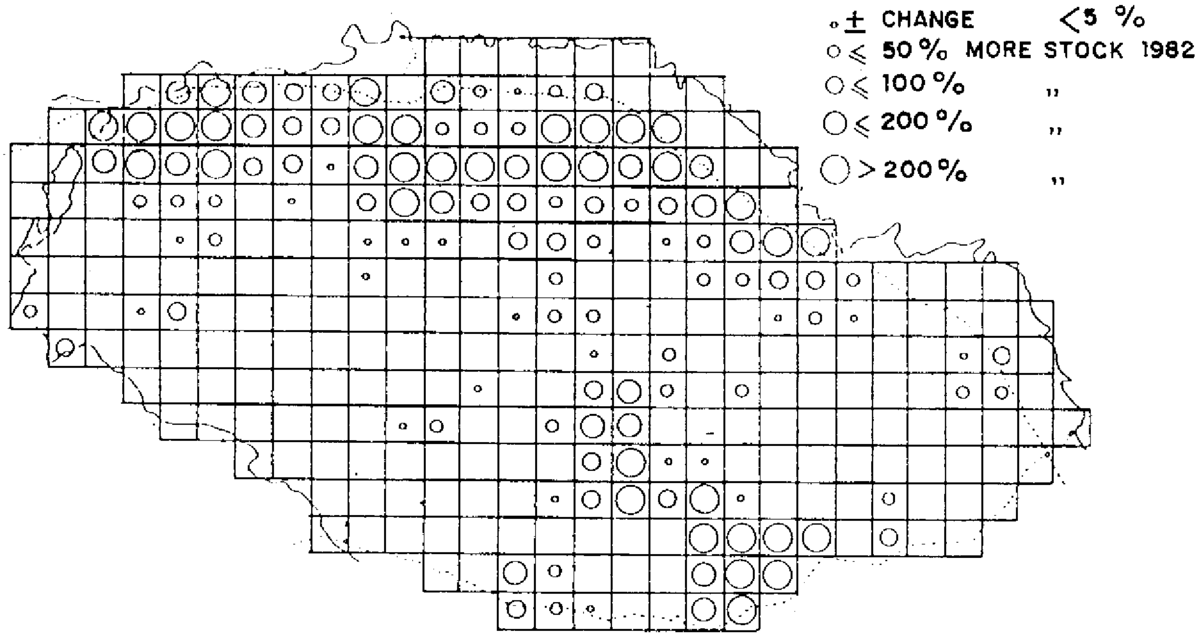


Figure 50

CHANGES IN LIVESTOCK NUMBERS BETWEEN TWO SRFs IN 1982 AND 1983
(SHARMAN, 1983 a)



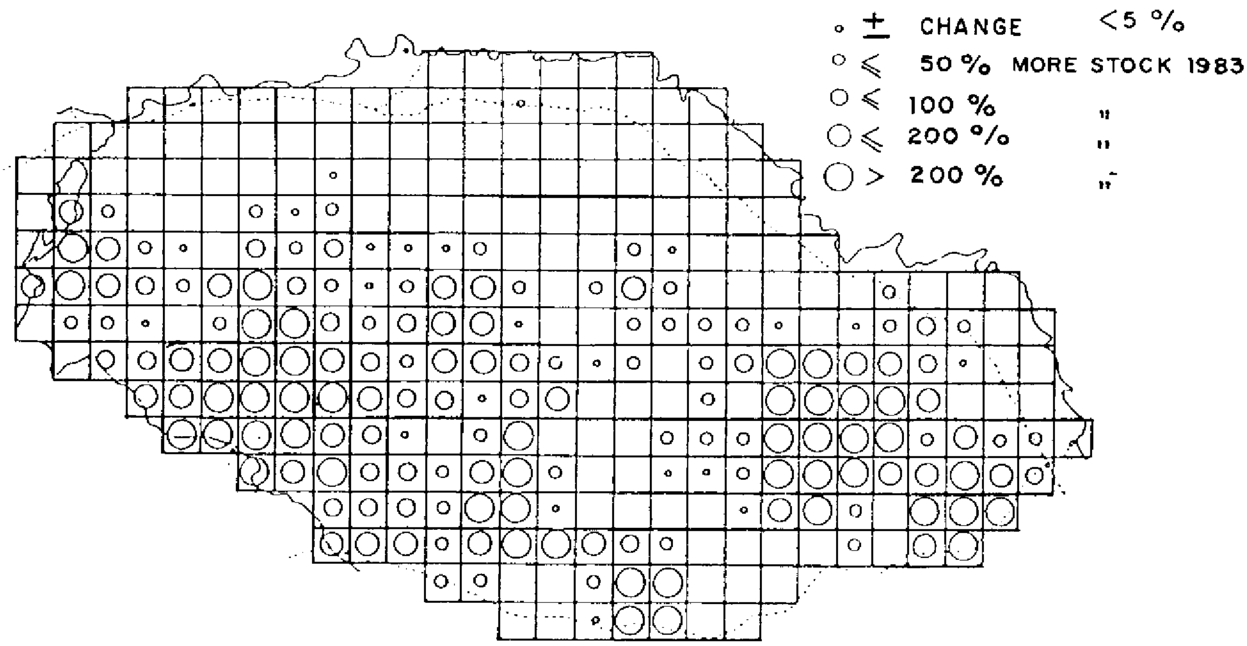


Figure 51

COMPARISON OF ESTIMATES OF LIGNEOUS CANOPY COVER BY FOUR DIFFERENT OBSERVERS IN 1980, 1981, 1982 AND 1983

(SHARMAN, 1983 a)

