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United Nations
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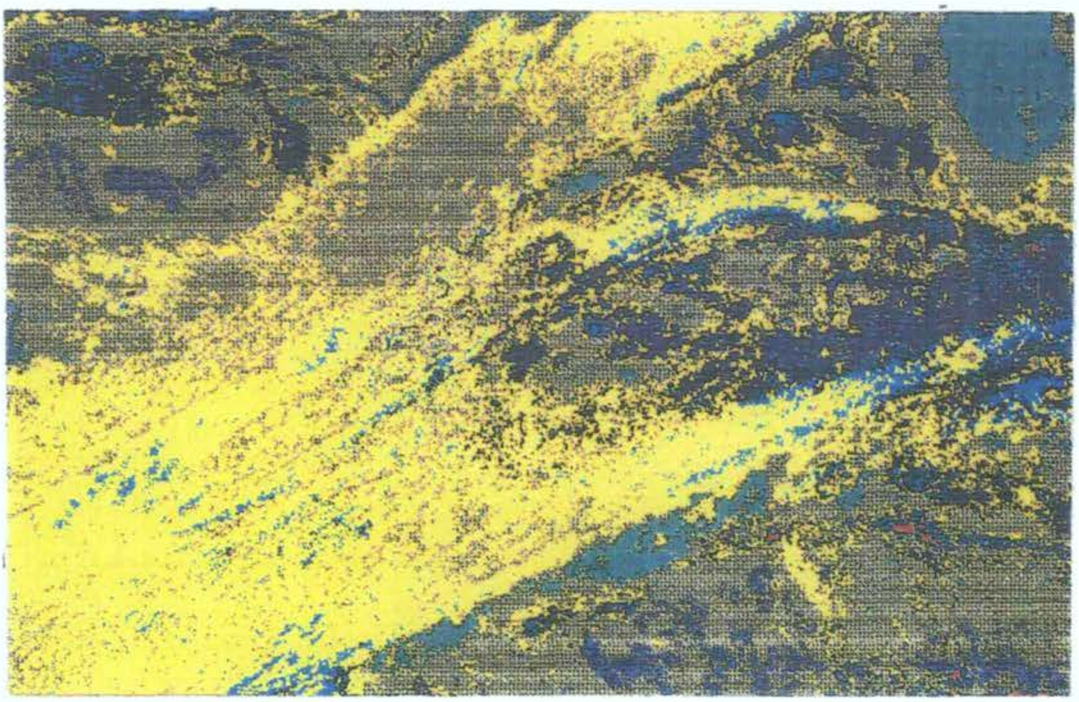
UNITED NATIONS ENVIRONMENT PROGRAM

FRENCH MINISTRY OF FOREIGN AFFAIRS

DEVELOPMENT OF A NEW METHOD OF DESERTIFICATION EVALUATION OF THE SAHEL REGION

The Land Use component is analized by Remote Sensing and GIS Techniques

1950 - 1990



FINAL REPORT OF STAGE 1 - STUDY OF 4 TRANSECTS

April 1993
Dec 1994

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DEVELOPMENT OF A NEW METHOD OF DESERTIFICATION EVALUATION OF THE SAHEL REGION 1950 - 1990

Final Report of stage 1 - a study of 4 transects

1. GENERAL INTRODUCTION

1.1. Historical

In May 1985 the DC/PAC of U.N.E.P. (United Nations Environment Program) decided in Nairobi to explore different methods of desertification evaluation.

In 1987 I.G.N. FRANCE INTERNATIONAL proposed to U.N.E.P. and to The French Ministry of Foreign Affairs the application and the evaluation of a method presented in this final report.

Work began in 1987 and aerial shots were taken. The firsts results concerning the Mauritania - Mali, transect were published in February 1989; those of the second transect, ie. Mali - Burkina-Faso, were published in October 1990 and those of the third and fourth transects, ie. Niger - Mali and Niger - Nigeria, in July 1991 (cf. figure1).

A summary of these reports and a review of basic results obtained are presented in chapters 2 and 3 hereafter.

The project also explored the possibilities of using satellite images in order to attempt an extrapolation of results obtained from transects over the entire area South of the Sahara threatened by the desertification phenomenon. The results obtained are described in chapters 5 and 6 of this paper.

A first version of the present report dated April 1993 was submitted to an expert panel gathered at U.N.E.P. in Nairobi in Decembre the same year. The questions raised, experts' concerns and recommendations are taken into account in the present revised version. The expert meeting proceedings can be found in Annex hereinafter.

1.2. Objectives

The project's objective is to develop a method allowing for an evaluation of a possible environmental degradation occurred in various Sahelian countries in the last decades. In case this method (after improvement as recommended in the last chapter) is considered as valid, it will provide Sahel countries and the international community with localised and homogeneous geographical information concerning the desertification phenomenon, over the entire West African area (as a first step).

For a long time, nature was considered as an inexhaustible force, forever regenerating itself. Since, people in Europe and in Africa or in other parts of the world became aware of the fact that nature is not inexhaustible and that it suffers due to human intervention. In view of these problems, a few years ago, the international community became conscious of the fragility of natural spaces and of the necessity to provide the decision makers with easy to handle information in this field. This data bank to be created will allow to combine data on physical surroundings (land use, climate, etc.) with socio-economic considerations in order to produce a concise assessment of the area and to foresee a possible evolution, once the phenomenon is understood.

In Africa data concerning the environment is small and dispersed; therefore, action should be taken to fill in the gap. The only complete topographic coverage dates back to the 50's and there are few thematic maps of that time covering the area. The matching scarcity of recent data hinders all statistical evaluation of land use. Thus, any changes which occurred in the past decades cannot be seen.

The project is in line with the International Convention on Desertification recommended at The United Nations Conference on Environment and Development held in Rio (Brazil) in June 1992. It contributes to stimulate the activities of The Sahara and Sahel Observatory Programme (O.S.S.).

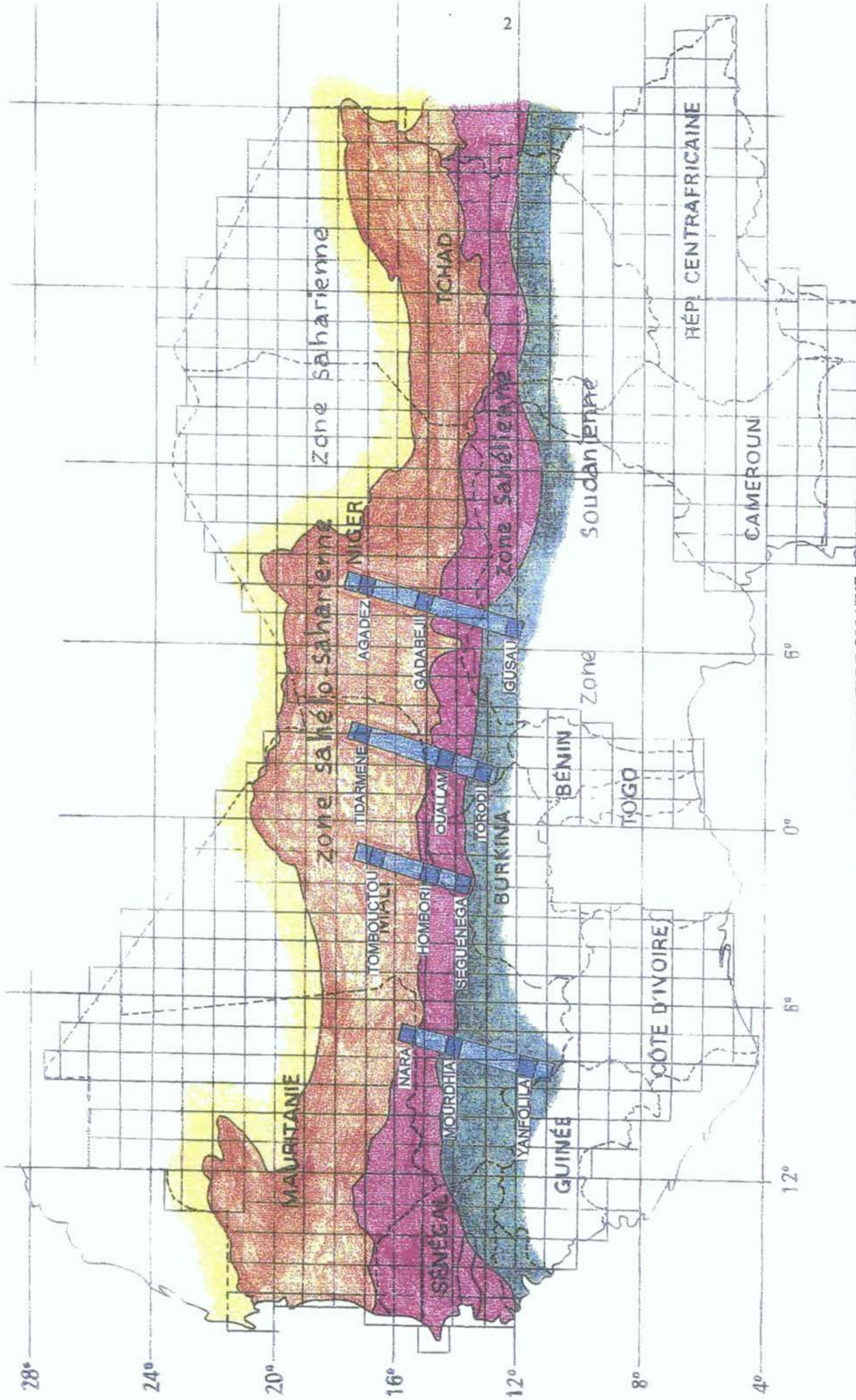


FIGURE 1: MAP SHOWING THE LOCATION OF TRANSECTS AND BIO-CLIMATIC DOMAINS.

In order to manage the environment efficiently, statistical and cartographic - updatable - information of the area concerned should be available. The possibility of updating information is an essential condition for any organisation in charge of managing the area. It is indispensable to gather, compare and combine all sorts of geographic, economic and demographic information.

This task can be undertaken by employing modern methods, as computer system capacity is continuously increasing while immense technological progress in the field of spatial data collection make it possible now to envisage new means of collecting and using information.

In the context of continuous progress in cartography and in the analysis methods used to study the desertification phenomenon, the U.N.E.P. recommendations to test the remote sensing method in connection with Geographical Information System Capacity (G.I.S.) is totally justified.

The advantages of satellite data on aerial photographs, when large zones are involved, are evident because data is always available throughout the world, it is cheaper, it allows an overall view of large areas (3,600 square kilometres for a SPOT scene and 32,500 square kilometres for one Landsat). Moreover, data is digital, therefore easier to analyse and to insert in the G.I.S.

However, it would be a mistake to assume that numerical techniques can answer every question. Satellite data, without a good knowledge of the terrain and without the support of photo interpretation, is difficult to use. Hence, its use requires a rigorous method and the employment of exogenous data. We will attempt to evaluate the advantages of the different means of research throughout this report.

The objectives defined by the U.N.E.P. are summed up as follows:

In the short term:

1/ To develop and test an evaluation method of desertification based on the combined use of aerial photographs from distinct periods, of SPOT satellite imagery and of terrain data.

2/ To obtain a qualitative and, if possible, a quantitative evaluation of desertification throughout the transects in West Africa.

In the long term:

1/ To obtain a real evaluation of desertification in Africa, South of the Sahara in the last thirty years and establish an accurate data base i.e. a Geographical Information System (G.I.S.), to monitor desertification in cooperation with the States concerned.

2/ To develop a continuous desertification evaluation method, economically viable and applicable to every area in the world undergoing this phenomenon.

3/ To use the G.I.S. to produce maps at various scales and statistics.

1.3. Method applied

The study on feasibility was undertaken in 1988, supervised by I.G.N. FRANCE INTERNATIONAL associated with ORSTOM and with the University of Reims. It aimed at developing an evaluation method of desertification easily and economically transferable like a handy tool for operators involved in the developing countries concerned. This preliminary study revealed that variations in land use occurred between the 50's and 1987 could be put in evidence by a visual analysis of aerial photographs. Analysis has proved possible for 18 themes, while 13 of them described natural vegetation according to the Yangambi classification.

The desertification phenomenon can doubtless be studied by using different indicators of ecological status. Land use is one of the most important indicator and it is **the only one** appearing on both old and recent remote sensing data. Some land cover types are difficult to determine unambiguously and may not be ecologically significant; we discuss the matter in the following pages. Also, due to the necessity to obtain data of the same season as the 1950s coverage (end of the rainy season: Novembre to February), the recent data may not have been acquired at times when the land cover characteristics of interest are discriminated to the maximum extent.

Other indicators than land use might be more pertinent to assess a possible environmental degradation. An examination of changes in plant growth rates on cultivated lands which might be correlated with loss of productivity, for example, is such an indicator; possible modification of species population balance in a phyto-society, as well. These indicators **are not** reachable through remote sensing data interpretation.

The first and foremost idea was to consult aerial photographs from the 50's stored in the French National Geographic Institute (I.G.N.) archives. These shots were taken at the time in order to produce a topographical map of West Africa at a scale of 1:200.000 but they provide information on land use at that time. Four transects oriented North-East - South-West, 500 km apart, corresponding to SPOT satellite traces, were selected South of the Sahara so as to cross the Sahel and Sudan ecozones.

Aerial photographs of the four transects taken in the 50's were retrieved and in 1987, 1989 and 1990 (depending on the transects) a new aerial coverage was produced along the same transects and **in conditions comparable** to those in the 50's (i.e. scale of the photographs, black and white emulsion, **season** of the year). Moreover, recent aerial work was doubled in certain transects with infrared false colour shots (I.R.C.). These I.R.C. photos facilitate a comparison with SPOT satellite images where spectral bands XSI, XS2, XS3, are respectively centred on green, red and near infra-red corresponding to the three layers of photographic emulsion.

Tentative automated measurements of the grey density conducted on the two sets of Black & White photographs of the 50s and of the recent coverage did not prove reliable enough. We thought that the grey density could give an indication on the vegetation cover. This method has been dropped.

The diachronic data, from the 50's and end of the 80's, (on one aerial photograph strip 10 kilometres wide) was photo-interpreted by the same operator and the result of this interpretation was transcribed onto a space-map, in other words, a reference document at a scale of 1:100,000. obtained by geometric correction (registration) of SPOT images.

Then the interpretations were digitized (by scanning or digitizing at the table, as the case may be) in order to create files which lend themselves to computer processing to obtain statistics on land use, on cross-referencing and in some cases, evolution maps. All the data collected on the transects are the basis of a Geographical Information System (G.I.S.) which could, in the future, be fed with new studies on others indicators, at larger scales, etc. The transects could always be used to watch over the environment and periodically study it in the same way.

A visual interpretation of colour composites of infrared false colours SPOT satellite images was made by the **same operator** and with the **same legend** themes. Subsequently, a comparison of interpretations of aerial photographs and satellite images was made.

To end the operation, we had to evaluate the viability of **extrapolating** to the entire SPOT scene (60 kilometres wide), the land use information obtained on a width of 10 kilometres (an aerial photographs strip). Apart from a visual analysis mentioned above, several automated methods were attempted and the reliabilities (a margin of trustworthiness) of all methods were compared.

Now, if we want more than a localised information on land use in the Sahel area obtained by sampling (transects), and we want to obtain a map covering the entire zone threatened by the desertification phenomenon, the use of satellite images of the area between one transect and another is necessary (**interpolation between transects**).

Margins of trustworthiness, obtained in the process of extrapolation to the entire width of a satellite image (60 km) from information gathered from aerial photographs (which cover the width of 10 km only), will be better preserved by an automated method than by a visual interpretation when interpolating between transects. This fact gives preference to a more automatic method. Without any human intervention in the process of classification, the only error possible may occur in theme characterisation and not in their spatial extent. In other words, if the results of **extrapolation** obtained automatically from an aerial photo strip (10 km) on the whole SPOT scene (60 km), are acceptable, then, an **interpolation** between transects based on images of the same satellite, processed automatically, will also be acceptable.

2. THE FIRST TRANSECT: NARA - MOURDIAH - YANFOLILA

2.1. Choice of an appropriate method

The choice was limited by the fact that we wanted to compare between the years 50s and the recent ones what can be apparent on remote sensing data. From the years 50s we had only a few documents: a topographic map at a small (1:200.000) scale with some global indications on land use and the aerial photographs taken at the time for the purpose of this cartography. Aerial coverage had been done at a given scale (1:50.000), at a given time (end of the rainy season), on a given support (Black & White film). For the recent years the choice was dictated by the facts that we had to get data as similar as possible to the old documents and, also, to open new possibilities for a future monitoring with modern tools (satellites).

The double set of constraints dictated the scale of our work (1:100.000), the choice of a thematic domain (land use) and the legend (simple enough to reduce ambiguity in class discriminations).

A first test study, conducted in 1987, on a small area (50 km^2) proved that, for some legend items, measurable changes had occurred between the 50s and the recent times. To our original legend, akin to the one of the regular topographic map, were then added themes which had been proved relevant by the test study, like "annual cultivation", "agricultural lands", etc.