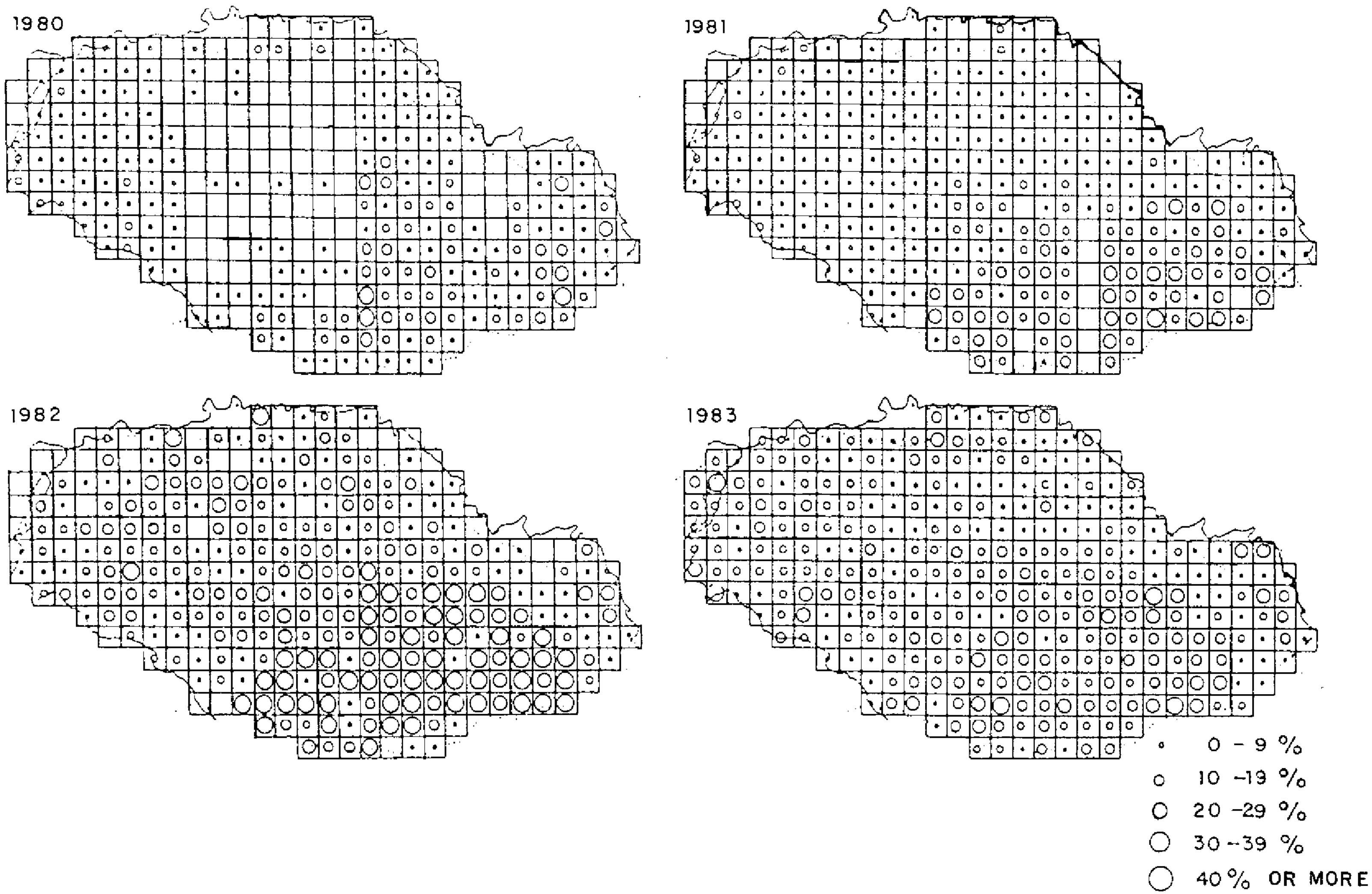


Figure 52

MEAN ESTIMATES OF LIGNEOUS CANOPY COVER OVER FOUR YEARS
(SHARMAN, 1983 a)

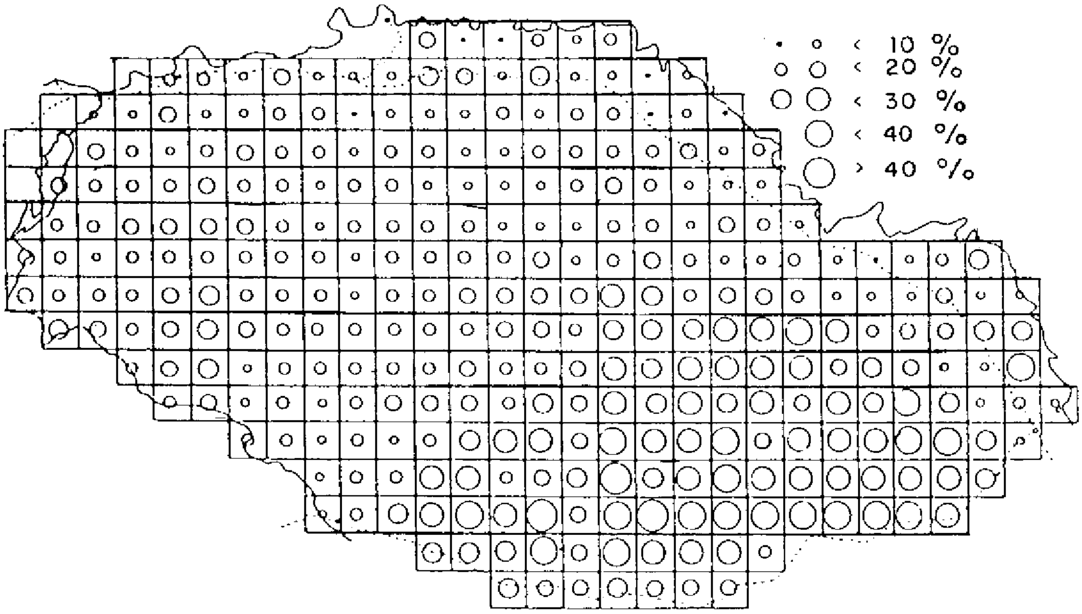


Figure 53

DISTRIBUTION OF STANDING HAY OVER THREE YEARS
(SHARMAN, 1983 a)

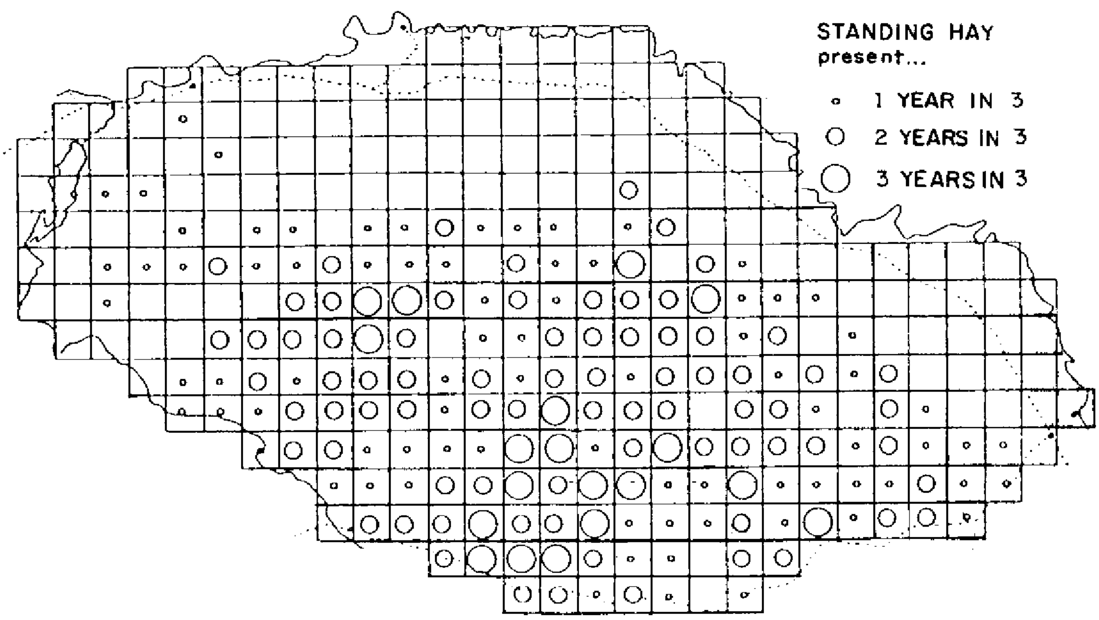


Figure 54

DISTRIBUTION OF BARE GROUND, JUNE 1983 (SHARMAN, 1983a)