With a view to minimise the level of error and the impact of interpreters subjectivity, the **same** experienced photo-interpreter has conducted all his visual analysis in the same way:

First, a stereoscopic photo-interpretation of aerial photographs or simple visual analysis of satellite hard copies was done by the operator, based on his experience, available thematic studies, topographic, geologic or pedologic maps, etc.

With the results of this photo-interpretation, a field ground-truthing campaign was conducted, where the photo-interpreter was assisted by local thematicians of the various countries and a **qualitative** evaluation of errors in land cover determination was made. A new photo-interpretation made on the field, on small areas was then compared to the ground conditions, until iterations give a stable and consistent result.

At the end, the final photo-interpretation of the complete area was done back in office.

We can remark, at this point, that even if a **quantitative** estimate of the interpreter subjectivity in the land cover classes determination could have been measured for the recent times (by another operator using G.P.S., for example), the same could not have been done for the years 50s and a doubt would have remained anyway.

2.2. Data processing on the first transect

The results from the first transect were presented in full detail in a voluminous report dated February 1989 and in a summarised version of it with the same date. In the report only a visual analysis of analogous documents (aerial photographs and printed SPOT satellite images) was employed. Only later, an automated classification of Spot digital images was used in order to compare the results with those discussed in paragraph 2.4. below.

In each of the two diachronic studies, one dated in the 50's and the other in Novembre 1987, two interpretations were made, one showing the vegetation cover theme while the other, linear elements. Thus, 4 maps exist. In addition, there is a map on external dynamics phenomena i.e. erosion, superficial deposits and geomorphology and one map on villages. This amounts to six documents for each of the three SPOT scenes retained.

Cartographic edition i.e. its definite imposition, is based on the scale of 1:100,000; it is drawn on stable material (film) which can be overlaid on a geometrically corrected satellite image (space-map). These films can be digitized by scanning to compile numerical files.

For convenience, SPOT scenes are then designated by applying the name of the most important and the closest locality. Thus, from North to South, scenes 40-319, 40-322 and 40-327 are designated as the Nara, Mourdiah and Yanfolila scenes.

Three **uninterrupted** zones 60 km long (corresponding to one SPOT scene) oriented North-East - South-West (SPOT paths) and 10 km wide (which correspond to the width of an aerial photographic path) were studied. They represent three domains with a different rainfall quota: Nara with 400 millimetres, Mourdiah with 800mm. and Yanfolila with 1, 200mm.

2.3. Comments on rainfall variability

The drawing on the next page shows the position of isohyets with different time intervals:

- a period of almost 60 years, from 1922 to 1960 including abundant and poor rainfall episodes,
- a period of 10 damp years, from 1950 to 1960 which means a rise in the isohyet lines to the North,
- a period of 10 dryer years, from 1971 to 1980, which means a fall in the isohyet lines to the South.

The amplitude of oscillations in the isohyet lines is of the order of 100 kilometres as shown in the table below :

Isohyet concerned	Oscillation amplitude in the West*	in the Centre *	in the East *
400 mm	-	-	125 km
600 mm	135 km	120 km	100 km
800 mm	40 km	40 km	60 km
1000 mm	90 km	160 km	120 km
1200 mm	75 km	150 km	140 km
* in relation to the zone studied which ends at the MOPTI longitude			

TABLE 1: ISOHYET OSCILLATION IN DIFFERENT BIO-CLIMATIC DOMAINS.

Comment: These isohyets are in the form of curves established on the basis of rather slack measurements. Recent studies, in which NOAA satellite images were used in the Sahelian and Sudanian areas, made it possible to confirm their drawing.

The table is an interesting piece of information on the oscilation amplitude between the dry and damp periods shown by different isohyet curves. The amplitude is lowest on the 800 millimetre isohyet covering only about 50 km. In other ones, the amplitude is of the order of 100 km. As a matter of fact the Mourdiah zone is situated on the 800 mm isohyet. See figure 1.

The figure on the following page illustrates marked variations in the average precipitation between the dry and damp decades of an area. The Southern location of the 400mm isohyet, refering to a dry decade, is very close to the most Northern position of the 600 mm isohyet of the damp decade. Similar variations can be seen, in couples i.e. 600 mm in the dry season, 800 in the damp season and 800 in the dry season, 1,000 in the damp season. Concerning the couple representing 1,000 mm in the dry season, 1,200 in the damp one, and their equivalents: 1,200 and 1,400, the oscillation is such that isohyets X in the dry season crossed in its drop to the South isohyets X+200, in the damp period.

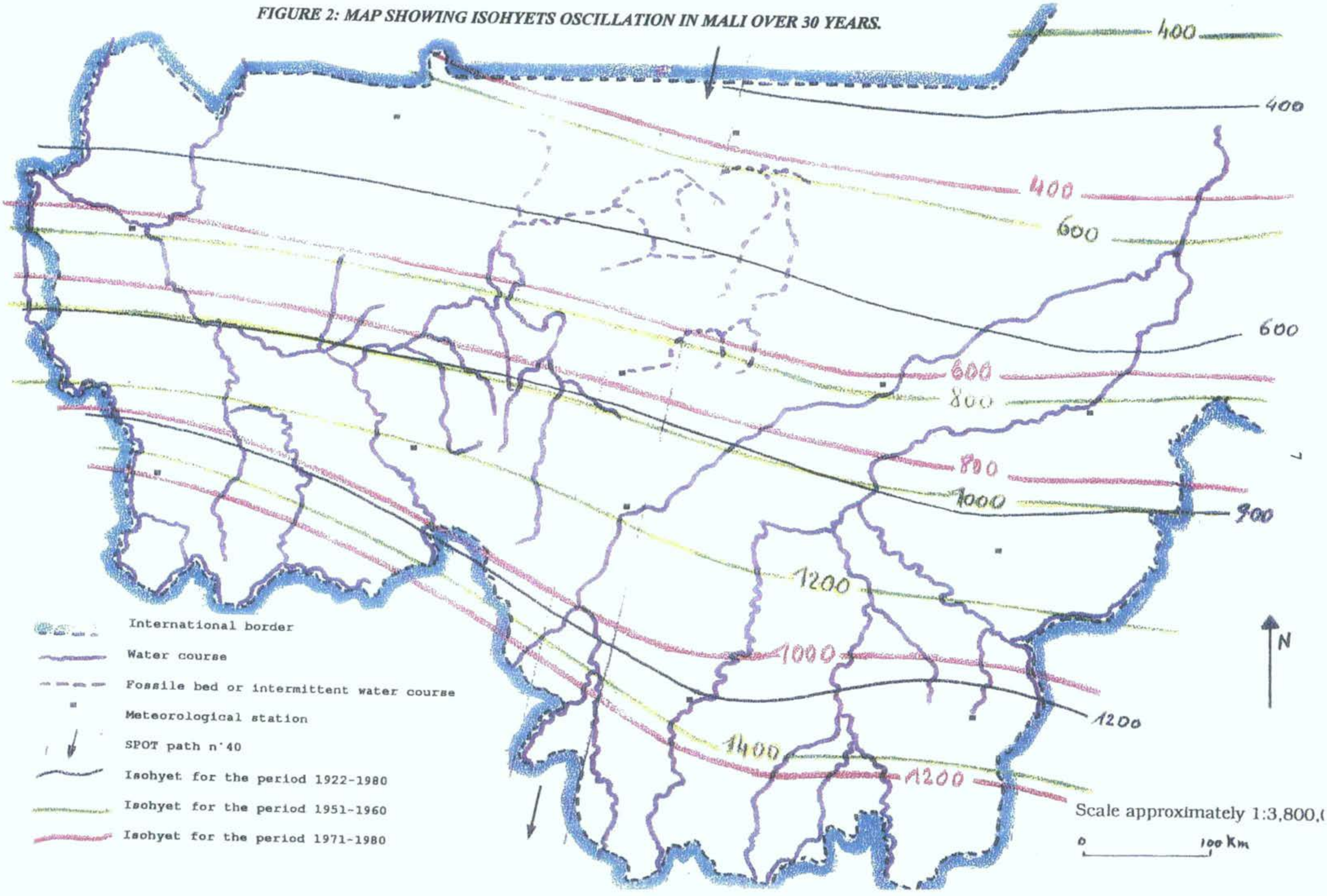
The consequences of such variations are probably less damaging in the South where rainfall varies from 1,400 to 1,200 mm than in the North. In the Nara zone for example, rainfall available varies between less than 400 mm to just over 600 mm depending on the decade. Surely, the total amount of precipitation is not the only item to take into account and the distribution of precipitation over the whole year is of paramount importance.

2.4. Results obtained from field work and from a comparison of two aerial coverages

The main result obtained from a computerised crossing (in the G.I.S.) of interpretations based on photographs from the 50's and from 1987, is an evolution map which shows that:

- cultivated land in one year increased in all the three zones, sometimes significantly, like in Nara, whereas in Mourdiah, farming tended to occupy all the land available, from the bottom of valleys going up to the head of thalwegs.
- different categories of natural vegetation covering large stretches of land in the 50's somehow divided up and, generally, there was a trend to move from more towards less natural vegetation. However, locally, in favourable conditions i.e. satisfactory rainfall or smaller human exploitation, vegetation can show a denser cover. This is the case of Yanfolila.

FIGURE 2: MAP SHOWING ISOHYETS OSCILLATION IN MALI OVER 30 YEARS.



2.4.1. Results concerning agricultural areas

Interpretation was related to the themes of annual cultivation and of agricultural land defined as every area cultivated at least once (traces of such cultivation are visible for a long time on aerial photographs) including, of course, annual cultivation.

The maps of two zones i.e. Nara and Mourdiah, are presented on the following pages. The synoptic table below clearly shows:

-a doubling of cultivated land surface area between the 50's and 1987,

-a comparable increase of agricultural land only in Nara. Elsewhere, agricultural land already corresponded to every cultivable soil, so an increase was not possible.

-as a result of what is said above, a time of recurrent cultivation on the same soil which was halved in Mourdiah and Yanfolila. The following table summarises these results:

	NARA		MOURDIAH		YANFOLILA	
Total acreage in ha	60,300	100 %	69,700	100 %	66,800	100 %
Cultivation in the 50's C1	2,498	4.1 %	4,500	6.4 %	2,920	4.4 %
Cultivation in 1987 C2	4,397	7.3 %	10,500	15.1 %	7,130	10.7 %
Agricultural land in the 50's T1	16,300	28 %	45,300	65 %	49,430	74 %
Agricultural land in 1987 T2	33,600	55 %	49,500	71 %	48,800	73 %
Agricultural land vs. annual cultivation *	T1 / C1 **6.5**		T1 / C1 **10.1**		T1 / C1 **16.9**	
	T2 / C2 **7.6**		T2 / C2 **4.7**		T2 / C2 **6.8**	
* Gives an indication of the cultivation rotation periods.						

TABLE 2: TIMES OF AGRICULTURAL ROTATION IN NARA, MOURDIAH AND YANFOLILA

The following pages illustrate these facts in Nara where the acreage of agricultural land grew at the same pace as the acreage of land under annual cultivation. For Mourdiah, on the contrary, almost all the cultivable soils were already under cultivation in the years 50s and the increase in land cultivated for 1987 (from 4,500 to 10,500 ha) results in a shorter cultivation rotation period (cf. figures 3 and 4).

2.4.2. Results concerning natural environment

In each of the 3 zones, Nara, Mourdiah and Yanfolila, the diachronic land cover maps with 18 legend items were digitised as layers in a G.I.S. Statistics were computed on these layers to obtain comparative matrixes for the 3 areas with their various themes of land use at two dates.

A summarised data table placed hereafter (see table 3, page 11) shows the proportion of the total acreage covered by a given theme in relation to the entire area studied (about 60,000 hectares for each of the zones). Transfers from one theme to another (expressed in percentage of the total acreage) are represented in the form of arrows. For example, in Nara tree-covered savanna represented 38,639 hectares or 64% of the total area of 60,241 hectares.

From the said 38,639 hectares, only 18,483 hectares or 31% remained classified under the same theme, whereas 16,189 hectares (27%) became shrub savannas and 2,906 hectares or 5% were used for cultivation.

There was a transition from the theme of tree-covered savanna to the theme of a sparcer natural vegetation cover for 27% of the total acreage and this phenomenon was accompanied by a loss of acreage (5%) due to its clearing for cultivation purposes.

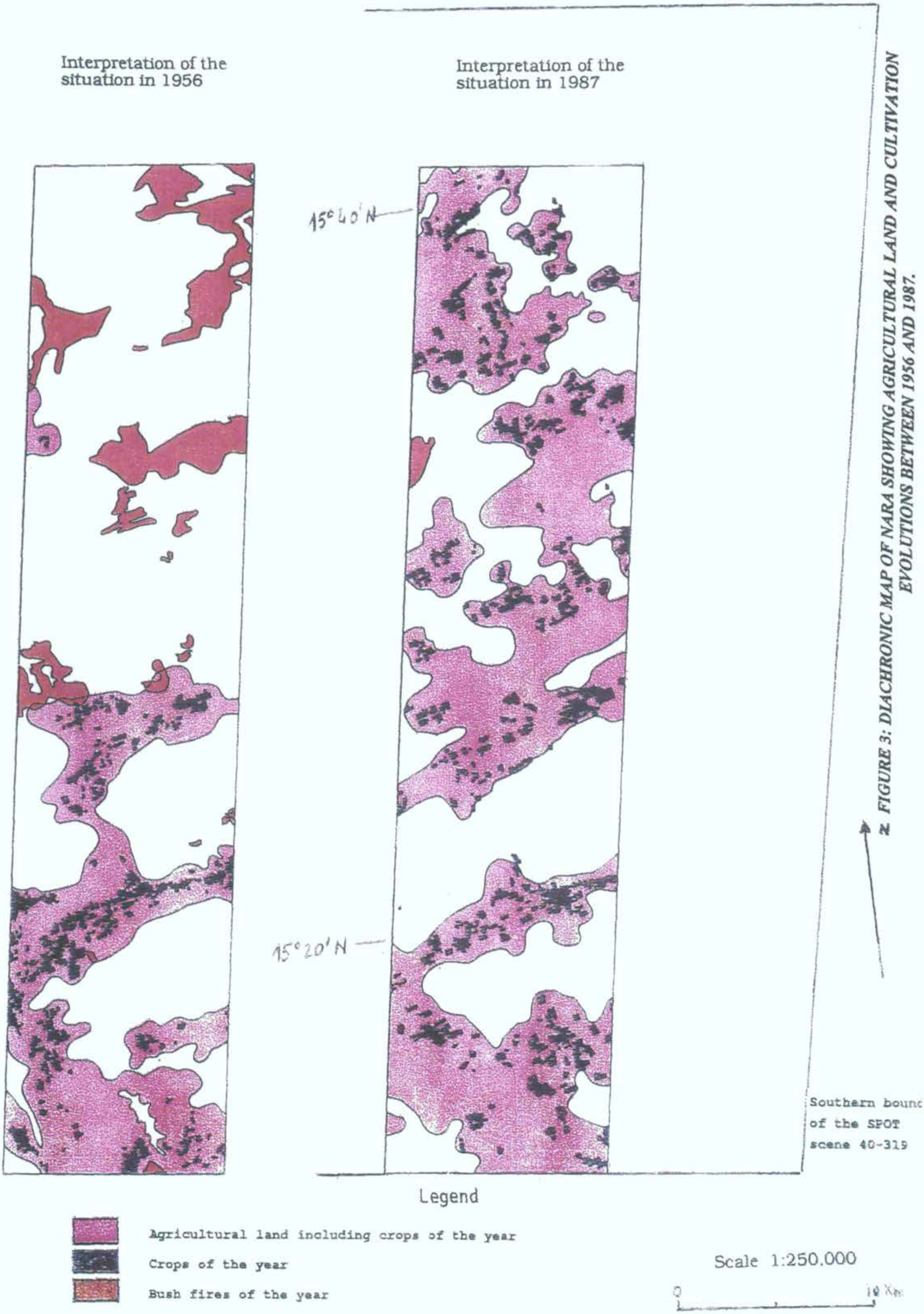


FIGURE 3: DIACHRONIC MAP OF NARA SHOWING AGRICULTURAL LAND AND CULTIVATION EVOLUTIONS BETWEEN 1956 AND 1987.

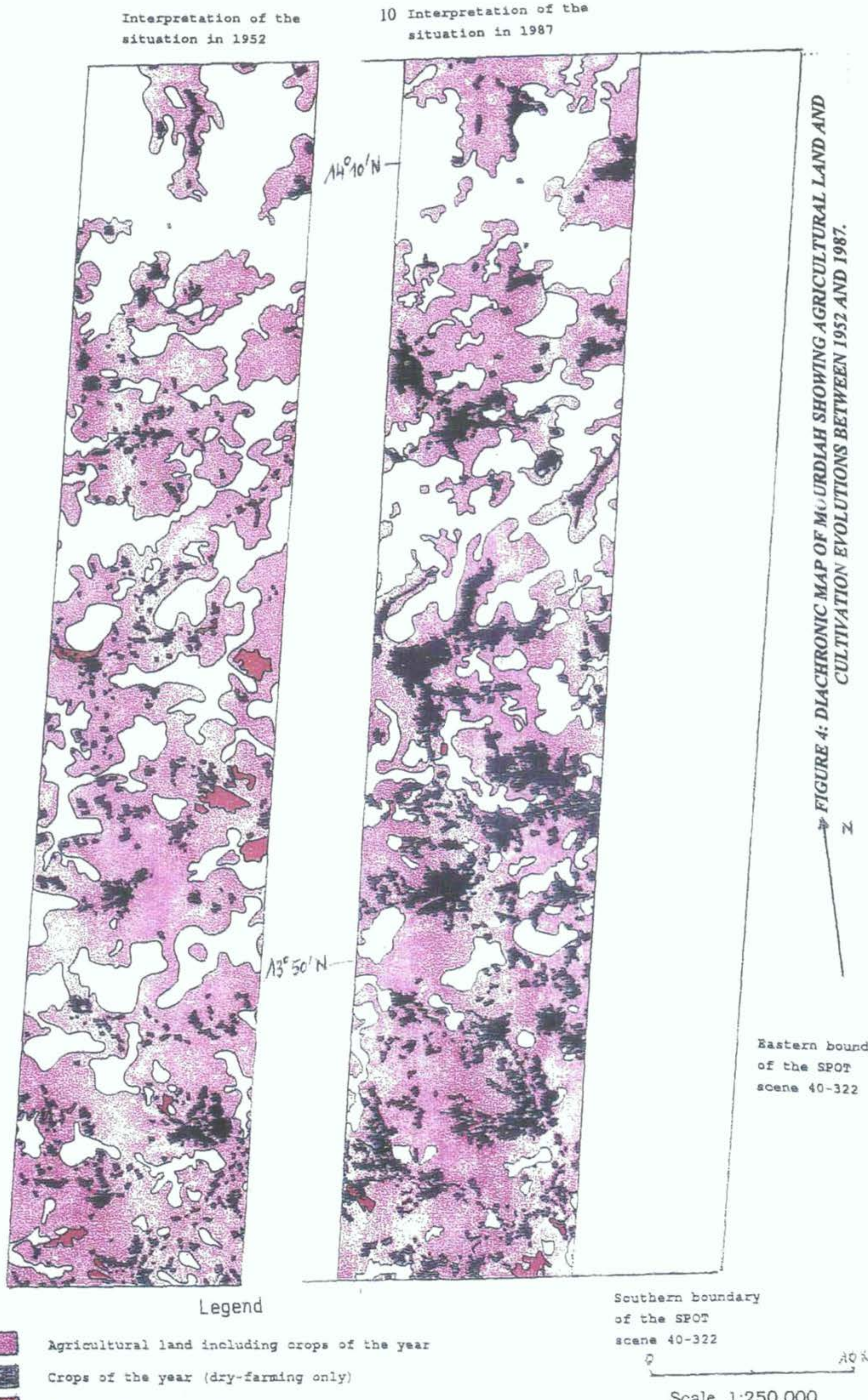


FIGURE 4: DIACHRONIC MAP OF MOURDIAH SHOWING AGRICULTURAL LAND AND CULTIVATION EVOLUTIONS BETWEEN 1952 AND 1987.

%	NARA		MOURDIAH		YANFOLILA	
	1957	1987	1952	1987	1952	1987
Annual cultivation	4,1	7,3	6,4	15,1	4,4	10,7
Irrigated areas						
Clear forest					0,3	1,3
Woodland savanna	1,2	1,3	10,8	6,5	28,0	63,2
Tree savanna	64,1	38,3	73,4	53,0	41,8	12,2
Shrub savanna	20,9	44,1	8,6	16,8	14,9	2,2
Herbacious savanna	0,9	0,8			3,4	1,9
Tree steppe	3,4	1,8	0,1			
Shrub and bush steppe.	2,4	2,8	0,2			
Herbacious steppe	2,7	2,6				
Aquatic meadow					0	0,4
Swampy meadow					1,9	0,2
Bowal			0,1	0,2	1,4	1,2
Tree bowal			0,2	1,0	2,3	2,0
Gallery forest					1,0	1,4
Bare soil	0,1	0,9	0	7,2	0	0,4
Villages		0,1		0,1	0,2	0,5
Rivers					0,6	0,2

Surface area (in %) by different themes

$A \xrightarrow{x} B$

movement of x % from A towards B

TABLE 3: EVOLUTION OF LAND USE THEMES BETWEEN 1952/57 AND 1987 IN NARA, MOURDIAH AND YANFOLILA.

A similarity in figures can be seen in the Mourdiah zone whereas in the Yanfolila zone the situation for savannas is reversed. This is confirmed by the direction of the theme movement from the sparsest vegetation cover theme to themes of denser vegetation. However, the use of the natural spaces in Yanofolila for cultivation is not to be neglected (6% of the total acreage).

The results seem interesting and may lead to a more detailed analysis of a phenomenon which appears to be rather complex. The method is slightly heavy and time-consuming for the thematic specialist. Could the sample be reduced in size while keeping reasonable accuracy?

An attempt was made in which an extract of 1,000 hectares was selected in the numerical data basis compiled during the study of Mourdiah (Geographical Information System). This land is part of a larger stretch of 4,000 hectares. With the help of a computer, land use tables were produced with two dates in order to compare them with the interpretation made over the entire 60,000 hectares studied in the Mourdiah zone. Table 4 of the following page shows the results.

These results show that too small an extract (and 4,000 hectares is still too small) can considerably prevaricate certain themes which are by their very nature localized as cultivated land is.

Taking into account the zonal character of land use in the Sahelien environment in which climatic conditions vary rapidly in the North-South direction, and very little in the East-West direction, a study of North-South transects over a large area (of the order of 60,000 hectares) is probably the best compromise possible.

2.4.3. Results concerning men and animals

There is a clear sedentary tendency throughout the Northern part of the transect in which population density is under 10 inhabitants per square kilometre. In the Eastern and Southern parts of the Mourdiah zone, population density is over 10 and locally over 15 inhabitants per square kilometre.

Urban population density is increasing rapidly. In 1965 Mali had only one city of over 100,000 inhabitants: Bamako, and 25 agglomerations of over 5,000; whereas now, there are 2 towns of over 100,000 inhabitants: Bamako and Segou, and there are 65 agglomerations of over 5,000 inhabitants.

Agricultural production data shows a quasi stagnation (an increase of only 4.3% between 1960 and 1982).

Insofar as breeding is concerned, significant variations are involved, i.e. cattle breeding increased by 2.6% per year from 1965 to 1972, followed by a period of decrease during the draught of 1972 and 1973 (due to a high mortality rate and/or migration to other regions). Then there was a period of livestock regeneration, followed by another period of decrease during the draught from 1982 to 1984. Sheep and goat livestock underwent the same variations so the curves are parallel.

It is difficult to produce data, which can be used over the period of our study (over 30 years) from figures, altered by climatic variations, which fluctuate so rapidly.

TABLE 4: COMPARISON OF LAND USE EVOLUTION IN MOURDIAH BETWEEN 1952 AND 1987 FOR THE ANALYSIS OF TWO EXTRACTS (4,000 HA AND 1,000 HA).

LARGE EXTRACT 4,000 HECTARES EVOLUTION 1952/1987	Cultivation of the year 1987	Clear Forest 1987	Woodland Savanna 1987	Tree Savanna 1987	Shrub Savanna 1987	Tree Bowal 1987	Bare Soil 1987	Villages 1987	TOTAL in ha in 1952	TOTAL in % in 1952	A reminder of the total in % in 1952 of the entire zone 69622 ha
Cultivation of the year 1952	217		1	93	35		3	6	355	8,9	6,4
Clear Forest 1952	1		12	5	5		5		28	0,7	0
Woodland Savanna 1952	5		97	105	30	12	21		270	6,8	10,8
Tree Savanna 1952	938		84	1156	743	4	168		3093	77,3	73,4
Shrub Savanna 1952	56			70	112		16		254	6,3	8,6
TOTAL in ha in 1987	1217	0	194	1429	925	16	213	6	4000	100	99,2 *
TOTAL in % in 1987	30,4	0	4,9	35,7	23,1	0,4	5,3	0,2	100		

A reminder of the total in % in 1987 of the entire zone 69622 ha									
	15,1	0	6,5	53,0	16,8	1,2	7,2	0,1	100

SMALL EXTRACT 1, 000 HECTARES EVOLUTION 1952/1987	Cultivation of the year 1987	Clear Forest 1987	Woodland Savanna 1987	Tree Savanna 1987	Shrub Savanna 1987	Tree Bowal 1987	Bare Soil 1987	Villages 1987	TOTAL in ha in 1952	TOTAL in % in 1952	A reminder of the total in % in 1952 of the entire zone 69622 ha
Cultivation of the year 1952	67		1	16	4		2	4	94	9,4	6,4
Clear Forest 1952	1		1		1				3	0,3	0
Woodland Savanna 1952			4	15		2	1		22	2,2	10,8
Tree Savanna 1952	221		5	331	181		61		799	79,9	73,4
Shrub Savanna 1952	18			9	46		9		82	8,2	8,6
TOTAL in ha in 1987	307	0	11	371	232	2	73	4	1000	100	99,2 *
TOTAL in % in 1987	30,7	0	1,1	37,1	23,2	0,2	7,3	0,4	100		

A reminder of the total in % in 1987 of the entire zone 69622 ha									
	15,1	0	6,5	53,0	16,8	1,2	7,2	0,1	100

* the difference to 100 % is due to the themes steppe and bowal represented in the entire zone and not in the extracts

2.4.4. Conclusions drawn from results of aerial photography interpretation

In view of the results obtained, it seems that **the Mourdiah region** in which rainfall is relatively stable (800 millimetres) and which **was already extensively used for farming in the 50's, was in 1987 the most exploited area by man.** All seems to imply that population withdrew from the North in the dry period, (without leaving the semi-arid environment, which they were used to) and migrated to already densely populated zones thus exerting more demographic pressure on those zones. In considering land cultivation, the said temporary migration brought about **a shortening of the fallow period** to less than 5 years.

In more Northernly latitudes, in least rainy areas (400 millimetres isohyet), an increase in the surface area of agricultural land was the result of a demographic boom. In Yanfolila in the Sudanian sector with a rainfall of 1,200 mm, the period of agricultural rotation also diminished but it still remains of the order of 7 years. Thus, it is indeed in the middle part of the transect on the border between the Sahelian and Sudanian sectors that the pressure of man on environment is marked most clearly.

For the 18 legend items an evolution map was produced by a computerised crossing of the digital data stored in the Geographical Information System (G.I.S.). This maps shows the **locations** where the changes we already knew of statistically have occurred. Generally, throughout the transect, everything concerning natural vegetation i.e. different categories of vegetation cover which in the 50's formed large colonies, broke up, giving rise to a decrease in vegetation density. On the other hand, it has been confirmed that, in more favourable conditions i.e. higher rainfall, smaller human pressure etc., vegetation regenerates itself and tends to expand in terms of its cover density.

2.5. Results summary of the diachronic interpretation of aerial photographs

Statistics obtained on land use show that:

1/ A recession of the tree-covered savanna occurred everywhere; exceptionally in favour of wooded savanna in Yanfolila, but most frequently in favour of shrub savanna.

2/ Bare soil increased on every latitude.

3/ Cultivated land virtually doubled in size everywhere.

4/ It was not the Sahelian domain which deteriorated most but that of the Sudan-Sahelian sectors, in which, around the 800 mm isohyet, the climatic conditions vary least between the damp and dry periods. In that zone the population seems to settle, chased away by the draught from the North, when climatic conditions become too severe.

2.6. Results of a visual interpretation of SPOT satellite images

A visual interpretation of SPOT satellite images was attempted in the following themes: bare soil, annual cultivation and agricultural land. In the two latter ones, a visual analysis of images seems to present an advantage over a digital analysis as cultivation (present or past) can be identified on an image or on an aerial photograph not by its colour or by a particular shade of grey, but by an original **spatial layout called parcel pattern.** It is not marked very clearly in an African environment but it is recognisable.

The advantages of having an operator on a machine in distinguishing forms are important. So, there is hope of obtaining interesting results.

On the following pages (see figures 5 and 6 on pages 16 and 17) a side by side presentation of visual interpretations for the themes annual cultivation and agricultural lands is presented for the transect on Nara. Even if the themes seem well interpreted on the SPOT image at first glance, a digital comparison produces the following figures.

They concern the visual interpretations of SPOT images for the themes: "annual cultivation" and "agricultural land" for Nara, Mourdiah and Yanfolila compared with results of aerial photography interpretations.

Table 5 below, summarises the results of this comparison:

	Annual cultivation		**Bare soil**		**Agricultural land**	
Total acreage in ha	**Aerial photos**	**SPOT visual analysis**	**Aerial photos**	**SPOT visual analysis**	**Aerial photos**	**SPOT visual analysis**
60,241 ha NARA	4,406 ha 7.31 %	4,856 ha 8.06 %	519 ha 0.86 %	143 ha 0.24 %	33,600 ha 55.8 %	34,636 ha 57.5 %
69,622 ha MOURDIAH	10,601 ha 15.23 %	6,700 ha 9.62 %	5,008 ha 7.19 %	2,083 ha 3.46 %	49,500 ha 71.1 %	49,856 ha 71.6 %
67,888 ha YANFOLILA	7,202 ha 10.61	7,489 ha 11.03 %	280 ha 0.41 %	76 ha 0.11 %	48,800 ha 71.9 %	48,241 ha 71.1 %

TABLE 5: VISUAL INTERPRETATION OF SPOT IMAGES AND AERIAL PHOTOGRAPHS FROM THE SAME DATE.

Agricultural land in its totality is clearly recognisable. It is not so in "annual cultivation" in Mourdiah or in "bare soils" in the three zones where aerial photographs have to be used.

In view of these results **it is difficult to decide that the method is completely efficient even for themes related to agriculture** which are easier to interpret than natural vegetation themes. The results closest to those of photo-interpretation, used here as a standard, are obtained on the images of Nara and Yanfolila. The Mourdiah image corresponds to a more complex environment and it gives less satisfactory results except for agricultural land.

Following our experience, the possibilities offered by using visual interpretation on different analog documents are represented in figure 7 (page 18).

FIGURE 5: NARA - COMPARATIVE INTERPRETATION OF AERIAL PHOTOGRAPHS AND SPOT IMAGE IN THE THEME: LAND CULTIVATION OF THE YEAR IN 1987.

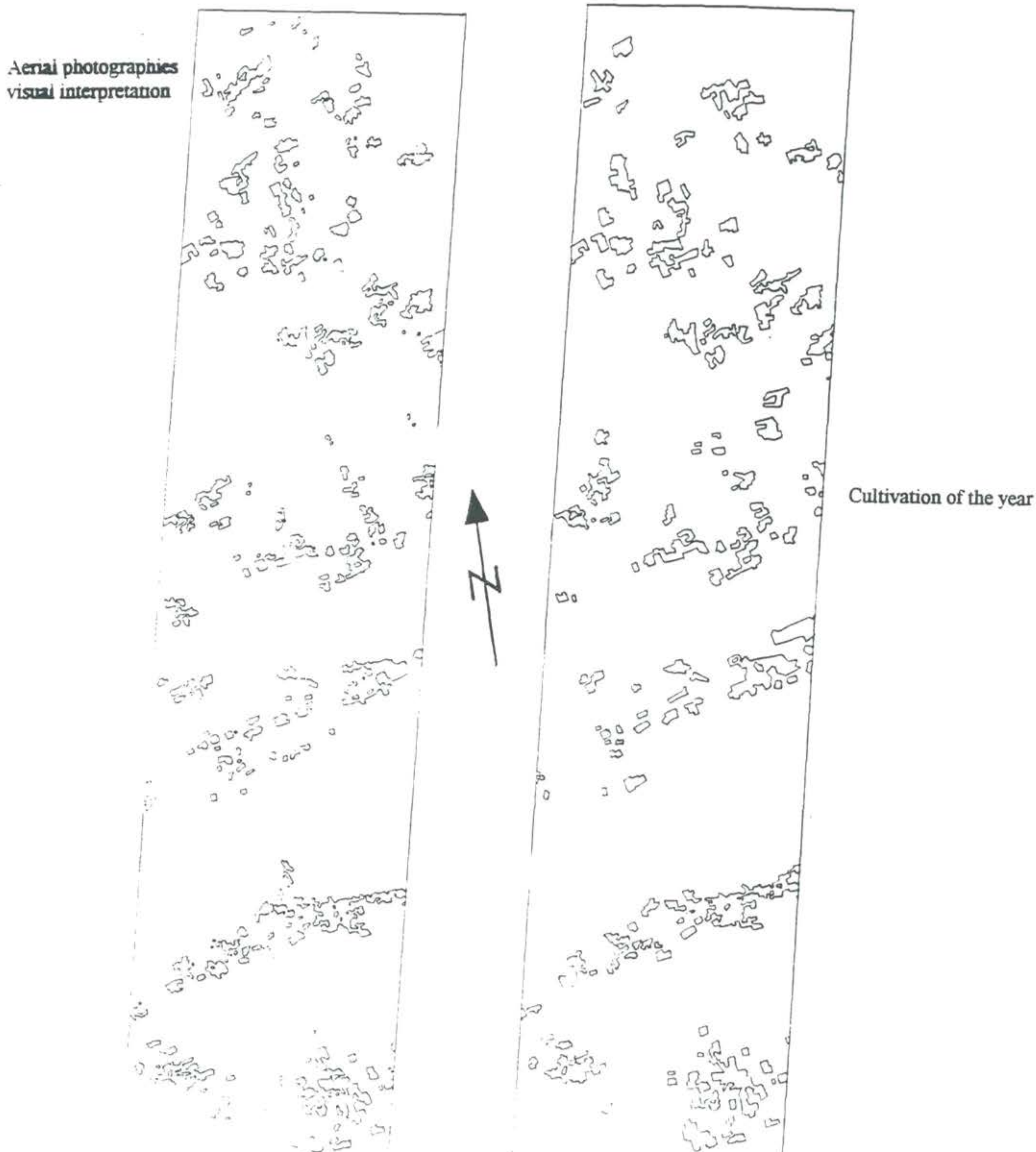


FIGURE 6: NARA - COMPARATIVE INTERPRETATION OF AERIAL PHOTOGRAPHS AND SPOT IMAGE IN THE THEME: AGRICULTURAL LAND IN 1987.