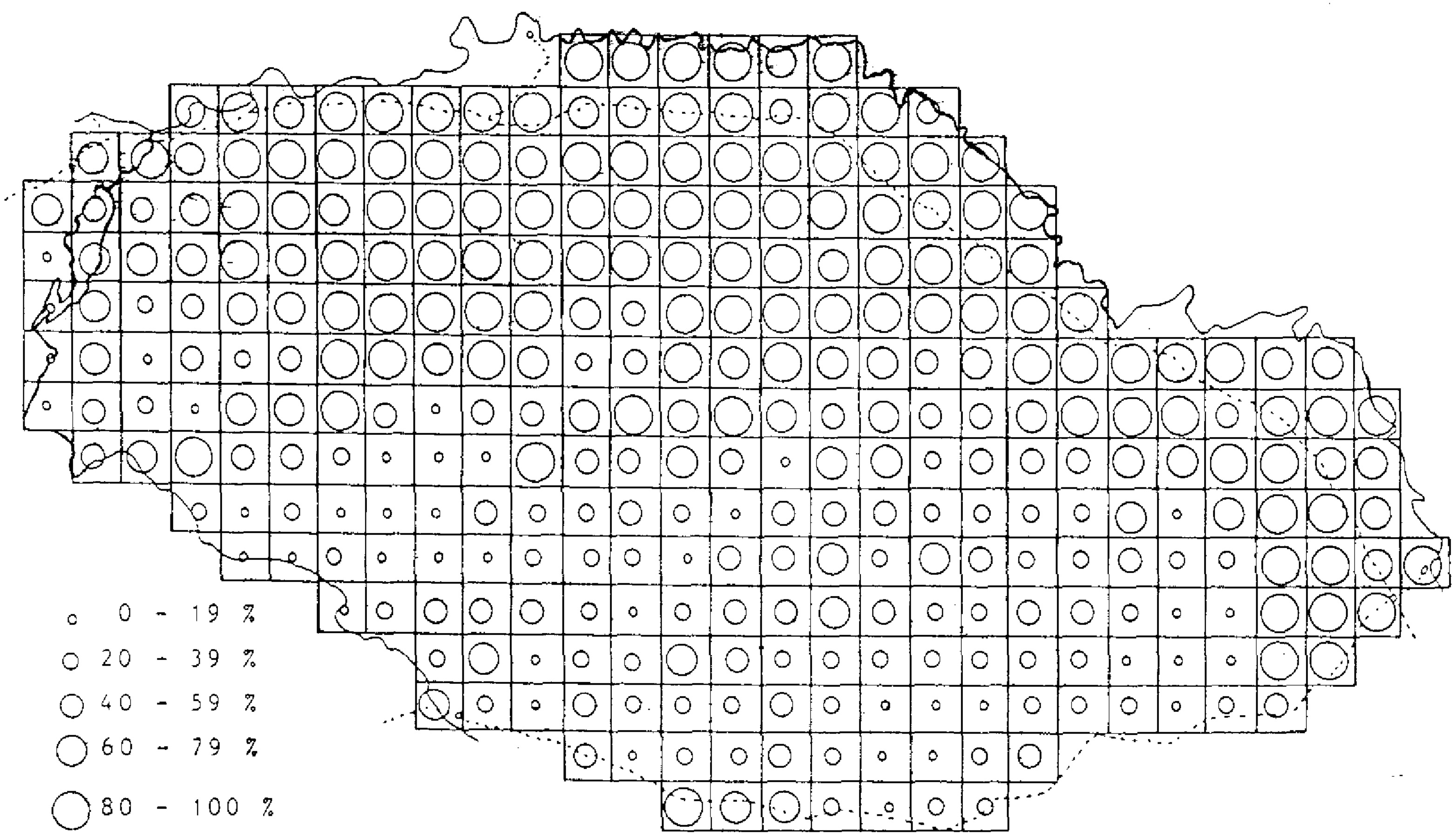


Figure 55

AREAS AFFECTED BY WIND EROSION IN 1982 AND 1983 (SHARMAN, 1983a)

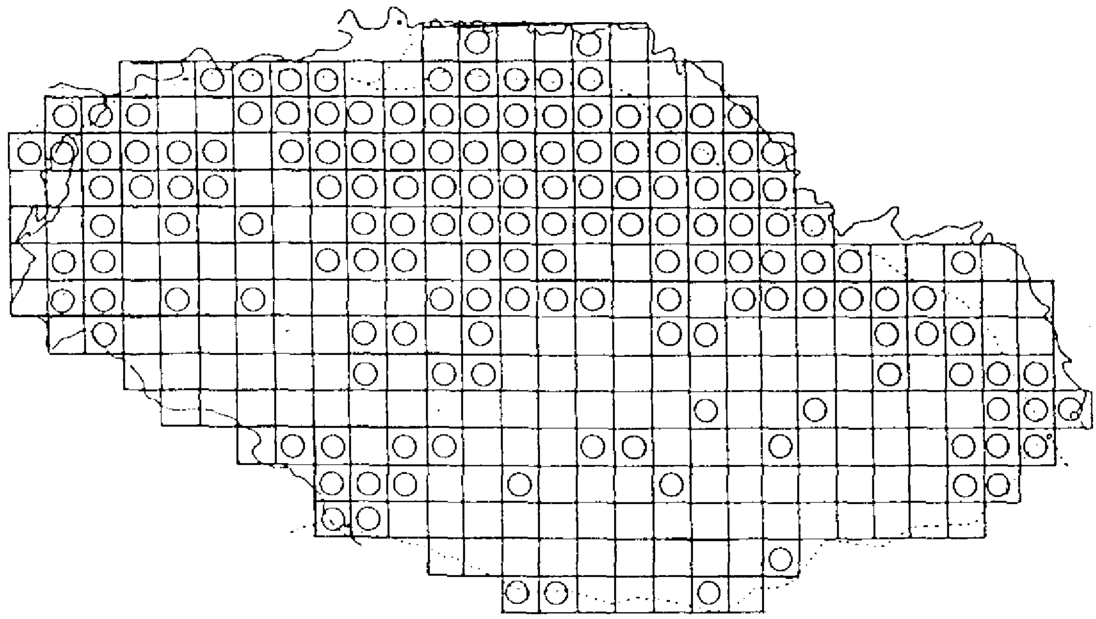


Figure 56

DISTRIBUTION OF HUMAN POPULATION (Data from the Office of Land Use and Management)

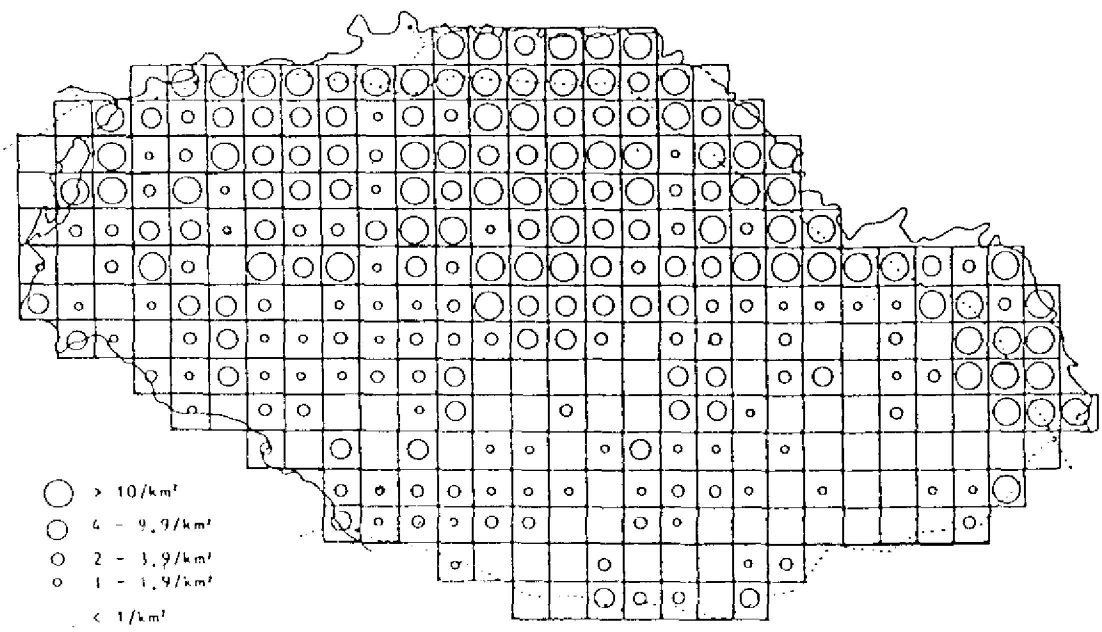


Figure 57

AREAS AFFECTED BY BUSH FIRES AT LEAST ONCE IN FOUR YEARS
(SHARMAN, 1983a)