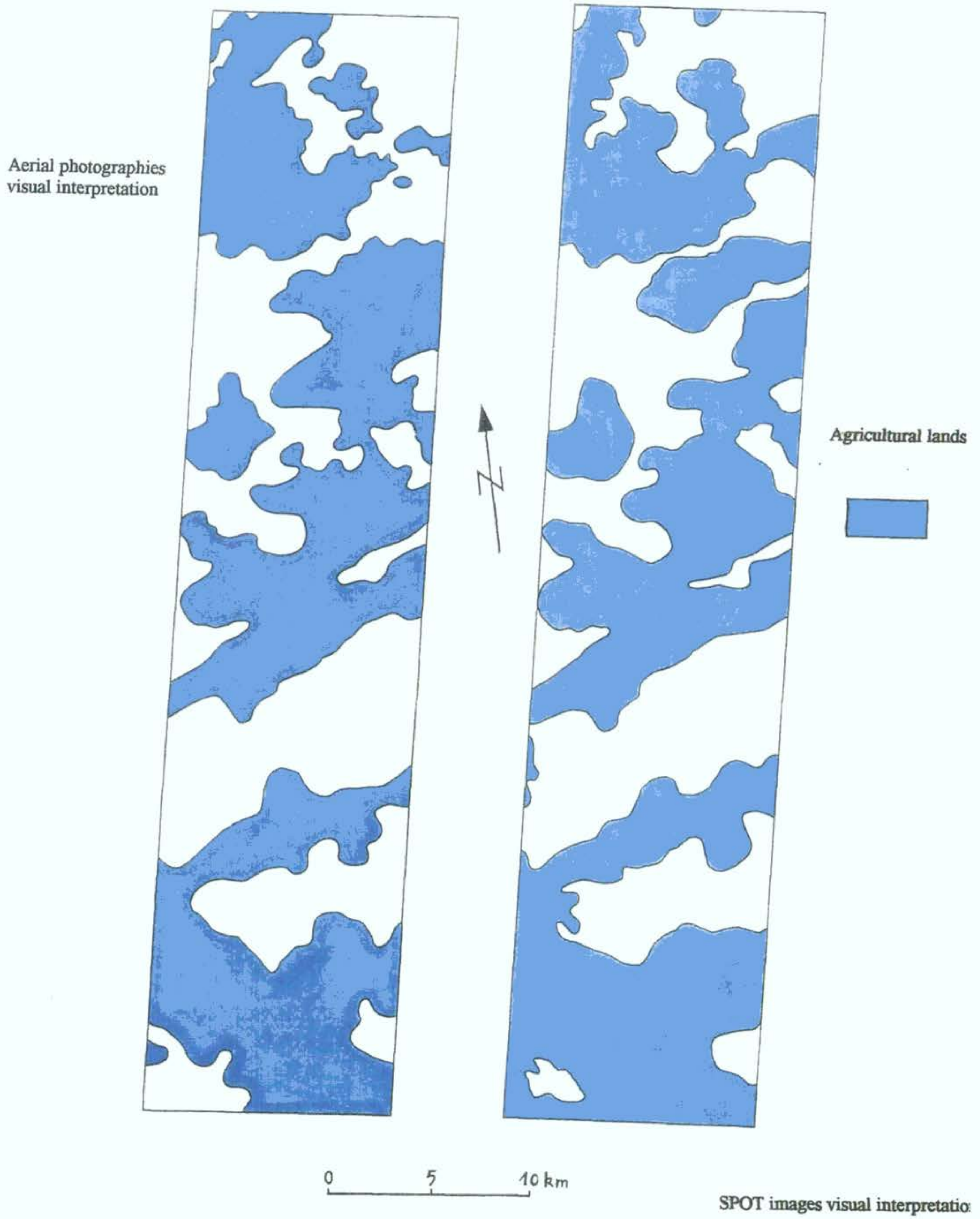


FIGURE 7 COMPARATIVE ANALYSIS OF DIFFERENT DOCUMENTS TO VISUALLY INTERPRET DIFFERENT THEMES OF LAND USE.

++++ excellent — inoperable	Black and white aerial photograph 1:50,000	IRC aerial photograph 1:50,000	SPOT XS (false colour) 1:100,000
Bare soil	++++	++++	++
Bowal	++++	++++	+++
Annual cultivation	++++	++++	++
Herbacious steppe	+++	+++	—
Shrub and bushy steppe	++++	++++	—
Tree-covered bowal	++++	++++	++
Tree-covered steppe	++++	++++	—
Grass savanna	++++	++++	—
Shrub savanna	++++	++++	—
Tree-covered savanna	++++	++++	—
Wooded savanna	++++	++++	—
Clear forest	++++	++++	++++
Gallery forest	++++	++++	++++
Marshy meadow	++++	++++	++++
Aquatic meadow	++++	++++	+++
Irrigated area	++++	++++	++
River, open water	++++	++++	++++
Village	++++	++++	++++ from a given size
Agriculture land	++++	++++	++++
Camp	+++	++++	—
Hamlet	++++	++++	—
Medium size village	++++	++++	+++
Village noticeable at 1:100 000	++++	++++	++++
Well	++	++++	—
Pond	++++	++++	++++
	(even	dried up)	(full)
Humid area	++++	++++	+++
Flooding aera	++++	++++	—
Permanent hydrographic network	++++	++++	++++
Temporary hydrographic network	++++	++++	+++ (according to order)
Tracks (except cattle)	++++	++++	+ the most important
Cattle tracks	++++	++++	+ the most important

3. THE SECOND TRANSECT: TOMBOUCTOU - HOMBORI - SEGUENEGA

3.1. Data processing for the second transect

In the study of the first transect, described above in detail, our objective was to explore all the possibilities of a visual analysis of the existing documents. An exhaustive study of aerial photographs from the 50's and from 1987 allowed us to produce a map with elements such as wells, tracks, hydrographic network, etc., a map of land use with a legend of 18 themes and a map of land use evolution covering the period between the two dates.

The study was completed by an interpretation of agricultural land, an analysis of human occupancy, of domestic animals and a dynamic geomorphological analysis. Finally, for certain land use themes the results of a visual analysis of aerial photographs were compared with those of SPOT images.

In the present transect only the methods that seemed to be most interesting among those used in the first transect were applied, namely, a comparison of land use interpreted on aerial photographs from two different dates. After photo-interpretation and a report on a metric document, in this case a space-map at a 1:100,000 scale, the resulting drawings were digitized in order to cross information on land use from the two dates.

Furthermore, the second transect marks a transition towards the search for an automated method, less subjective and more economic, using satellite images and applicable to all subsequent transects. In chapters 5 and 6 the results obtained by using the new method will be presented and compared with the results obtained from the photo-interpretation method.

3.2. Results from an aerial photography diachronic interpretation

3.2.1. Reading method of comparison matrix

In the tables overleaf pages 20, 22 and 24 (see tables 6 to 8) land use figures for different themes, from two dates are compared. The Hombori table will be taken as an example (cf. table 7, page 22) presented in 3.2.3. below.

The **columns** contain information on land use in 1989. The first theme, annual cultivation, shows a total of 2,101 hectares. Along the horizontal **lines** land use in 1955 is shown. Under the same theme, along the line, a total of 1,156 hectares is given.

If statistical information on global variations of land use is sought, only total figures should be considered and the figures of the last column and the last line should be consulted. In keeping with the same theme, the annual cultivation area increased from 1,156 to 2,101 hectares between 1955 and 1989.

The analysis can be more refined, and among the 1,156 hectares covered by the theme in 1955, one can look for what remained in the same location in 1989. Then, the figures at the crossing of the relevant column and line corresponding to the theme should be considered - the first column and the first line in this case. It was found that from a total of 2,101 hectares which were cultivated in 1989, only 246 hectares, or 21% of the area covered by the same theme in 1955 did not change place.

If only 246 hectares from 1,156 hectares of cultivated land in 1955 remained, what happened to the rest, how did it evolve? In order to answer the question it suffices to follow the first **line**. From the data it appears that, while 246 are still cultivated, 552 became wooded or tree-covered savanna/steppe, that 252 hectares became shrub savanna/steppe, and that 9 hectares turned into savannas or steppes.

For the same theme, in 1989, one may wonder on what type of land did cultivation gain surface. Again, the procedure is to follow the theme **column**, the first column in this case, to find out that: 246 hectares come from already cultivated areas in 1955, that 739 hectares were wooded or tree-covered savanna/steppe, that 981 hectares were turned into cultivated land from shrub savanna/steppe, that 53 hectares are former grass savanna/steppe, etc.

In the case of land cultivation, the geographical stability of the annual cultivation theme is not as high as other themes: 246/1,156 or 21% versus 9,403/19,489 or 48% in wooded or tree-covered savanna/steppe themes.

TABLE 6: DIACHRONIC (VISUAL) INTERPRETATION (1952 - 1989) OF LAND USE IN TOMBOUCTOU.

VISUAL INTERPRETATION OF AERIAL PHOTOS FROM FEBRUARY 1955	VISUAL INTERPRETATION OF AERIAL PHOTOS FROM JANUARY 1989								
THEMES	Annual cultivation 1989	Savanna/steppe woodland/tree 1989	Savanna/steppe shrub 1989	Savanna/steppe 1989	Miscellaneous (pools, villages) 1989	Forest 1989	Bare soil 1989	Tree bowal 1989	**TOTAL in ha 1955**
Annual cultivation 1955	0	0	0	0	0	0	0	0	**0**
Savanna/steppe woodland/tree 1955	124	10030	8190	851	26	333	6604	0	**26158**
Savanna/steppe shrub 1955	24	1780	5291	651	14	270	4875	0	**12905**
Savanna/steppe 1955	0	305	1578	301	0	61	1184	0	**3429**
Miscellaneous (pools, villages) 1955	0	1	0	0	0	0	1	0	**2**
Forest 1955	0	1169	1740	222	5	688	1823	0	**5647**
Bare soil 1955	0	1055	1896	312	2	120	15161	0	**18546**
Tree bowal 1955	0	16	182	2	0	3	326	0	**529**
TOTAL in ha 1989	**148**	**14356**	**18877**	**2339**	**47**	**1475**	**29974**	**0**	**67216**

TOMBOUCTOU

Here is a type of analysis which allows an interpretation of matrix comparisons between land use themes, obtained from an interpretation of aerial photographs, with a 34 -year- long interval.

3.2.2. Analysis of results from Tombouctou (table 6)

According to the rules defined above, reading of data is done in the following way: the theme land use in January 1989 can be found in the **columns**. For example, under theme 2, wooded or tree-covered savanna/steppe, there are 14,356 hectares in 1989. Likewise, land use in October 1955 can be found by reading of data along the horizontal **lines**, and it amounts to 26,158 hectares under the same theme.

3.2.2.1. Statistics reading

Here only the last column concerning totals should be read, i.e. land use in 1955 and the last line with land use in 1989.

Areas covered by wooded or tree-covered savannas or steppes decreased significantly between 1955 and 1989, from 26,158 hectares or 39% to 14,356 hectares or 21% of the zone studied. On the contrary, shrub-covered savannas or steppes increased in area from 12, 905 to 18, 877 hectares.

The surface of bare soil increased from 18,546 hectares, or 28% to 29,974 hectares, or 45% of the area studied.

3.2.2.2. Localisation reading

Themes are more or less stable in terms of localisation. Under wooded or tree-covered savanna or steppe, from 26,158 hectares in 1955 only 10,030 hectares or 38% remained in the same place in 1989. Likewise, under shrub savanna or steppe, from 12,905 hectares in 1955, merely 5,291 hectares or 41% could be found in the same place 34 years later.

Under bare soil the opposite tendency can be seen; it is stable in terms of localisation (but very much on the increase in area) as, from the 18,546 hectares registered in 1955; 15,161 or 82% was still found in the same place in 1989.

3.2.2.3. Thematic reading

Wooded or tree-covered savannas or steppes decreased a great deal during the period discussed. What happened to them? By reading line 2 it appears that, while 10,030 hectares remained under the same theme, 8,190 turned into shrub savannas or steppes and that 6,604 turned into bare soil.

Similarly, in line 3 it can be seen that, while 5,291 hectares of bush savanna or steppe remained the same, 1,780 became wooded or tree-covered savannas or steppes and that 4,875 deteriorated into bare soil.

These transformations, which seem to indicate a general degradation of natural vegetation, were observed on the field, where the operator noted during his survey "Next to the remnants of a vast hydrographic network, which collects some water in the rainy season, vast sterile zones can be seen. These areas are covered by a powdery deposit, prone to a splashing effect, as light as flour which, with the slightest blow of air, rises, forming turbulent columns or by spreading debris and lateritic gravel. At that time (mid-January) we met very few people. Water points were already dried up. At 16°40'N, on the sides of pools with remnants of water at Tin Echeri, representatives of a group of Marabouts, the Tamacheqs, (Chériffen) stayed for as long as possible next to a well, which has never produced a drop of water.

Some weeks later, the group, although decided to settle in the area (huts made of hard material, show this), had to leave and assemble around a patch which offered a few permanent water sources.

On our way Southwards, the relics of a water network allowing some vegetation to grow around it, could be seen and it is dense enough to shelter and feed numerous elephants. Interfluves dried up and skeletons of dead trees show just how severe the climate is. Eroded and flattened termite cathedrals bear testimony of a long-forgotten abundance of tree-like matter in times of greater splendour."

TABLE 7: DIACHRONIC (VISUAL) INTERPRETATION (1955-1989) OF LAND USE IN HOMBORI.

VISUAL INTERPRETATION OF AERIAL PHOTOS FROM OCTOBER 1955 (rows) / VISUAL INTERPRETATION OF AERIAL PHOTOS FROM JANUARY 1989 (columns)

THEMES	Annual cultivation 1989	Savanna/steppe woodland/tree 1989	Savanna/steppe shrub 1989	Savanna/steppe 1989	Miscellaneous (pools, villages) 1989	Forest 1989	Bare soil 1989	Tree bowal 1989	TOTAL in ha 1955
Annual cultivation 1955	246	552	252	9	10	69	17	1	**1156**
Savanna/steppe woodland/tree 1955	739	9403	5157	54	15	1797	2046	278	**19489**
Savanna/steppe shrub 1955	981	16157	10853	79	21	993	1608	204	**30896**
Savanna/steppe 1955	53	955	949	784	2	42	207	15	**3007**
Miscellaneous (pools, villages) 1955	8	51	27	1	16	89	99	7	**298**
Forest 1955	62	1607	1475	30	5	3603	2048	500	**9330**
Bare soil 1955	12	646	597	66	4	505	1655	154	**3639**
Tree bowal 1955	0	162	83	7	1	144	738	162	**1297**
TOTAL in ha 1989	**2101**	**29533**	**19393**	**1030**	**74**	**7242**	**8418**	**1321**	**69112**

HOMBORI

3.2.3. Analysis of results from Hombori (table 7)

The reader could make figures speak by using the comments above. The instructions below are merely examples. See table overleaf.

3.2.3.1. Stastics reading

Only total figures are considered, land use in 1955 in the last column and land use in 1989 in the last line.

Annual cultivation changed from 1,156 hectares or 1.7% to 2,101 hectares or 3% of the aerial photograph strip studied. Areas covered by wooded or tree-covered savannas or steppes increased a great deal, going from 19,489 to 29,533 hectares over the period in question. This represents an increase from 28 to 43%.