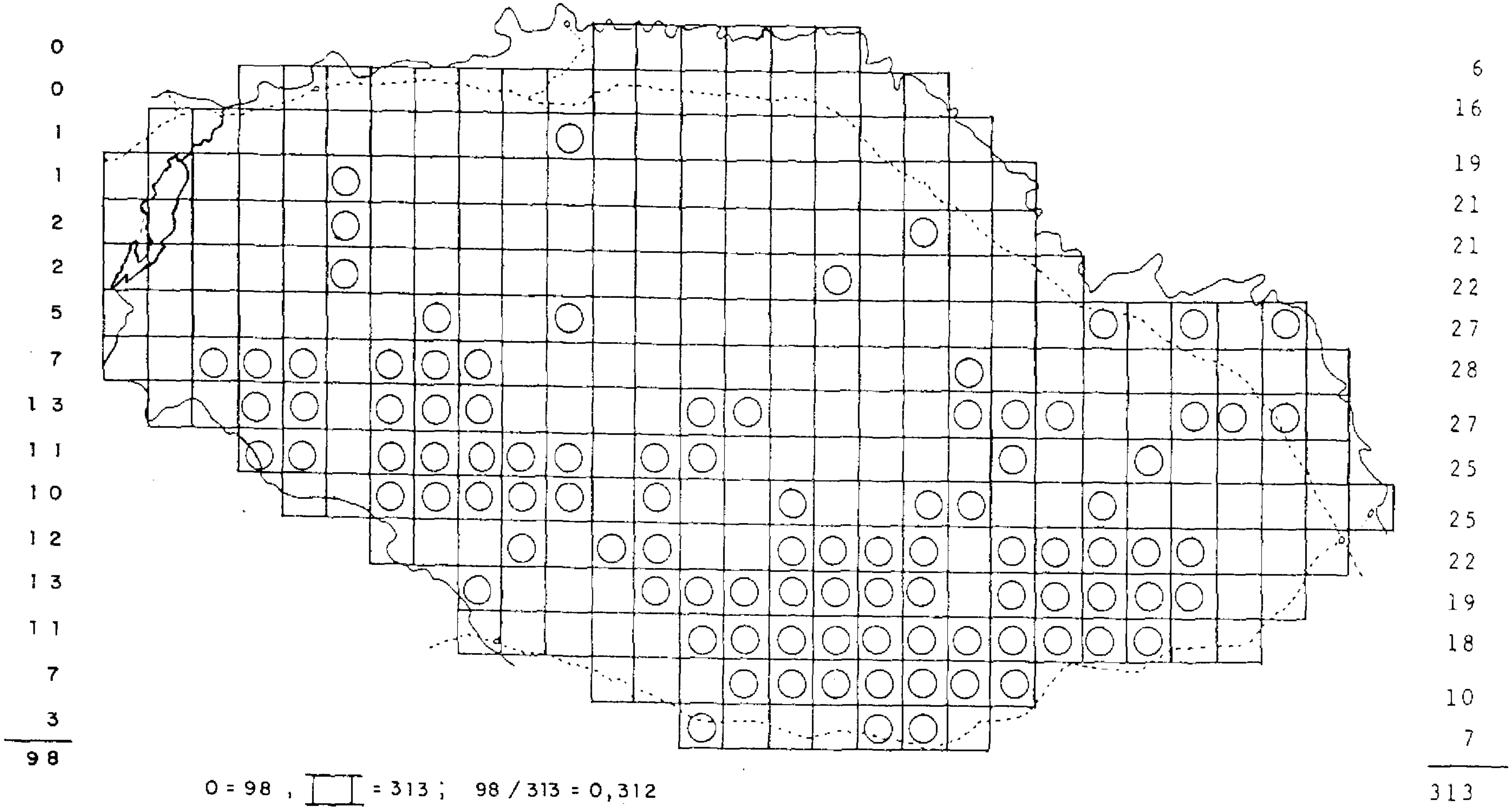


Figure 58

CORRELATION MATRIX BETWEEN CERTAIN ECOLOGICAL VARIABLES

(Data from various sources) (Sharman, 1983b)

	BIOMASS	STANDING HAY	TREES AND SHRUBS	BARE GROUND	GULLEY EROSION	SHEET EROSION	WIND EROSION	BUSH FIRES	HUMAN POPULATION
STANDING HAY	+								
TREES AND SHRUBS									
BARE GROUND	-	-	-						
GULLEY EROSION									
SHEET EROSION					+				
WIND EROSION	-		-	+					
BUSH FIRES			+	-					
HUMAN POPULATION	-			+			+	-	
DISTANCE TO SURFACE ROAD	+	+		-			-		-

Figure 59

DISTRIBUTION OF LIVESTOCK IN RELATION TO DISTANCE FROM PERMANENT WATER SUPPLY IN THE DRY SEASON (S RF DATA) (SHARMAN, 1983b)

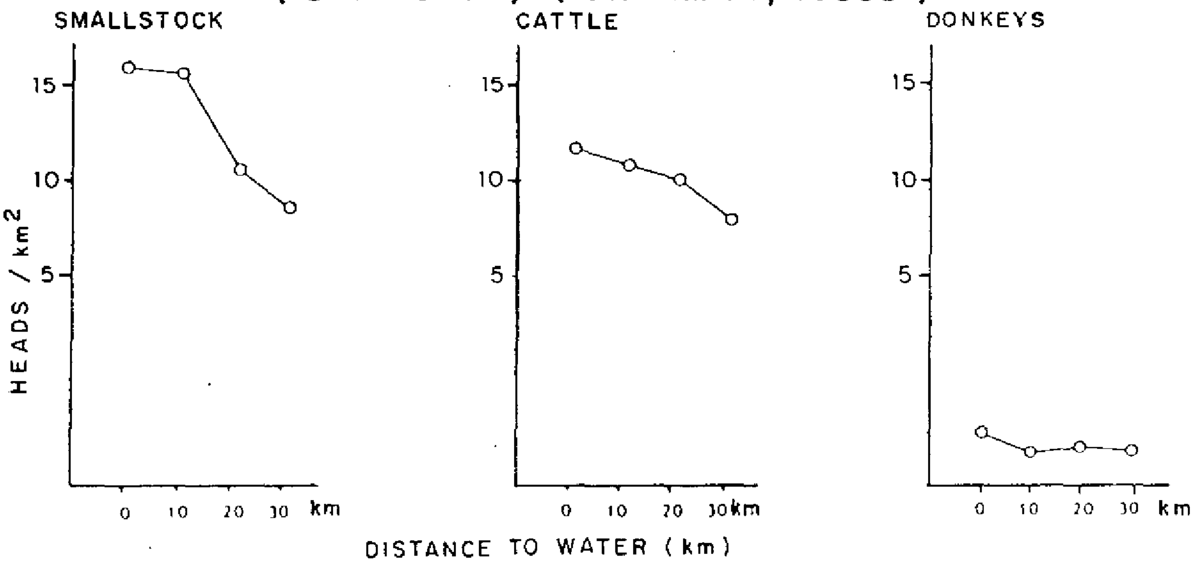


Figure 60

RELATIONSHIP BETWEEN HUMAN AND LIVESTOCK DENSITIES
(SRF AND GROUND DATA) (SHARMAN, 1983b)

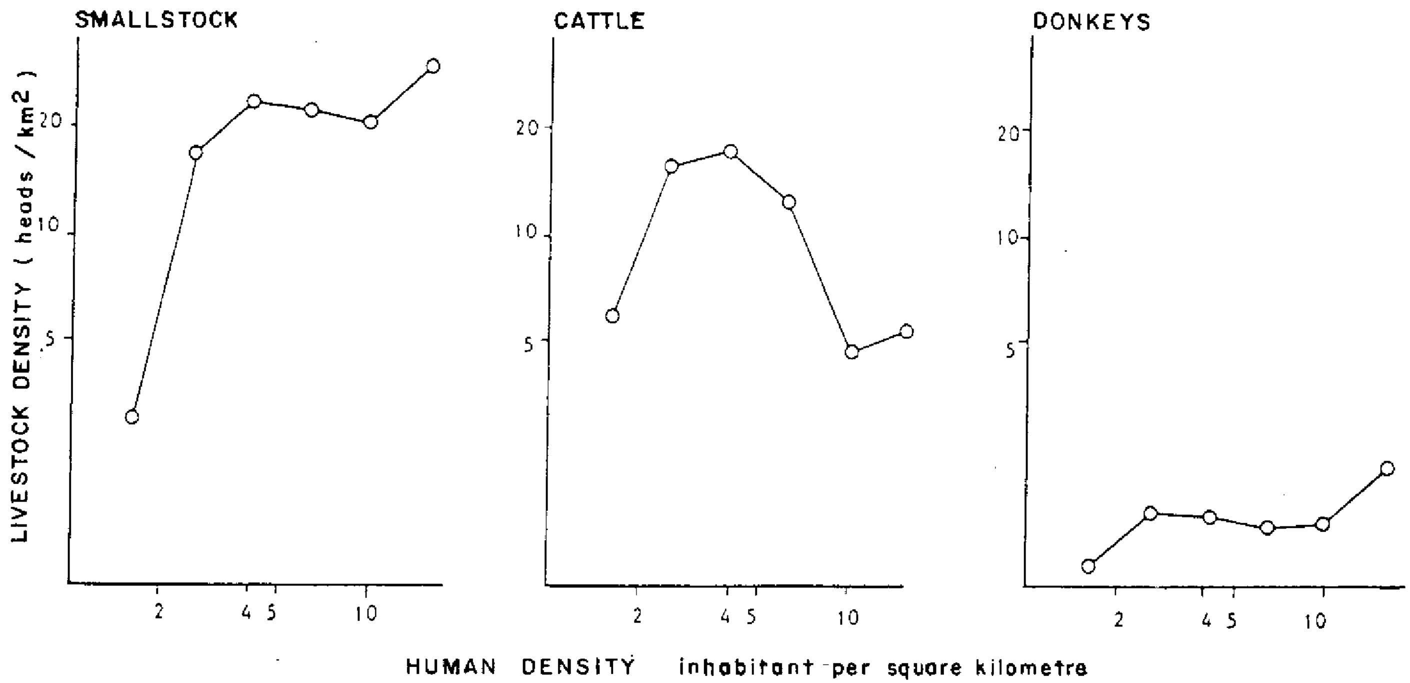


Figure 61

NUMBER OF DIET-DAY/TLU AVAILABLE AT THE END OF THE RAINY SEASON, TAKING INTO ACCOUNT THE ACTUAL STOCKING RATES AS OBSERVED FROM SRF (FORAGE PRODUCTION ESTIMATED FROM NOAA/AVHRR DATA COMPLEMENTED WITH GROUND TRUTH) (SHARMAN, 1983a)

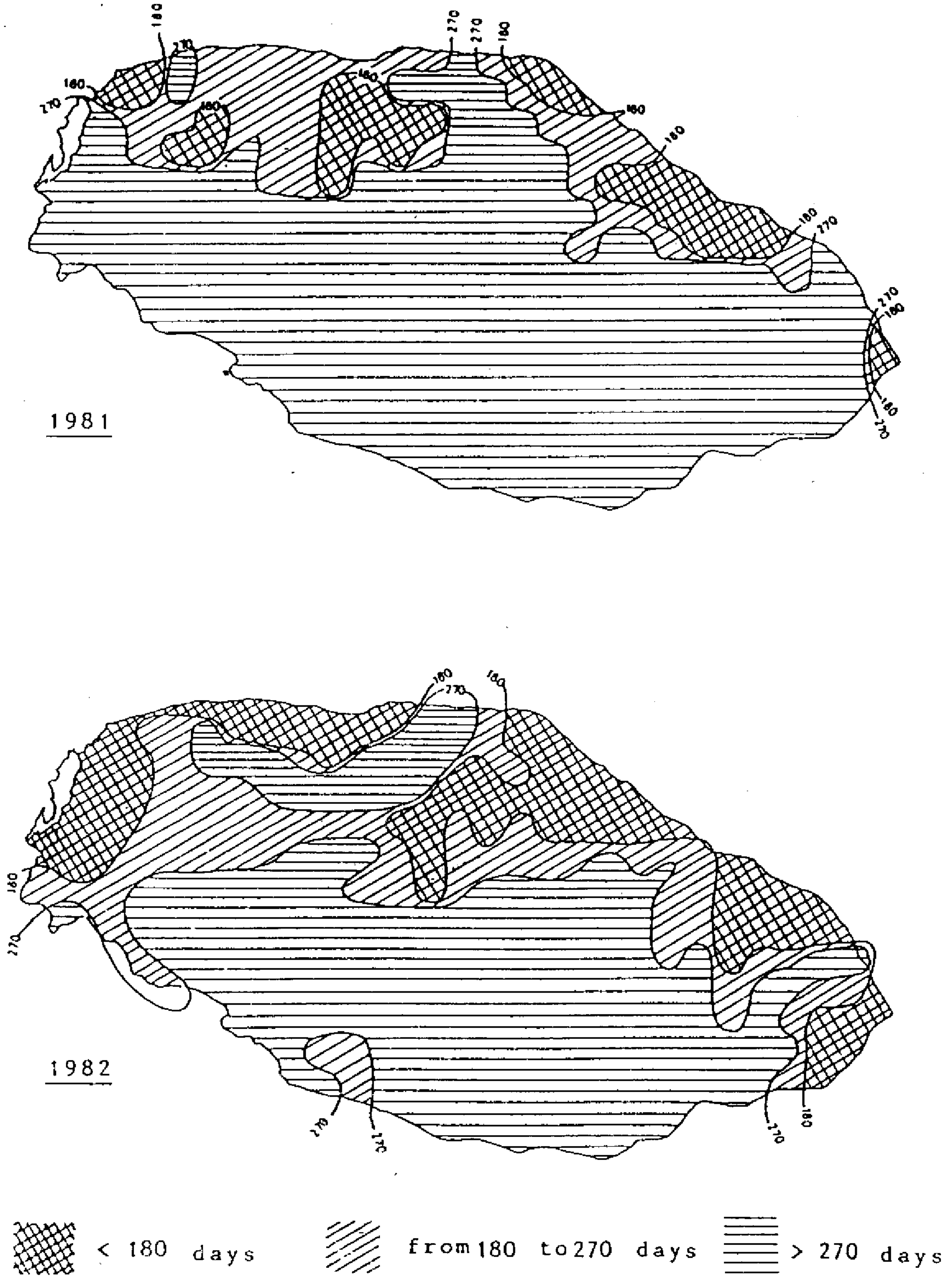


Figure 62

COMPARISON BETWEEN CARRYING CAPACITIES (NOAA/AVHRR DATA) AND ACTUAL STOCKING RATES (SRF DATA), AREAS WHERE STOCKING RATES WERE ABOVE CARRYING CAPACITIES FROM 1980 TO 1983 (SHARMA, 1983a)

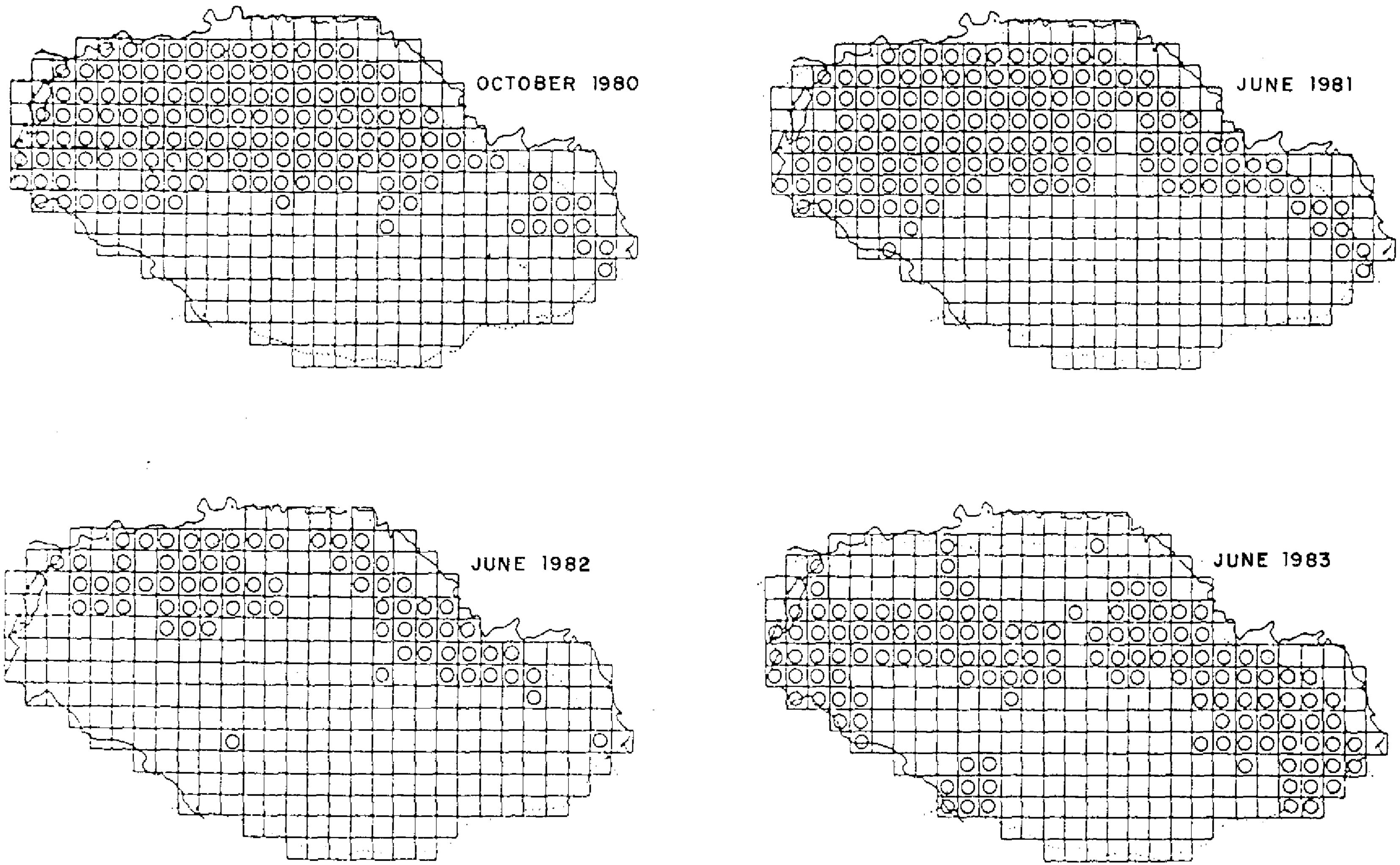


Figure 63

RELATIONSHIP BETWEEN SEASONAL RAINS AND DESTRUCTIVELY GROUND-MEASURED HERBACEOUS PRODUCTION FROM 1979 TO 1981 (BOUDET, 1983)