Moreover, observations of the area indicate that a concentration of semi-nomadic population occurred in the 50's. The phenomenon started already in 1955 and the photo-interpretor notes: "On photographs from the 50's, it can be seen that there are more, evidently abandoned old human establishments and, most often in tiger bush or mottled bush zones, than on photographs from 1989. It can be assumed that in the past, settled and semi-settled population was spread out more regularly and in smaller groups than now in depopulated areas. This presumption seems to be a valuable one in view of the fact that tiger bush used to be a refuge from the attacks of predatory peoples.

In terms of the infrastructure, it can be said that road density, of all categories has diminished in Gourma. Some important ones which connect agglomerations and pastoral communities over long distances, have disappeared or have survived in a fragmented form. Simultaneously, the number of small human settlements and establishments seem to have diminished a great deal. If objective results of photo interpretation are added to impressions of a field trip, depopulation and a decrease in the pastoral community seems to have occurred. It may be assumed that a pastoral way of life is undergoing a crisis and that a tendency to a sedentary way of life is becoming more and more marked in existing villages, which are expanding or in temporary hamlets, which are perpetuating themselves. This is particularly true of ergs in the South of Hombori".

3.2.3.2. Localisation reading

A remarkable part of wooded or tree-covered savannas/steppes and of shrub savannas/steppes remain static in time: 9,403/19,489 hectares and 10,853/30,896 hectares or 48% and 35% respectively. Furthermore, there are exchanges between the two themes. If we consider the two themes together, it is 82% of their total area in 1955 that did not change in 1989.

Similarly, 1,655/3,639 hectares of bare soil representing 45%, did not move either.

3.2.3.3.Thematic reading

It can be informative to find out where does increase come from, in the themes of wooded and tree-covered savanna or steppe, and which themes contribute to this increase of areas occupied by this particular theme. It suffices to follow column 2 to see that 552 hectares were cultivated in 1955, that 16,157 hectares were shrub savannas/steppes that, 955 hectares were herbaceous savannas or steppes, that 1,607 hectares come from forests degradation, etc.

TABLE 8: DIACHRONIC (VISUAL) INTERPRETATION (1952-1989) OF LAND USE IN SEGUENEGA.

VISUAL INTERPRETATION OF AERIAL PHOTOS FROM FEBRUARY 1952	VISUAL INTERPRETATION OF AERIAL PHOTOS FROM JANUARY 1989								
THEMES	Annual cultivation 1989	Tree savanna 1989	Shrub savanna 1989	Savanna/steppe 1989	Miscellaneous (villages) 1989	Forest 1989	Bare soil 1989	Tree bowal 1989	**TOTAL in elements of 400 m² 1955**
Annual cultivation 1952	8161	3153	183	283	262	2576	155	1847	**16620**
Tree savanna 1952	13748	9343	1354	2776	171	2922	2779	7787	**40880**
Shrub savanna 1952	3952	4048	138	2402	183	913	330	5063	**17029**
Savanna/steppe 1952	409	204	199	317	8	97	337	622	**2193**
Miscellaneous (villages) 1952	56	3	0	0	0	45	3	42	**149**
Forest 1952	4268	1994	836	280	161	1500	116	1476	**10631**
Bare soil 1952	130	388	7	100	0	27	77	130	**859**
Tree bowal 1952	0	0	0	0	0	0	0	0	**0**
TOTAL in elements of 400 m² 1989	**30724**	**19133**	**2717**	**6158**	**785**	**8080**	**3797**	**16967**	**88361**

SEGUENEGUA

3.2.4. Analysis of results from Seguenega (table 8)

Comment: In the following analysis the results obtained from a comparison of numerical files concerning an extract of only 3,534 hectares will be studied. It was mentioned above in 2.4.2. that care should be taken here, not to take the results for granted because certain themes can be biased to a large extent when the sample area is not large enough. The results are expressed as elements of the pixel size of SPOT images, 20 by 20 metres, amounting to 400 square metres. See table overleaf.

3.2.4.1. Statistics reading

As a reminder it should be noted that, only total figures are to be considered i.e. the last column with land use in February 1952 and the last line with land use in January 1989.

Annual cultivation doubled in terms of area going from 16,620 elements or 18.8% to 30,724 or 34.8% of the total extract area. The tree-covered savanna and shrub savanna surface area decreased considerably as the figures diminished from 57,909 to 21,850 elements, or 65.5 to 24.7% of the total area in the extract. At the same time, herbaceous savannas/steppes increased from 2,193 in 6,158 elements whereas bare soil statistics show a quadrupling of their area from 859 to 3,797 elements, or from 1% to 4.3%.

These measurements confirm the observations made on the field by the operator: "On the SPOT scene of Seguenega human activity should be considered as a determining factor in ecozone degradation. Great population density, rigid social sructures, overuse of lowlands, very strong pressure of breeders and, to top it all, aridity all have contributed to this. It is not surprising that it has become a priviliged area of technical assistance from the West and of scientific research (ORSTOM studies). An immense amount of work has been carried out there such as water conservation, systems of erosion prevention, etc."

3.2.4.2. Localisation reading

Going by a small extract, natural environment themes are not very stable and there are a great deal of exchanges in terms of surface area between different types of savannas and even between savannas and forests. Cultivation in which, from 16,620 elements in 1952, 8,161 elements or 49.1%, was found in the same place in 1989 is the most stable theme in terms of localisation (note that its total acreage is expanding rapidly).

3.2.4.3. Thematic reading

Under the annual cultivation theme, an increase in surface area occurred mainly to the detriment of tree-covered savannas where 13,748 elements or 33.6% of the existing area in 1952 was cleared. Shrub savannas also paid a high price due to its clearing for agricultural purposes, its area decreased of 3,952 (23.2%) from the 17,029 elements which formed the theme in 1952. Same thing for forest which lost 4,268 of its 10,631 elements (40.1%) to the benefit of annual cultivation.

The appearance of the tree-covered bowal theme which did not exist in 1952 is interesting, and this type of landscape is the result of a transformation of tree-covered and bush savannas and forests.

3.3. Results summary concerning second transect analysis

A parallel can be drawn between these results with those obtained in 2.5. in the first transect. The following statments can be made:

1/ Tree-covered savannas receded everywhere, except for the Hombori image where they gained ground over shrub savannas and over steppes in general. There was a pastoral nomads settlement in that zone.

2/ Bare soil increased on all latitudes, particularly in Seguenega where its surface area increased 4 times.

3/ Cultivation surface area increased everywhere with a considerable progression in Seguenega where, 18.8% became 34.8% of the studied area.

All these results confirm those obtained in the first transect in which it appeared that, apart from events linked with the economic situation (strong settlement tendency due to the creation of irrigation perimetres in some cases, and to a feeling of insecurity, in others) the strong pressure of shepherds and extensive agriculture is damaging the environment by reducing its natural vegetation cover.

3.4. General conclusions on methods employed in the second transect

While results of a study of the first transect made it possible to produce a map on environment evolution in the period between the two dates by using aerial photography interpretation, we intended in this second transect to draw comparative tables by using computing methods which make way for the purely digital methods which will be employed in the study of the following third and fourth transects described below.

The said tables are easy to read and we think that they can provide precious information to theme experts in their research on the desertification phenomenon.

4. THE THIRD AND FOURTH TRANSECTS

The validity and the advantages of comparisons of aerial photography interpretations from the 50's and present ones were proved at length in the first two transects. Moreover, it was shown how heavy this method was and how it depended on the expertise of experienced photo interpreters and on highly qualified staff which is becoming difficult to find.

This is why from the third transect onwards, we will concentrate on looking for a method in which automated means are used. Fieldwork and recent aerial photo interpretation were treated as "truths" and as a basis of comparison of results obtained from a numerical treatment of satellite images.

Drawings of aerial photography visual interpretations of land use in 1990 were digitized to provide an easy comparison with results obtained from the two methods of automated classification which we explored and which are described in detail hereafter.

The comparison results are given in detail in chapters 5 and 6 below.

5. AUTOMATED ANALYSIS METHODS OF SATELLITE IMAGES

Whatever the two methods described below are, the SPOT images underwent a routine, preliminary treatment. Radiometric calibration is done at the receiving station and we limited our treatment to the use of radiometric masks and spectral bands combinations (Principal Components Analysis, ratio of band3/band 2), for the Mourdiah and Nara images with the sole aim of eliminating haze and smoke from the images.

Geometric corrections were made by taking ground control points from a topographic map at a 1:200,000 scale and applied to classification results using the method of the nearest neighbour.

The analysis concerned 12 SPOT satellite images. The results would doubtless be comparable if another high resolution satellite was used as, for instance, Landsat TM.

Landscape diversity and climatic conditions in the Sahel region results in very heterogeneous forms on a SPOT image which complicate its analysis. This complexity is increased by the large quantity of information contained in a SPOT image (over 27,000,000 figures). All these elements contribute to complicate and make heavy all image processings. This is why we decided to resort to a type of non-supervised analyses at first in order to extract a maximum of information automatically. We give hereafter (see figure 10, page 29) the flow chart of our method.

Two examples of colour composites of images in the Sahelian and Sudanian domains can be seen on the following pages (see figures 8 and 9).

FIGURE 8: COLOUR COMPOSITE OF A SPOT IMAGE OF TOMBOUCTOU IN 1988.

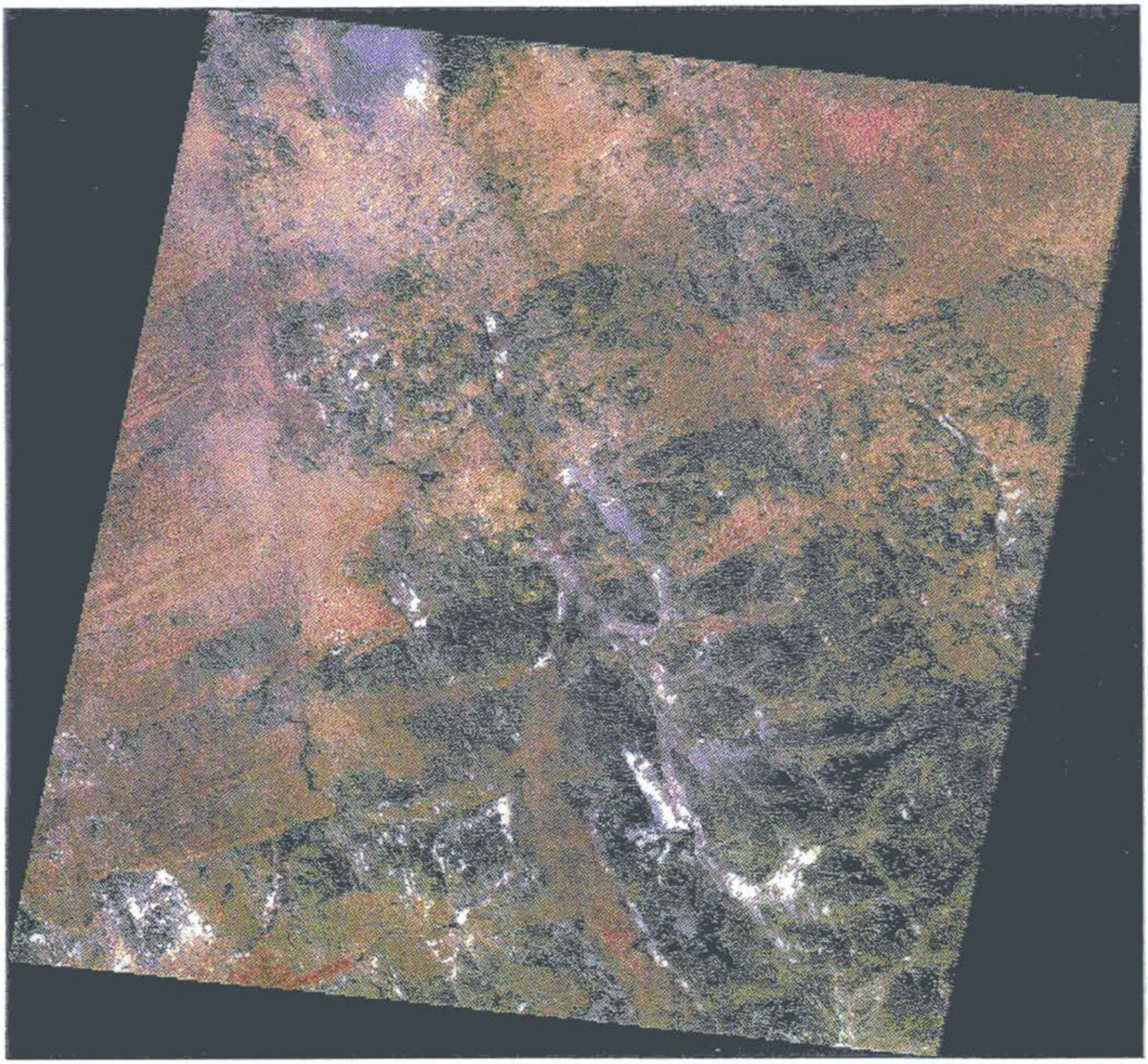


Image SPOT XS 052-317 03-12-1988
Echelle : 1/400 000

FIGURE 9: COLOUR COMPOSITE OF A SPOT IMAGE OF SEGUENEGA IN 1988.