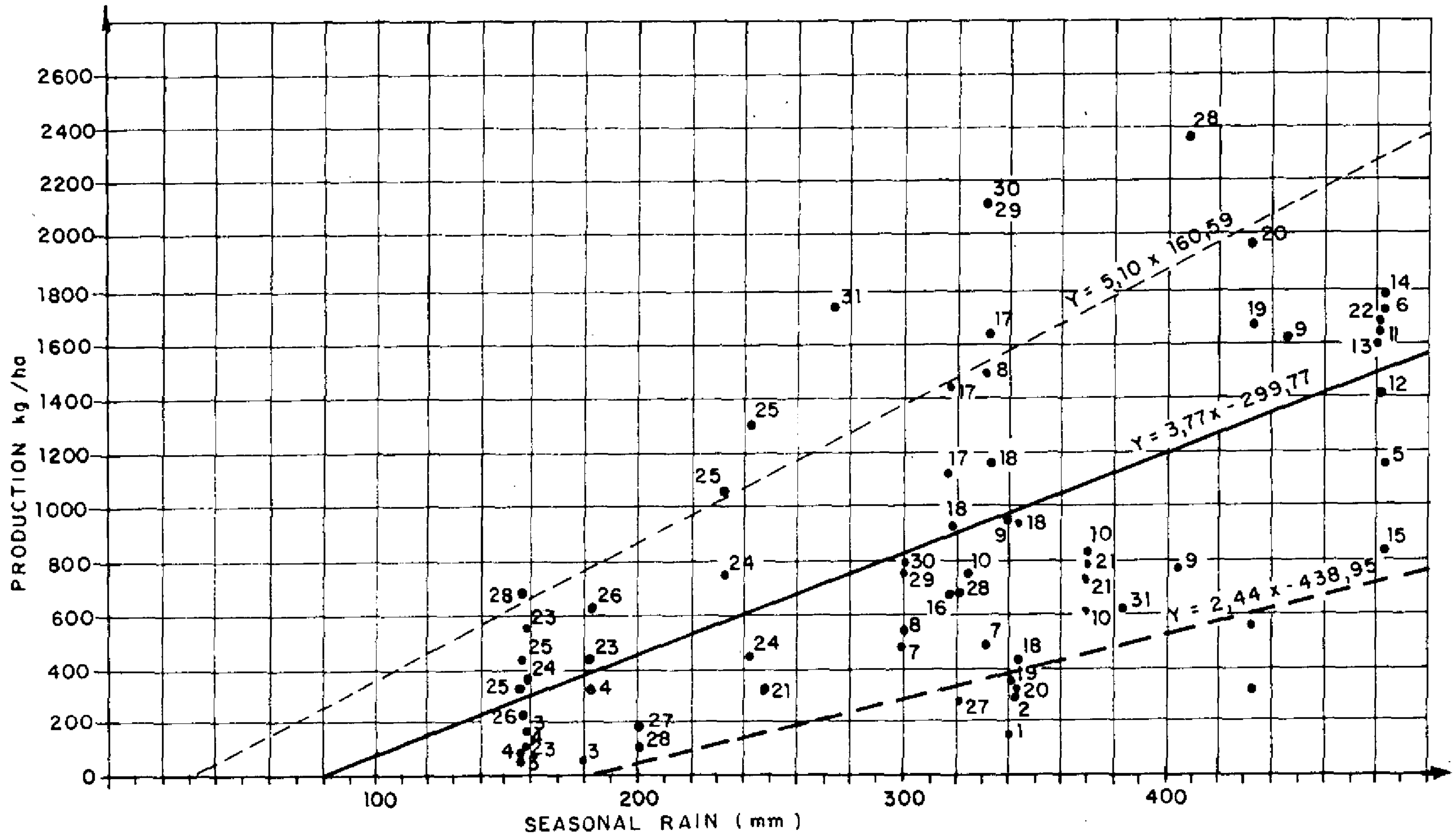
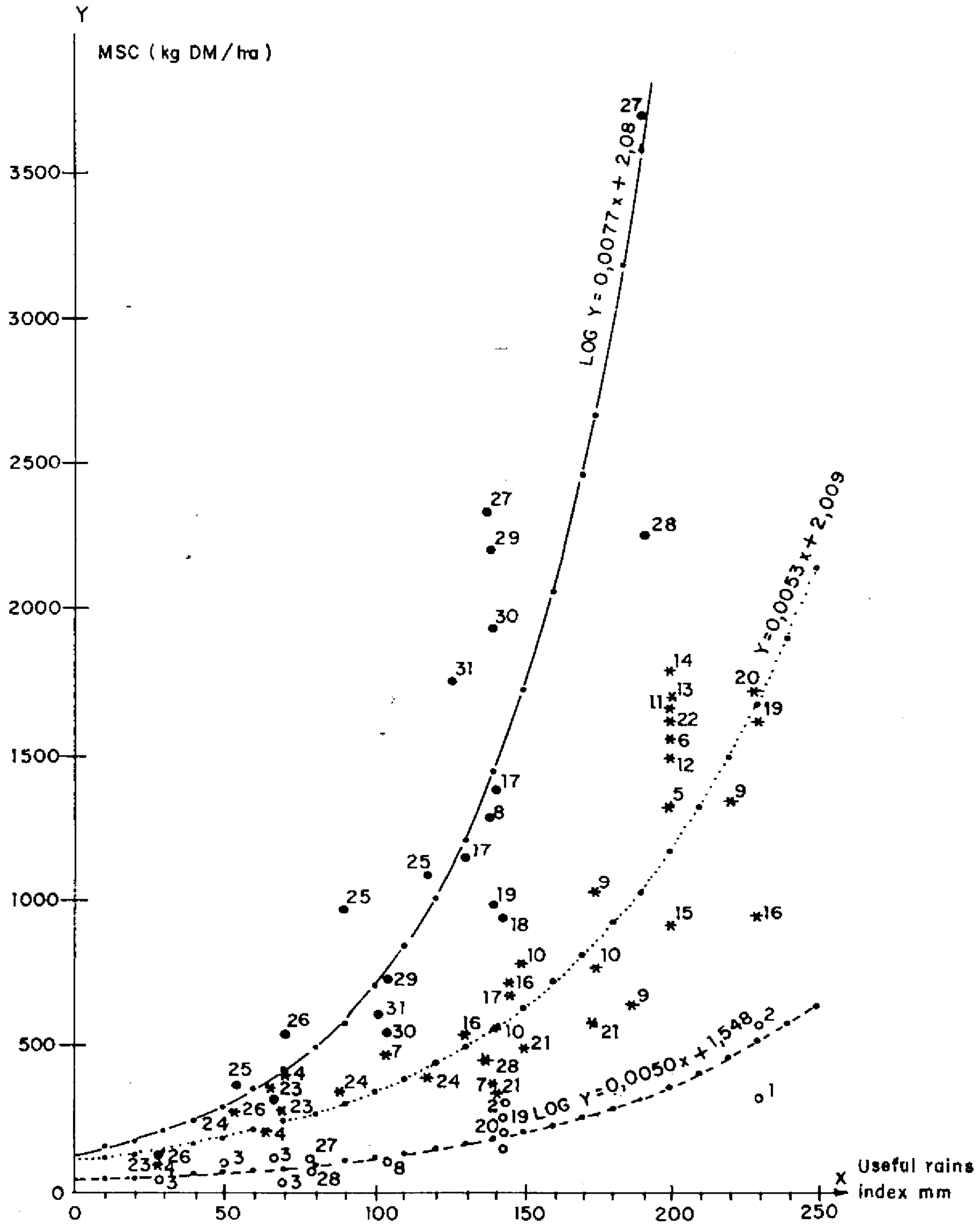


Figure 64

CORRELATIONS BETWEEN USEFUL RAINS AND HERBACEOUS PRODUCTION*
(BOUDET, 1983)



* See also Tables 2 and 19 and Figures 31 and 38.