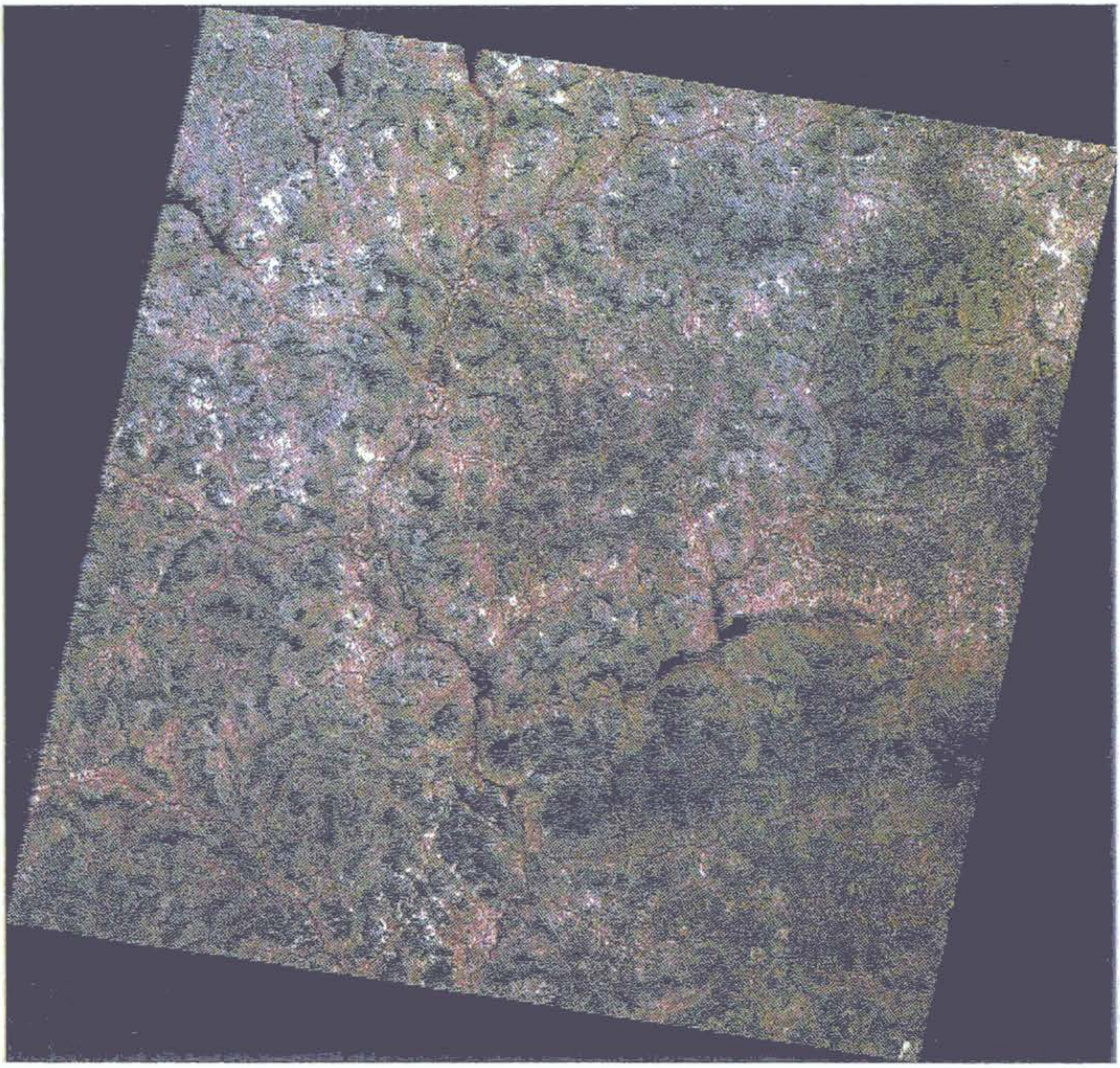
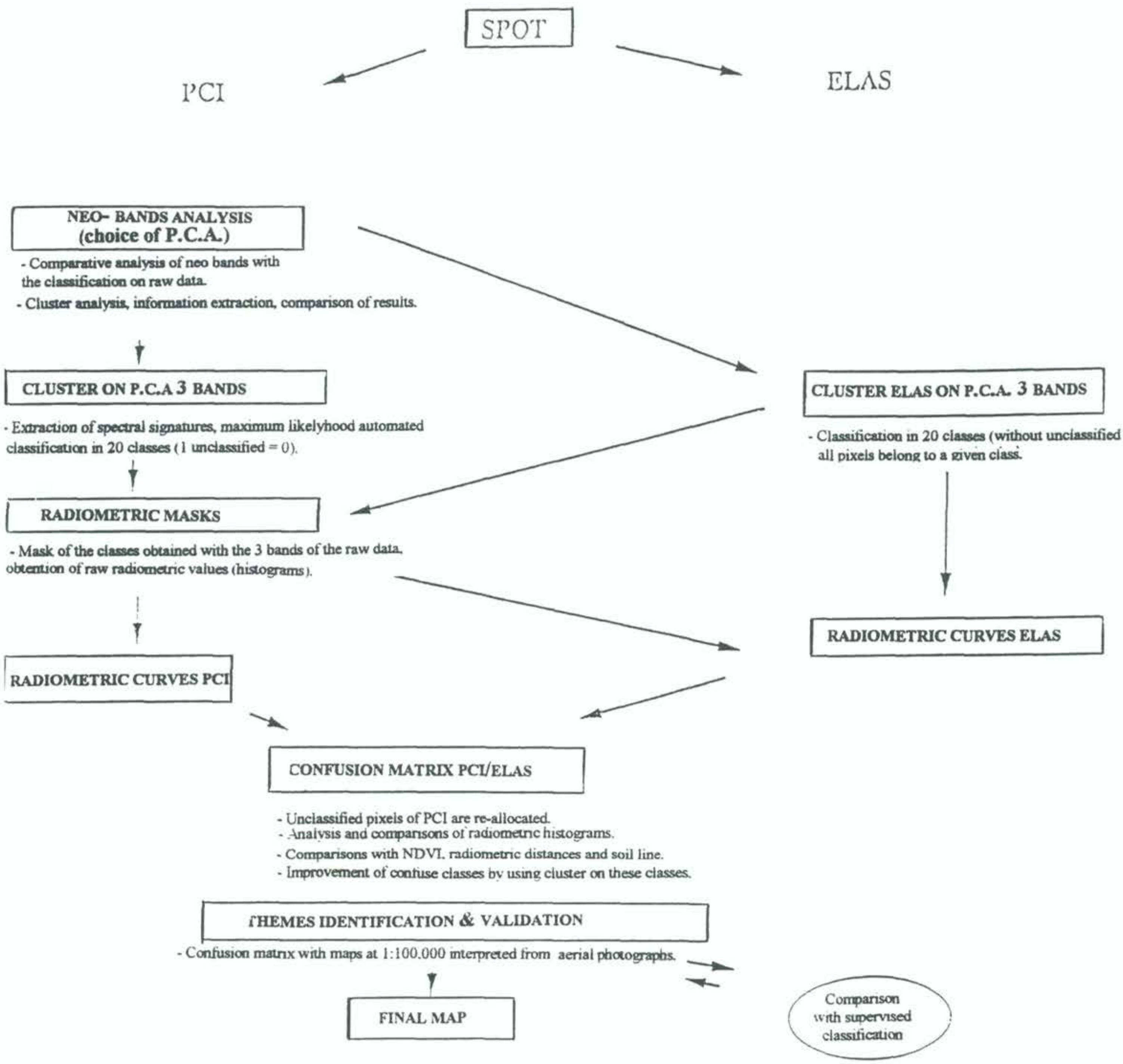


Image SPOT XS 052-323 03-12-1988
Echelle : 1/400 000

FIGURE 10: DIAGRAM SHOWING THE PRINCIPLE OF IMAGE ANALYSIS FOR A SEMI-SUPERVISED CLASSIFICATION.



5.1. Semi-supervised classification (cf. figure overleaf)

Firstly, we decided to study an (as closely as possible) automated approach; in other words, an almost non-supervised classification which we called a **semi-supervised** classification. This kind of classification allows for a rapid identification of the main types of land use shown on an image as well as for an objective view of radiometric image potentialities in order to differentiate land use themes.

The aim of the operation is to devise a method repeatedly applicable to a large number of scenes. We employed a "cluster" classification type, purely automatic at the time of classification, requiring limited human intervention only to assemble and to characterise the categories obtained.

One of the advantages of this method is that it provides a rapid means of analysis, that it is applicable to all satellites, and that it calls on well-known processing software. In the first two transects we used two complementary type of software: a Canadian one, PCI and an American one, developed by NASA: ELAS. Both belong to UNEP/GRID in Geneva and were kindly lent to us for this study. From the third transect on, we used image processing I.N.R.A. (National Agronomic Research Institute) programmes and Geographical Information Systems from the hydro-biological station in Thonon les Bains: IDRISI and ILWIS.

The method is transposable onto many other well-known image processing software with unsupervised classification algorhythms. The classification system requires only well-known programmes but the procedure is rather sophisticated and calls on interactive analyses of radiometric data, simultaneously on both types of software mentioned above. The method can be schematised in the following manner:

1/ An analysis stage composed of the following:

Principal Component Analysis (P.C.A.), to obtain important information with a reduced number of bands.

A non-supervised analysis, i.e. an image classification using "maximum likelyhood" to obtain radiometric classes on the P.C.A. values.

The P.C.A. classes mask is then combined with the raw data in order to extract the radiometric raw values corresponding to these classes.

2/ An interpretation stage which consists of:

A radiometric value analysis of initial (raw values) bands thus obtained.

Contingency tables on the classes obtained by using the pairs PCI+ELAS **or** IDRISI+ILWIS, thus introducing a higher level of sophistication and removing the ambiguity on uncategorised pixels; tentative thematic characterisation of the results according to radiometric values.

A normalised vegetation index (NDVI) for comparison with former results.

A spectral (radiometric) distance analysis between categories found.

A second non-supervised classification of seemingly uncertain or confused categories.

The diagram overleaf sums up the procedure used according to the stages described above:

Numerous spectral bands combinations were tested before producing the method described, namely: vegetation index, brilliance index, a combination of vegetation index and of SPOT band 3, etc.

A Principal Component Analysis was focused upon for many reasons. Firstly, it is the only way to eliminate the "column striping" of SPOT images. Secondly, it facilitated the location of foggy areas, haze and fumes.Thirdly, it is the only means of obtaining, by the unsupervised method, a number of categories close to the one relating to the initial work legend (16+2). Finally, it provides the smallest standard deviations compared to other, non-supervised classification methods using other spectral bands combinations.

In this method, radiometric data are systematically analysed and the results obtained with the two types of software of each pair (PCI+ELAS and IDRISI+ILWIS) are compared. The categories, after possible reshuffling, are then thematically validated by comparing the results obtained to photo interpretation, to vegetation index and to combinations of spectral bands Red and Infra-red, which gives an idea of the vegetation cover compared to the soil background line.

5.2. Supervised classification

The main objective of this paper is an exhaustive exploration of up-to-date methods. It is why the difficulties encountered in the process of the supervised classification method are presented in the examples below.

It should be remembered that, in this type of classification, training sectors are used. These are small zones of satellite images, seemingly homogeneous, in colour and texture, for which "ground truth" can be obtained, thus making characterisation, from a thematic point of view, possible. An algorhythm, in supervised classification, looks for all features, among image elements, comparable (within a parametrable range of variation) with those present in training sectors, and then, it gives them the same thematic meaning (cf. figure 11 below).

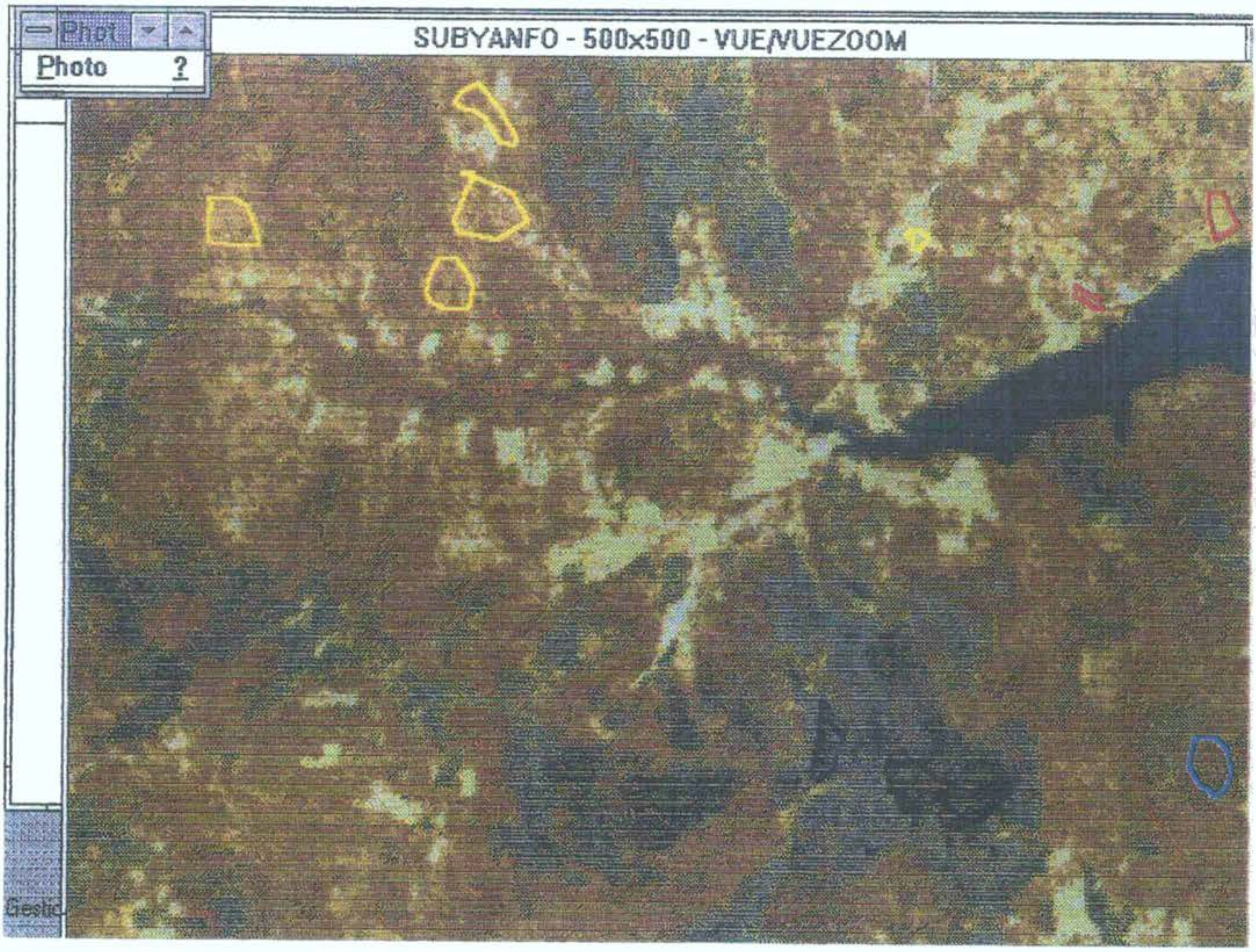


FIGURE 11: MAP SHOWING SELECTION OF TEST ZONES FOR A SUPERVISED CLASSIFICATION.

The first evaluation of classification results can be made on the training sectors (test zones) themselves in which all elements do not necessarily fall into the class defined at the beginning. This depends on how homogeneous the set of elements in the training sector are (standard deviation of the radiometries), on the number of categories looked for, on their distance in radiometric space and on whether there is a category of rejected items (unclassified).

In the following figures, a copy of a computer screen is presented. On it, the position of the mean radiometric values from elements of training sectors are shown on the plan drawn by radiometric values of SPOT band 2 and band 3. The oval-shaped figure corresponds to standard deviation of the sample sets (i.e. a dispersion of values compared to the average ones) (cf. page 33)

In the Yanfolila example the ovals can be seen quite distinctly, so that training sets correspond to easily separable radiometric categories. In the Mourdiah example, the situation is reversed, some ovals are coalescent, which illustrates the complexity of the environment and subsequently, contributes to the difficulty in separating the legend items according to their radiometric values.

We employed the supervised classification method on two extracts of images where we were in possesion of the aerial photo interpretation as well as the results of semi-supervised classification. Our classifications were thus based on two types of documents in order to choose the training sectors. The procedure is not commonplace, though it may be advisable in a complex type of landscape. Unsupervised classification is used to extract the maximum information from the image, and according to ground truth, a selection of samples similar in the two cases is refined.

In the present case, we were given optimal conditions as we strongly believe that the same theme identified on an aerial photograph as well as on the results of a semi-supervised classification has a higher chance of being correctly identified by the machine in the space of radiometries. The method was used as a comparison with the other one on two images only: Mourdiah and Yanfolila.

6. RESULTS OBTAINED BY AUTOMATED ANALYSIS METHODS OF SATELLITE IMAGES

Whichever method is concerned, of the two ones compared above, the results were evaluated in two different ways:

In what is called the **automatic calculation method**, files compiled from the digitisation of aerial photography interpretation and a digital classification of the satellite image were compared pixel by pixel.

In what is called the **manual calculation method** the graphic results of two sets of documents (on the one hand, a drawing of aerial photography interpretation and on the other, a print of the semi-supervised automated classification result) were "generalised" by simplifying the limits, reassembling adjacent zones and by abandoning too small zones, (less than 25 hectares). Thus, it is a kind of information-filtering system which introduces an element of subjectivity since the work is done by hand. However, the job allows one to get round, as far as possible, the disadvantages of possible faults made in putting documents under strict geometric correspondance; and the fact that we are dealing with areas in which land use is complex and heterogeneous, and where zones are small and dispersed, makes it even more relevant here.

The next step is to compare land use themes on each document according to a grid of 5mm by 5mm in size. It can be said that the manual calculation method gives more exact results than the ones resulting from automatic calculations as the first is less sensitive to possible faults in the geometric superimposition of documents. Figures 13 and 14 on the following pages show the result of the "generalisation" process on the classification of the Yanfolila sector.

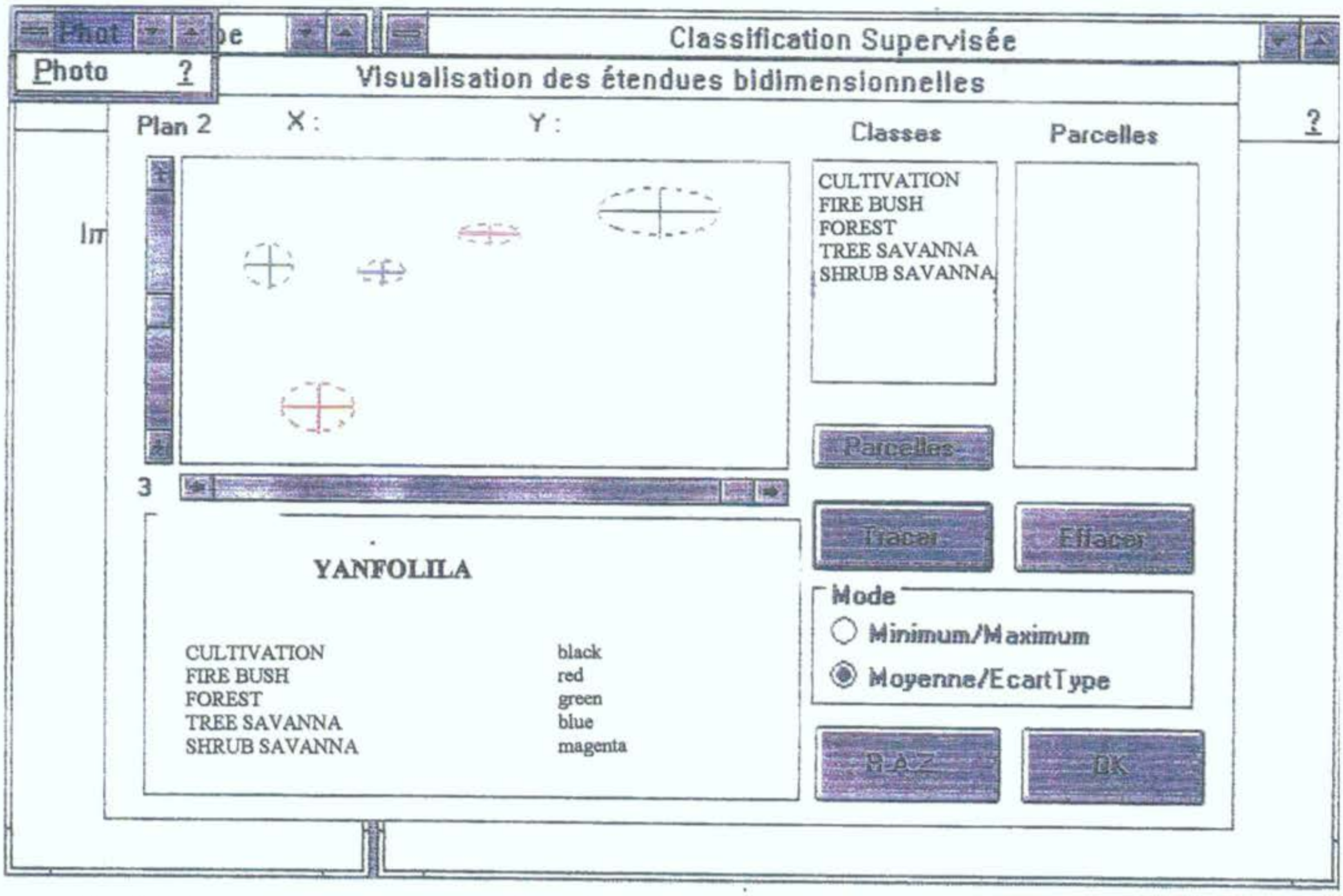


FIGURE 12: DIAGRAM SHOWING TWO-DIMENSIONAL STRETCHES OF RADIOMETRIES FOR SUPERVISED CLASSIFICATION TEST ZONES IN YANFOLILA AND MOURDIAH.

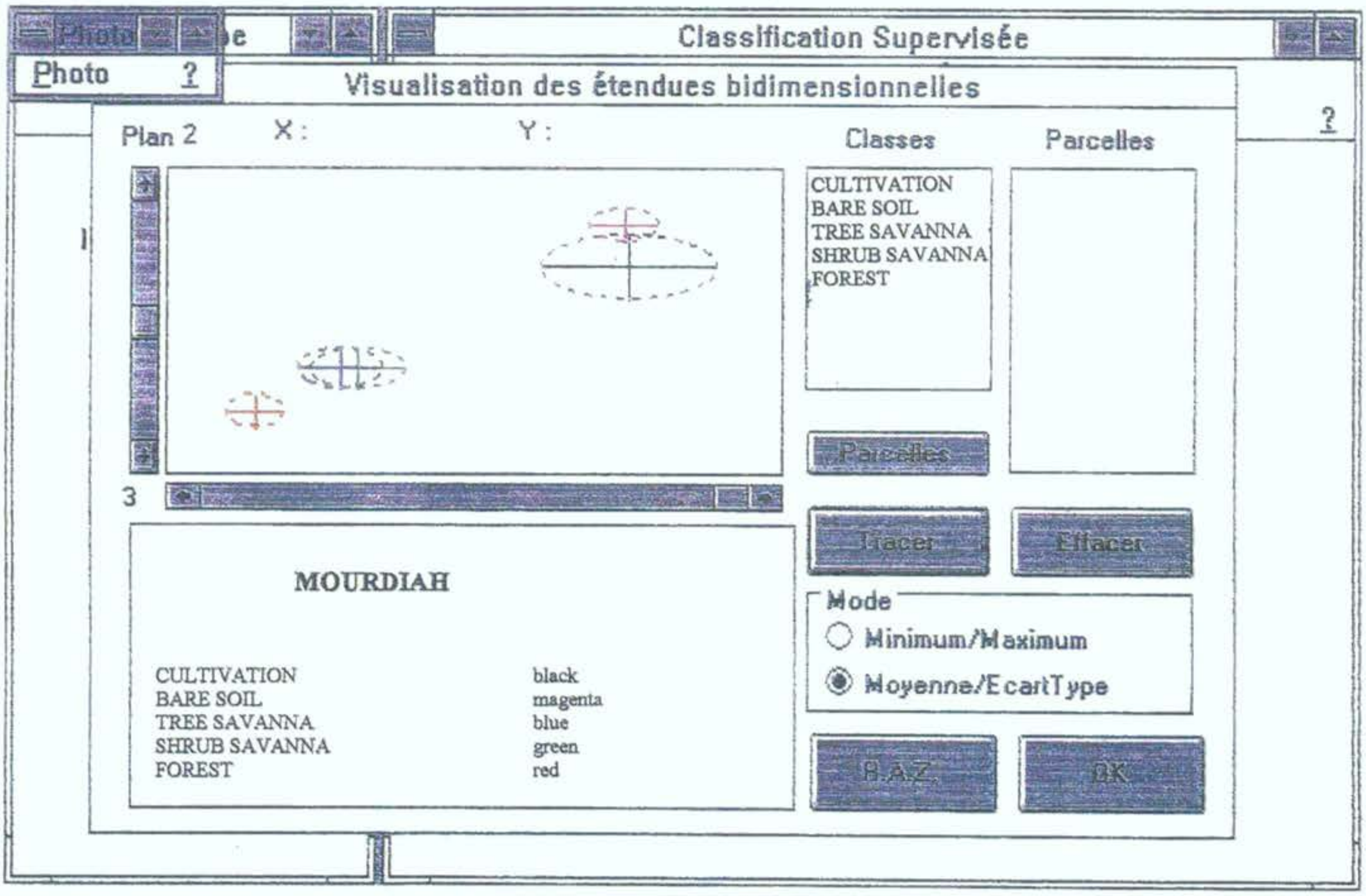
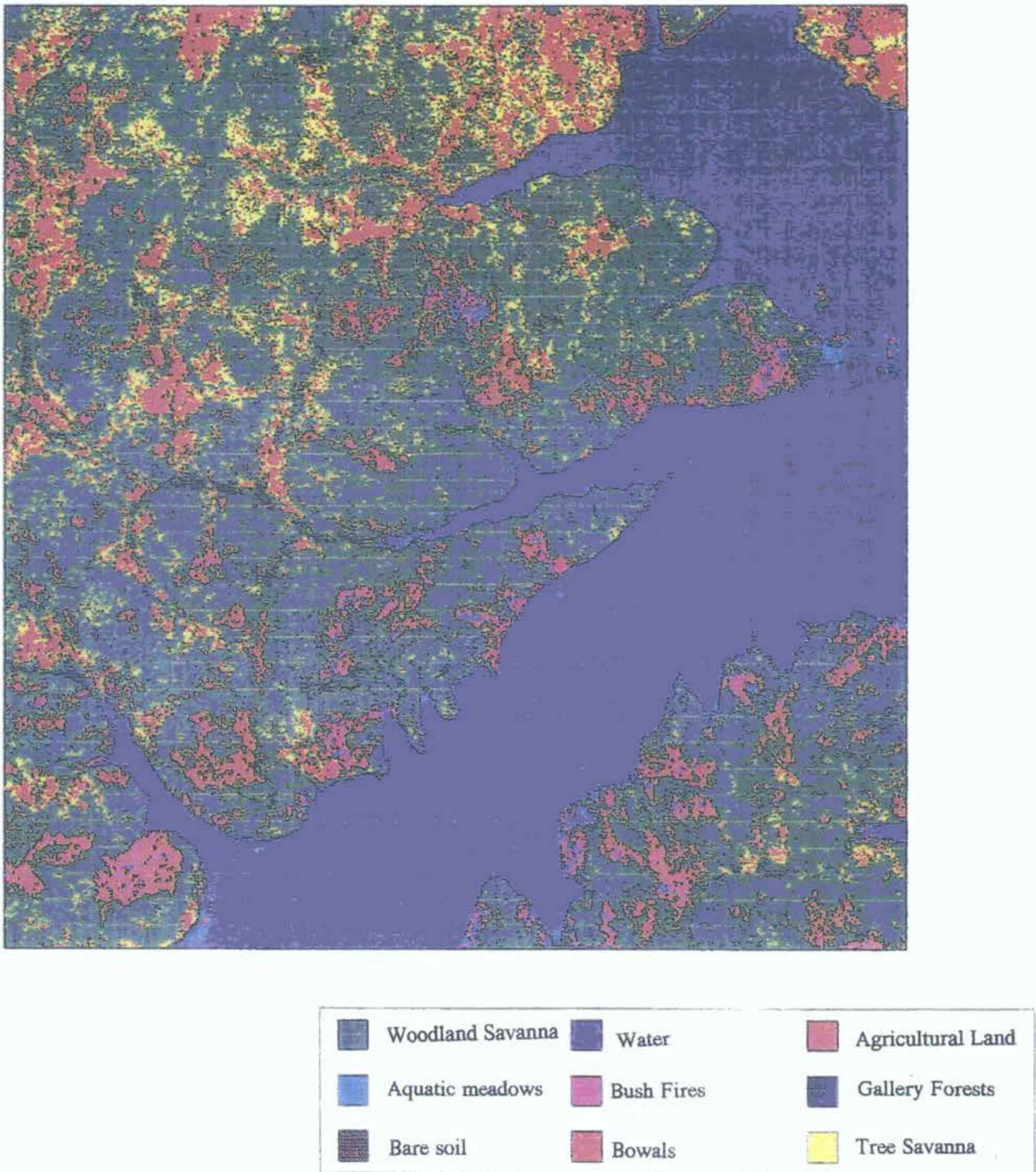
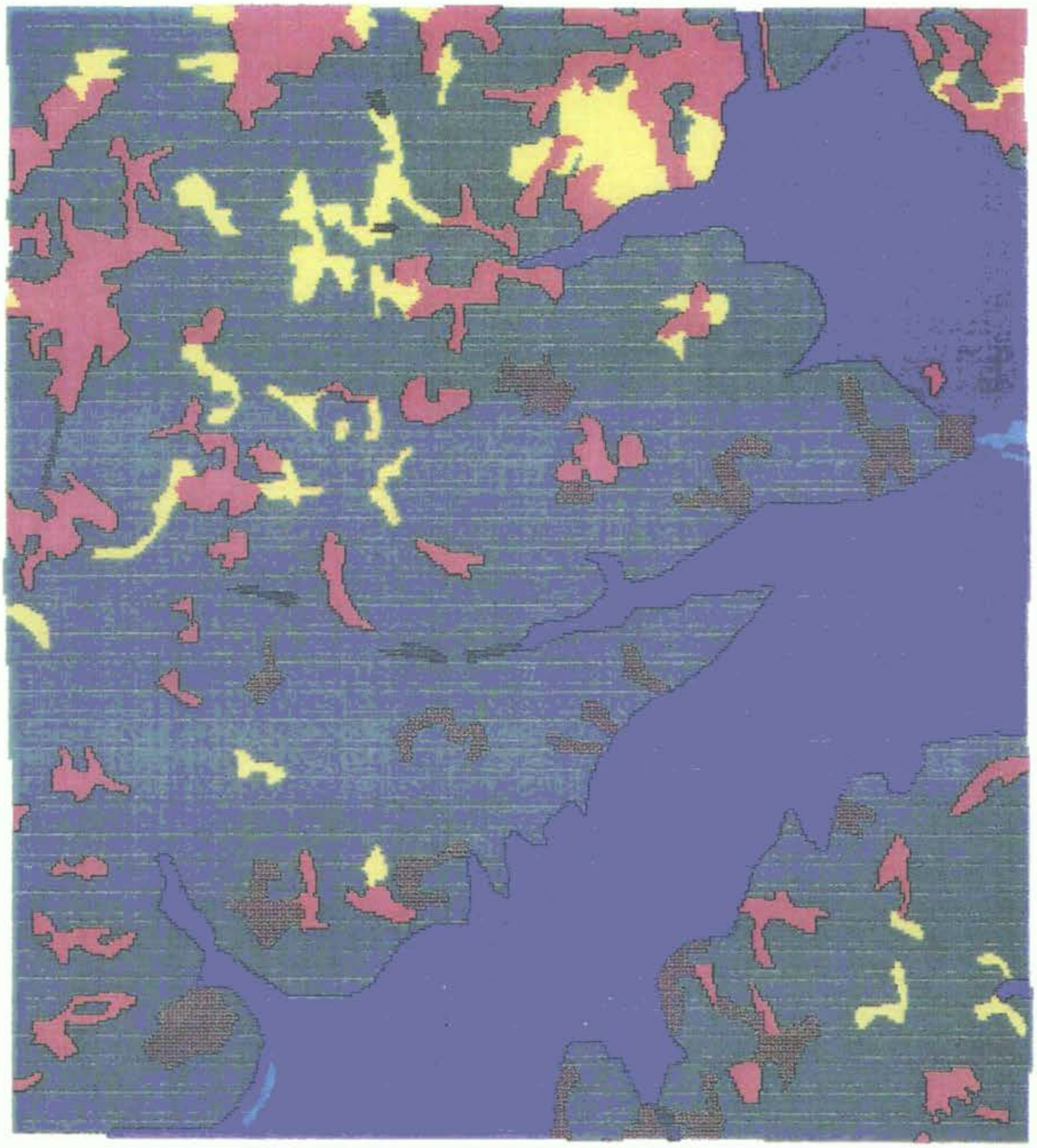


FIGURE 13: MAP SHOWING LANDUSE IN YANFOLILA OBTAINED BY SEMI-SUPERVISED CLASSIFICATION, NON-GENERALISED MAP.



SCALE 1/100 000

FIGURE 14: MAP SHOWING LAND USE IN YANFOLILA OBTAINED BY SEMI-SUPERVISED CLASSIFICATION, GENERALISED MAP.



SCALE 1/100 000

Bush Fires	Water	Gallery forests
Aquatic Meadows	Tree Savanna	Woodland Savanna
Agricultural Land		

6.1. Results obtained by the supervised classification method

On the Mourdiah image, 5 themes were identified: agriculture, forests, tree-covered savannas, shrub savannas, and bare soil. The analysed zone is 10 km by 10 km in size or 500 by 500 pixels (picture elements). For each one of the theme above, 2 to 4 samples (training sectors) from 20 to 300 pixels each, were selected. The training sectors were chosen with the smallest possible standard deviation.

Two classification types were attempted with a 5% and a 0% rejection threshold. The best results were obtained from a complete classification (rejection threshold of 0%, thus no unclassified items). Validation shows that the annual cultivation theme presents average or bad results with certain samples classified at 50%, while results of over 95% were obtained in bare soil and forest themes. However, it should be noted that in these themes, samples are small in terms of their surface area (20-40 pixels) thus, they are homogeneous and their results improved accordingly. The opposite situation can be seen in the cultivation theme in which heterogeneity in radiometry is very marked. The assessment of classification of the entire image obtains very poor results, to such an extent that comparable zones cannot be recognised in photo interpretation and in automated classification.

There is considerable confusion in distinguishing the cultivation theme from the bare soil theme because at that time of the year, harvesting was already over, so the fields were bare. Moreover, there is a 100% confusion in recognising the two savanna types and only the forest theme is properly identified.

The classification of Yanfolila, obtained in the same conditions is better. Table 9 presented below, shows validity obtained by the manual calculation method of equivalent points according to a grid 5mm by 5mm in size.

YANFOLILA THEMES	NUMBER OF POINTS FOR EACH THEME	WELL CLASSIFIED AND WELL LOCATED (comparison: supervised classification/photo)
Tree savanna	245	46 %
Agriculture	52	54 %
Fires	20	75 %
Shrub Savannas	11	72 %
Bowe	8	0 %
Gallery forests	5	40 %
TOTAL	**341**	**47 %**

TABLE 9: RESULTS OBTAINED OVER YANFOLILA BY SUPERVISED CLASSIFICATION.

To conclude, if these results are compared with those of semi-supervised classification, it appears that classification of all themes is worse. Thus, the overall result, of the entire zone brings about a good classification for only 47% of the elements against 77.3% using the other method (see table 10, page 37). This combined with the fact that poor results were also obtained in Mourdiah gives an extra argument in favour of a more automated method of the semi-supervised type in order to analyse images of the area discussed.

6.2. Results obtained by a semi-supervised classification method (tables 10 to 15)

Tables with figures obtained by automatic calculation methods or manual calculation are presented below. The reading of these tables demands a particular effort but it is necessary to have an idea of the precision that can be reached by the use of satellite images.

On the first two sets of tables hereafter, the two calculation methods are compared.

The first set of tables corresponds to the the zone in which the method gives the best results: the Yanfolila area (table 10). The second set shows that over Hombori (table 11), the results are less satisfactory.