Figure 65

HERBACEOUS BIOMASS IN THE FERLO: RAINY SEASON 1980

(Based on NOAA 7 satellite images and ground validation)

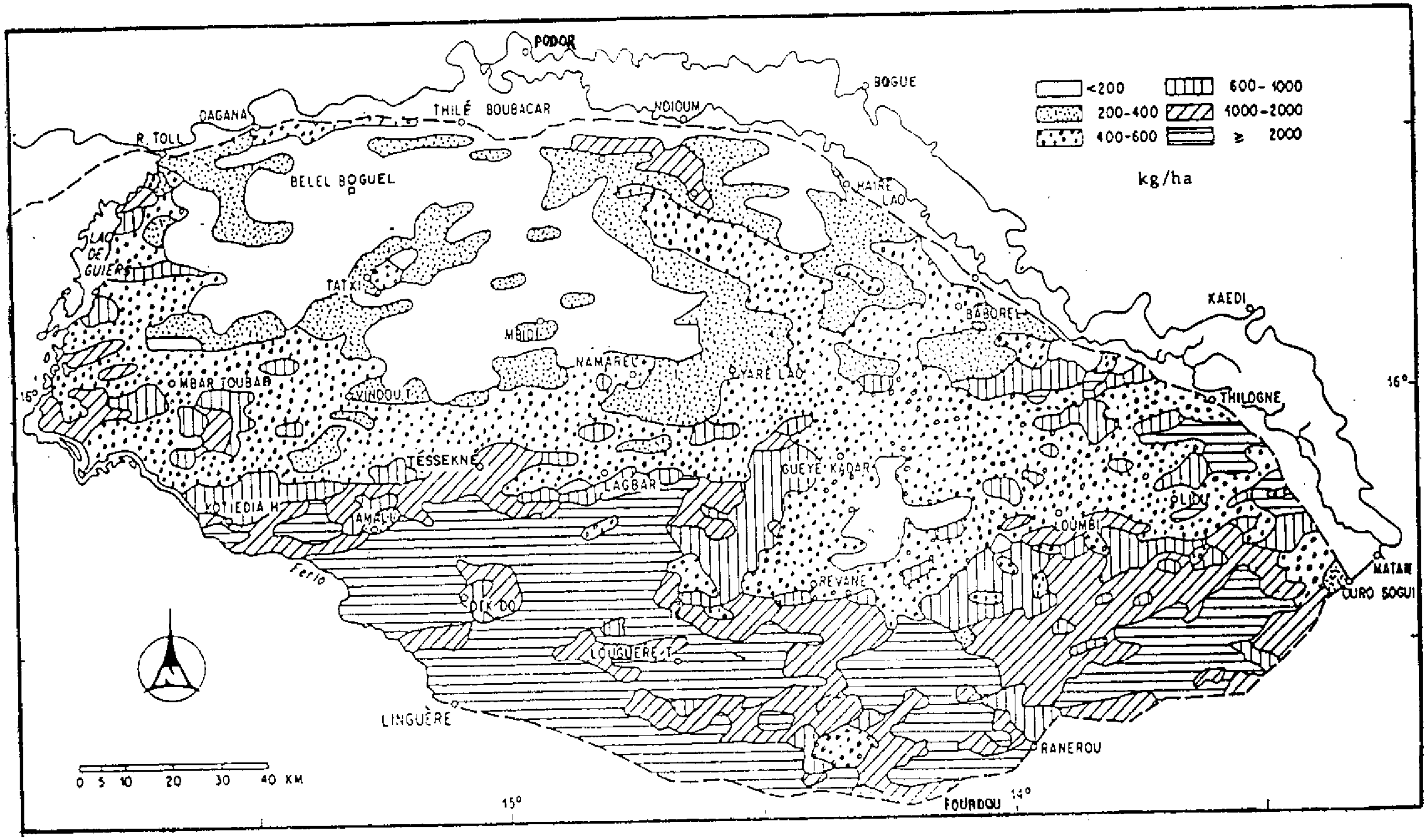


Figure 66

HERBACEOUS BIOMASS IN THE FERLO: RAINY SEASON 1981

(Based on NOAA 7 satellite images and ground validation)

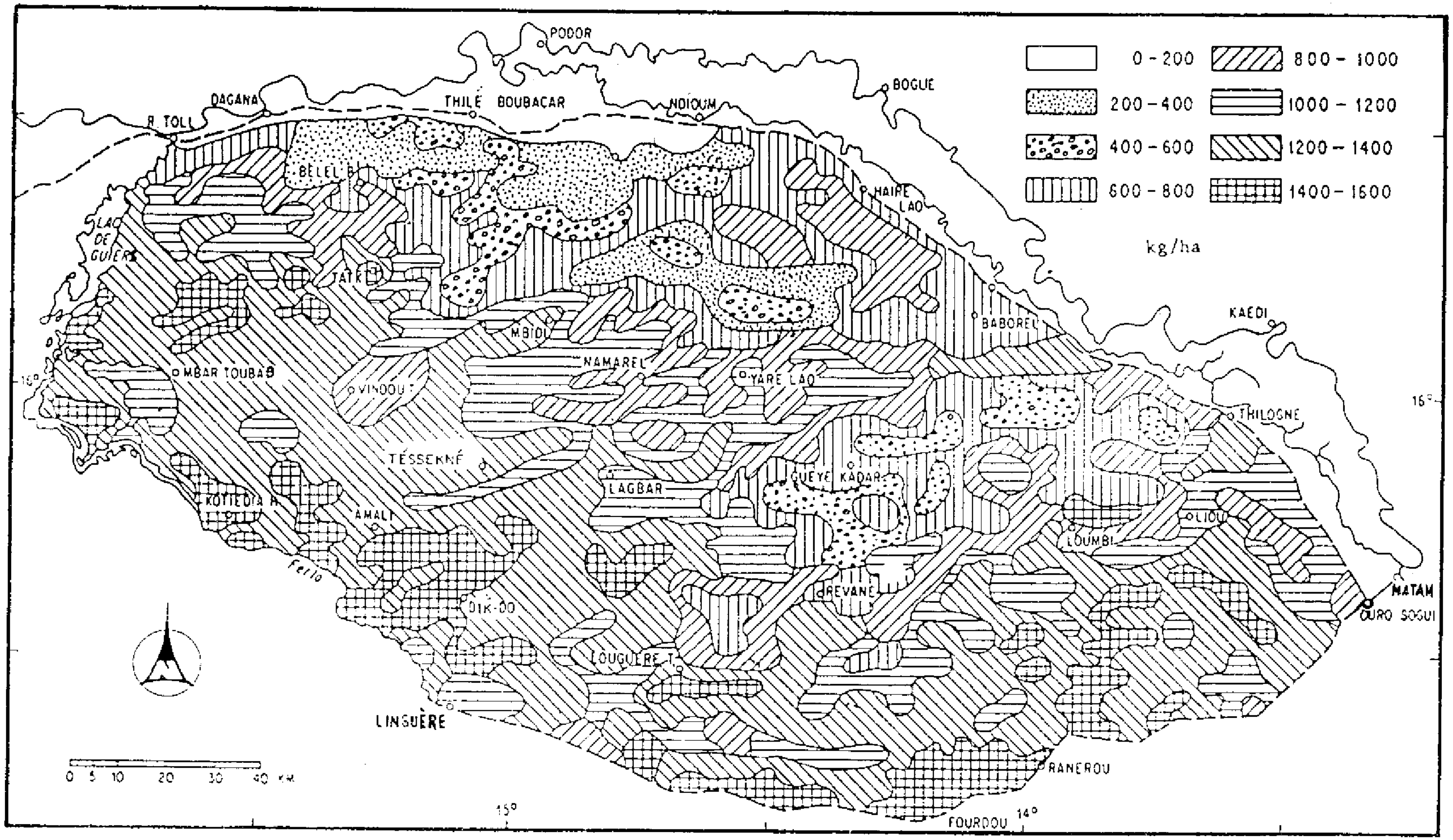


Figure 67

HERBACEOUS BIOMASS IN THE FERLO: RAINY SEASON 1982

(Based on NOAA 7 satellite images and ground validation)

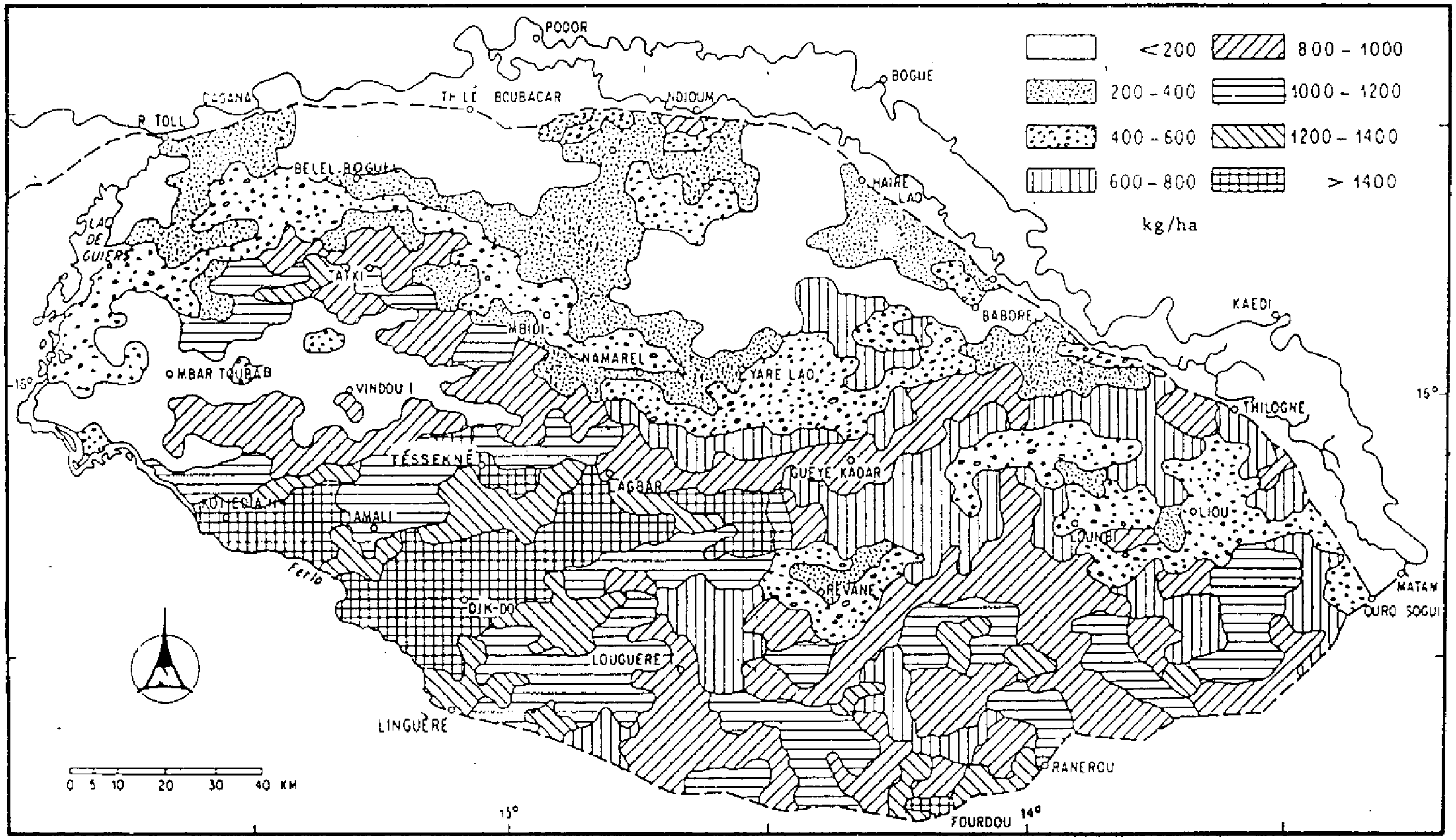


Figure 68

HERBACEOUS BIOMASS IN THE FERLO: RAINY SEASON 1983

(Based on NOAA 7 satellite images and ground validation)

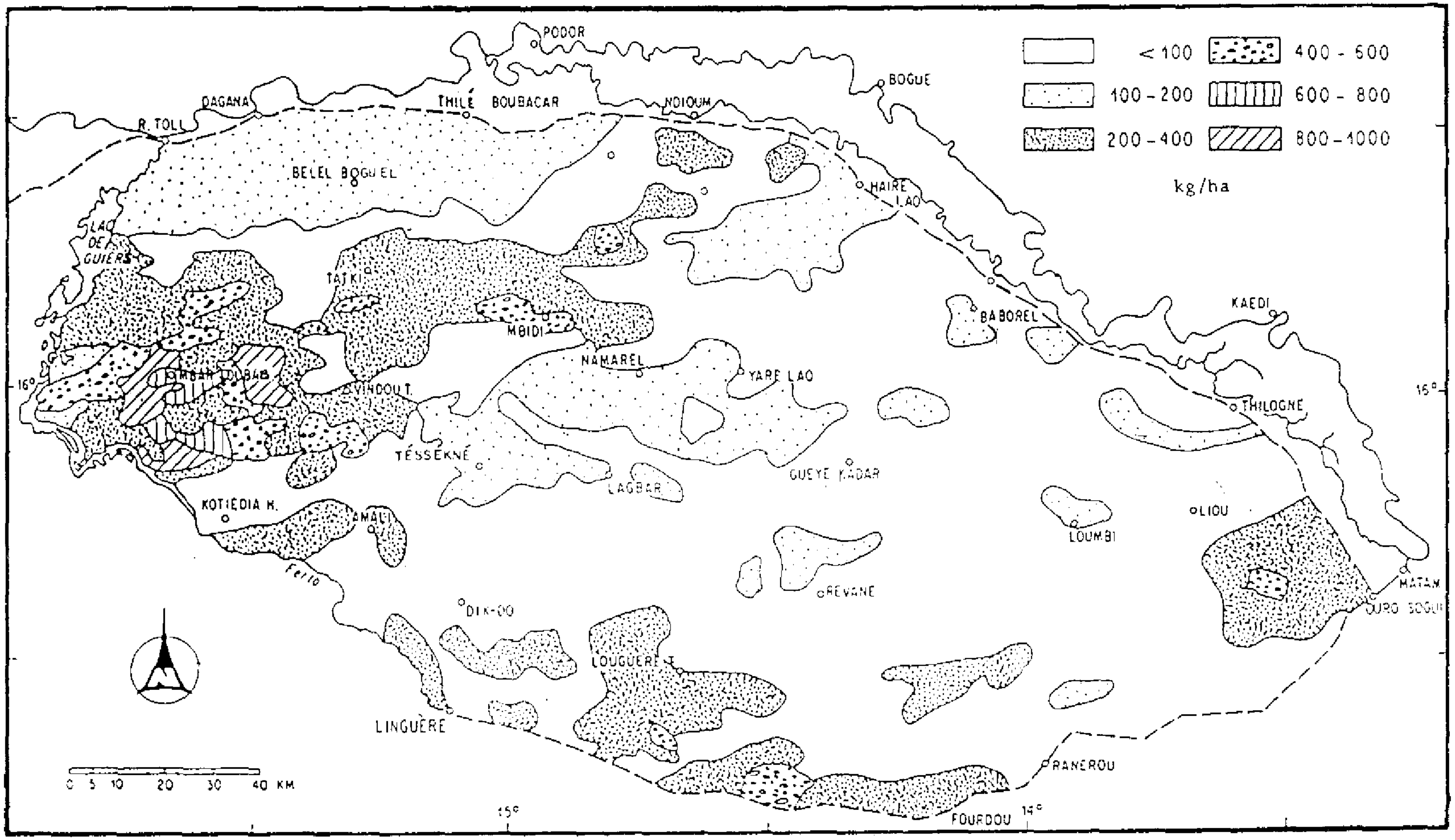


Figure 69

HERBACEOUS BIOMASS IN THE FERLO: RAINY SEASON 1984

(Based on NOAA 7 satellite images and ground validation)