RESULTS OF PHOTO INTERPRETATION OF AERIAL WORK FROM 28.11.1987 — THEMES	Agricultural land	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Water and aquatic meadow	TOTAL Photo interpret in ha
	RESULTS OF SEMI-SUPERVISED CLASSIFICATION OF THE SPOT IMAGE FROM 14.12.1987								
Agricultural land	5552	4619	1998		18	60		330	**12577**
Savanna/steppe woodland/tree	3007	49285	1304		1251	150		1191	**56188**
Savanna/steppe shrub	340	1400	591			21		24	**2376**
Savanna/steppe herbacious									
Miscellaneous (bush fires)	652	2229	17		1499	0		209	**4636**
Forest	28	593	0		99	82		23	**825**
Bare soil	136	108	2		21				**267**
Water and aquatic meadow	96	1838			202	44		27021	**29201**
TOTAL of the SPOT classification in ha	**9811**	**60072**	**3942**		**3090**	**357**		**28798**	**106070**

YANFOLILA
1st transect

Automatic calculation method

Statistical classification : quite good (9811/12577, 60072/56188, 3942/2376, 28798/29201)

Number of well-classified and well-located pixels : 74.2%

RESULTS OF THE PHOTO INTERPRETATION OF AERIAL WORK FROM 28.11.1987 — THEMES	Annual cultivation	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Tree bowal	TOTAL Photo interpret. in ha
	RESULTS OF SEMI-SUPERVISED CLASSIFICATION OF THE SPOT IMAGE FROM 14.12.1987								
Annual cultivation	77	15	3		4		1		**100**
Savanna/steppe woodland/tree	38	371	12		21	5	9		**456**
Savanna/steppe shrub	11	10	7						**28**
Savanna/steppe herbacious									
Miscellaneous (bush fires)		10			**21**				**31**
Forest		1			0	**2**			**3**
Bare soil									
Tree bowal									
TOTAL of the SPOT classification in ha	**126**	**407**	**22**		**46**	**7**	**10**		**618**

YANFOLILA
1st transect

Manual calculation method

Statistical classification : quite good (126/100, 407/456, 22/28)

Number of well-classified and well-located hectares : 77.3%

TABLE [illegible] : COMPARISON OF RESULTS FROM 2 VALIDATION METHODS OVER YANFOLILA

RESULTS OF SEMI-SUPERVISED CLASSIFICATION OF THE SPOT IMAGE FROM 03.12.1989 (columns); RESULTS OF PHOTO INTERPRETATION OF AERIAL WORK FROM 22.01.1989 (rows)

THEMES	Annual cultivation	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Tree bowal	TOTAL Photo interpret. in ha
Annual cultivation									
Savanna/steppe woodland/tree		33863	7421			622			**41906**
Savanna/steppe shrub		19096	8666			327	50		**28139**
Savanna/steppe herbacious									
Miscellaneous (bush fires)									
Forest		902	502			1091			**2495**
Bare soil		3505	4091			264	77		**7937**
Tree bowal									
TOTAL of the SPOT classification in ha		**57366**	**20680**			**2304**	**127**		**80477**

HOMBORI
2nd transect

Automatic calculation method

Statistical classification results : medium except for bare soil (57366/41906, 20680/28139, 2304/2495)

Number of well-classified and well-located pixels : 54.3%

RESULTS OF SEMI-SUPERVISED CLASSIFACTION OF THE SPOT IMAGE FROM 03.12.1989 (columns); RESULTS OF PHOTO INTERPRETATION OF AERIAL WORK FROM 22.01.1989 (rows)

THEMES	Annual cultivation	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Tree bowal	TOTAL Photo interpret. in ha
Annual cultivation									
Savanna/steppe woodland/tree		312	122			2	3		**439**
Savanna/steppe shrub	11	97	182			6	15		**311**
Savanna/steppe herbacious									
Miscellaneous (bush fires)									
Forest		3	9			16			**28**
Bare soil		4	15				24		**43**
Tree bowal									
TOTAL of the SPOT classification in ha	**11**	**416**	**328**			**24**	**42**		**821**

HOMBORI
2nd transect

Manual calculation method

Statistical classification : quite good (416/439, 328/311, 24/28, 42/43)

Number of well-classified and well-located hectares : 65 %

TABLE 11: COMPARISON OF RESULTS FROM 2 VALIDATION METHODS OVER HOMBORI.

Tables 12 and 13 summarise the results obtained in Yanfolila and Hombori.

YANFOLILA

	MANUAL CALCULATION METHOD		AUTOMATIC CALCULATION METHOD	
THEMES	**Total points on the grid**	**Well classified and well localised**	**Total of image elements**	**Well classified and located**
Tree Savanna	456	81.4%	56,188	87.7%
Agricultural land	100	77.0%	12,577	44.1%
Fires	31	67.8%	4,636	32.3%
Shrub Savanna	28	25.0%	2,376	24.9%
Forests	3	66.7%	825	9.9%
TOTAL	**618**	**77.3%**	**76,602**	**74.2%**

TABLE 12: RESULTS FROM SEMI-SUPERVISED CLASSIFICATION OVER YANFOLILA, COMPARISON OF TWO CALCULATION METHODS.

Comment: In order to assess a classification method, it is not sufficient to base the results merely on a single percentage figure of the elements found globally well-classified and well-located. Instead, a theme by theme procedure should be adopted. Only then will it become evident that some important themes are very badly treated.

HOMBORI

	MANUAL CALCULATION METHOD		AUTOMATIC CALCULATION METHOD	
THEMES	**Total points on the grid**	**Well classified and well localised**	**Total of image elements**	**Well classified and well localised**
Tree Savanna	439	71.1 %	41,906	80.8 %
Shrub Savanna	311	58.5 %	28,139	30.8 %
Bare soil	43	56.0 %	7,937	1.0 %
Forest	28	57.0 %	2,495	43.7 %
TOTAL	**821**	**65 0%**	**80,477**	**54.3%**

TABLE 13: RESULTS FROM SEMI-SUPERVISED CLASSIFICATION OVER HOMBORI, COMPARISON OF TWO CALCULATION METHODS.

Comment: The fact that only four categories are present after gathering of classes in the process of semi-supervised classification, is misleading and it gives, after automatic calculation, results impossible to use for the bare soils and shrub savannas. Medium quality results are reached by manual calculation for the same bare soil.

The last set of tables (13 and 14) corresponds to two different zones: Seguenega and Ouallam where only the manual calculation method is utilised.

RESULTS OF SEMI-SUPERVISED CLASSIFICATION OF THE SPOT IMAGE FROM 29.01.1990

RESULTS OF PHOTO INTERPRETATION OF AERIAL WORK FROM 24.01.1990

THEMES	Annual cultivation	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Tree bowal	TOTAL Photo interpret. in ha
Annual cultivation									
Savanna/steppe woodland/tree		221	22	85		100	49		477
Savanna/steppe shrub			2						2
Savanna/steppe herbacious		20	7	93		35	12		167
Miscellaneous (bush fires)									
Forest		5	1			17	3		26
Bare soil		14	2	6		9	126		157
Tree bowal									
TOTAL of the SPOT classification in ha		260	34	184		161	190		829

OUALLAM
3rd transect

Manual calculation method

Statistical classification results : bad 260/477, 34/2,161/26)

Number of well-classified and well-located hectares : 55.3%

RESULTS OF SEMI-SUPERVISED CLASSIFICATION OF THE SPOT IMAGE FROM 03.12.1989

RESULTS OF PHOTO INTERPRETATION OF AERIAL WORK FROM 22.01.1989

THEMES	Annual cultivation	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Tree bowal	TOTAL Photo interpret. in ha
Annual cultivation	73	53	10			11	24		171
Savanna/steppe woodland/tree	131	97	11	7		20	57		323
Savanna/steppe shrub									
Savanna/steppe herbacious		1		1					2
Miscellaneous (bush fires)									
Forest	7					38	2		47
Bare soil	18	18		7			90		133
Tree bowal									
TOTAL of the SPOT classification in ha	229	169	21	15		69	173		676

SEGUENEGUA
2nd transect

Manual calculation method

Statistical classification results : bad 229/171, 169/323, 173/133)

Number of well-classified and well-located hectares : 44.2%

TABLES 14 AND 15: RESULTS FROM SEMI-SUPERVISED CLASSIFICATION OVER OUALLAM AND SEGUENEGA BY MANUAL CALCULATION.

6.3. Conclusions from results obtained by automated classification methods

Supervised classification methods give worse results than the semi-supervised classification method focused upon in this paper. Surely, it would be theoretically possible to improve the results obtained by rendering the treatment more sophisticated. However, we believe that in this matter, among others, perfection is unattainable. So, in our case, it is not relevant, in terms of technology transfer, to create technical difficulties to increase the amount of extra information (difficult to quantify anyway), and we consider that the costs would be disproportionate. The methods employed were tested in terms of their practicality with a view to re-using them in normal economic conditions.

Classification results of certain images seem, at least globally, acceptable. For example, in Yanfolila there is 77.3% of well-classified and well-located elements, in Tidarmene 72.2%. In both these cases statistical classification (the number of classified elements under a given theme in relation to the total number of theme elements) is quite good for Yanfolila (126/100, 407/456, 22/28) and for Tidarmene (90/94, 359/300, 122/105).

Results obtained from other images are poor as for example, Seguenega where there are 44.2% of well-classified and well-located elements, or Ouallam with 55.3%. Furthermore, statistical classification is poor for certain themes (260/477, 184/187, 161/26, 190/197).

Finally, for some images giving poor statistical results, the situation can be improved, if themes corresponding to their natural environment are gathered together: wooded, tree-covered and shrub savanna or steppe. In the case of Mourdiah the following figures were obtained: 9,958/10,562; 49,369/47,781; 2,438/2,802; 0/642) for the themes remaining after gathering. On top than these results do not have a great thematic meaning, it should be remembered that the reassembly is done in order to obtain a standard of truthfullness which is **already known by other means.** In other images no reasssembly is able to improve the results. In the following table 16 the Mourdiah case is presented.

It may be curious to see if, on a global scale, images from the Sudan environment are better classified than that of the Sahel. A comparison does not show anything except that the worst classified images are those of Mourdiah, with only 42.7% (manual method) well-classified and well-localised items and Seguenega with 44.2%. This is because these two images are situated in areas where pluviometry is from 700 to 800mm, and to where population seems to migrate during episodic draughts. This could result in a greater complexity of environment due to local clearing of small parcels of what remains from the large areas of natural vegetation still visible on the years 50s aerial photographs.

NOTA: Both calculation methods (manual and automatic) are good in terms of statistics. Manual method results (closer to the results of photo-interpretation than the results obtained automatically) corroborate those obtained by the automatic method. Analysis of standard deviations reveal that both methods present an identical variability.

RESULTS OF PHOTO INTERPRETATION OF AERIAL WORK FROM 16.11.1987	RESULTS OF SEMI-SUPERVISED CLASSIFICATION OF THE SPOT IMAGE FROM 18.11.1987								
THEMES	Agricultural land	Savanna/steppe woodland/tree	Savanna/steppe shrub	Savanna/steppe herbacious	Miscellaneous (bush fires)	Forest	Bare soil	Tree bowal	TOTAL Photo interpret. in ha
Agricultural land	2513	3743	3480				826		10562
Savanna/steppe woodland/tree	5134	15899	16327				1192		38552
Savanna/steppe shrub	1656	3855	3406				290		9207
Savanna/steppe herbacious									
Miscellaneous (bush fires)									
Forest									
Bare soil	644	1041	987				130		2802
Tree bowal	11	530	101						642
TOTAL of the SPOT classification in ha	9958	25068	24301				2438		61765

MOURDIAH
1st transect

Automatical calculation method

Statistical classification results : bad
(9958/10562, 25068/38572, 24301/9209)

except after gathering of all woodland, tree and shrub themes
(9958/10562, 49369/47781, 2438/2802)

Number of well-classified and well-located hectares : 35.5%

TABLE 16: RESULTS FROM SEMI-SUPERVISED CLASSIFICATION OVER MOURDIAH BY AUTOMATIC CALCULATION.

7. GENERAL CONCLUSIONS AND SUGGESTIONS FOR THE FUTURE

7.1. Introductory comments

High resolution satellite images have only been in use for a few years and the only documents available for a diachronic analysis over several decades, are aerial photographs as well as a topographic map of the entire West Africa produced by The National Geographic Institute, France. The legend on land use on that map is sufficiently detailed to be of interest for research on the evolution of vegetation cover.

Our study is inevitably limited compared to the considerable area of the Sahel region as the total acreage mapped in the four transects covers a mere 50,000 square kilometres studied by using satellite images, and 5,000 square kilometres studied by means of aerial photography.

It is also limited in time; two examples may be quoted here: aerial photographs and SPOT images from January 1990 were compared with aerial photographs from 1954, 1955 and 1956 in the TIDARMENE zone in Eastern Mali and to aerial photographs from 1950 in the OUALLAM zone in Western Niger. Research was conducted, insofar as possible, in similar conditions (shots were taken in the same seasons). However, variations of climatic conditions during one year and rainfall variations from one year to another (see isohyet "oscillations" from one decade to another described in the study of the first transect), should make one beware of the relativity of such precautions.

The study is merely concerned with land use which is only one of many indicators of the desertification phenomenon. And land use is indeed broadly studied. The only adressed at sign of desertification is vegetation formation, whereby more subtle but equally important changes cannot be identified by our method. Changes in the balance of species within plant combinations, for example, out of reach of our method, may be of importance. Other matters studied in cooperation with ORSTOM or the University of Reims on the first transect, like crop yeld statistics, stock counts evolution, sand cover geomorphology, have proved disappointing.

7.2. Main results

The very nature of the existing "historical" data, dating back the years 50s, like aerial photographs and topographic maps imposed such constraints that they limited our investigation to 18 themes of land use. Limited as was the field of investigation, our study of changes in land use occurred in three decades provided interesting information:

- To be representative a sample must be rather large: at least some tens of thousand hectares.
- Sudan-Sahelian sectors deteriorated more than the Sahelian domain.
- When the pressure exerted by human activities decreases, natural vegetation recovers quickly.
- Images from satellites can provide stable information (through visual analysis) for a limited number of themes of interest like "agricultural land".
- Information can be integrated in a G.I.S.

This study has allowed us to compile a Geographical Information System including diachronic data on 4 first sectors of environment (the transects) and has explored the means available to continue the observation of how land use evolves.

7.3. Proposals for the future

Now, we can choose one of the many options:

One can, for example, use these four transects and periodically observe them.

It is also possible to extend the zone covered by the 4 sectors of environment to the East in the direction of Chad, the Sudan, and Ethiopia. It would be most interesting to extend our research to the Southern hemisphere, in the neighbourhood of Kalahari or the Namib Desert by using the same methods.

All this, however, would give us a local knowledge of the area. Would it be reasonable to hope to apprehend the evolution of this complex desertification phenomenon which we are studying **over the entire area involved**?

We have seen what amount of information is lost while attempting to extrapolate, by all means, our knowledge on land use to a SPOT image (60km) which we have on an aerial photograph strip 10 km wide. Is this loss of information tolerable? Can themeticians be content with it?

The use of satellite images taken at different times in the course of the same season would most likely improve the validity of an analysis by themes, but at the expense of high costs of purchasing and processing the images. Can this be accepted?

Certain important themes can, by their morphological features, be quite well classified by a visual analysis of satellite images. This is the case with agricultural land. Can one be content with such partial information though?

Whatever the answer may be, one should not stop at this point. Our study demonstrates that, thanks to some of the methods we have tried, one can reach good compromises between thematic accuracy and spatial extension. In order to deepen the analysis of the desertification phenomenon, it seems important to use high resolution satellite images for the following reasons:

Thematic point of view

Our investigation of the SPOT images capabilities shows that it is possible to locate and characterise some importants themes (gallery forets, agricultural land, annual cultivation). This can be obtained through a combination of visual analysis (for "agricultural land") and automated classifications.

Others satellites providing a large coverage per scene (185 x 185 km.) with a slighly reduced spatial resolution (30 x 30 m.) can give valuable information at a reduced cost when compared with SPOT. The Lünd University researchers, for example, demonstrated their interest for the measurements of bush and tree canopy cover. Also, the use of airborne videography could facilitate field investigations and should be explored.

Acquire the satellite data at a time when key cover types are spectrally most distinct and analyse multidate data could improve the results, as well as future developments to come in image processing technics.

In all the cases, however, whatever information can be derived from the satellites images analysis is rather sketchy. Is it enough?

Quantitative assessments of the extent of land degradation are complicated by changes due to rainfall variability and legitimate use of the soil. On representative ecosystems, it may be advisable to study in more detail a great number of small test-plots with an acreage of some hectares in order to produce evolution statistics on a large number of indicators.

Methodic point of view

High resolution satellites images (SPOT or Landsat TM) should be used to produce the basis for a geographical reference document. There are no topographical maps covering the entire Sahel region based on a scale under 1:200,000. In addition, this map is old as it dates back to the 50's. It would be most helpful for foreign research organisations and for the countries concerned, to cover the Sahel area by using registered satellite images at scale of 1:100,000. This would facilitate the location of land to be put under observation for scientific purposes. Moreover, it would allow the establishment of the reference layer for a Geographical Information System (DESERTIFICATION G.I.S.) with the aim of centralising all existing data on the region and of integrating it into future research information.

Such global coverage would allow a better choice of representative observation sites. After stratification of the image into homogeneous zones from a physical or demographical point of view, the sample segments (test-plots) could be studied in detail and their observation could be repeated periodically.

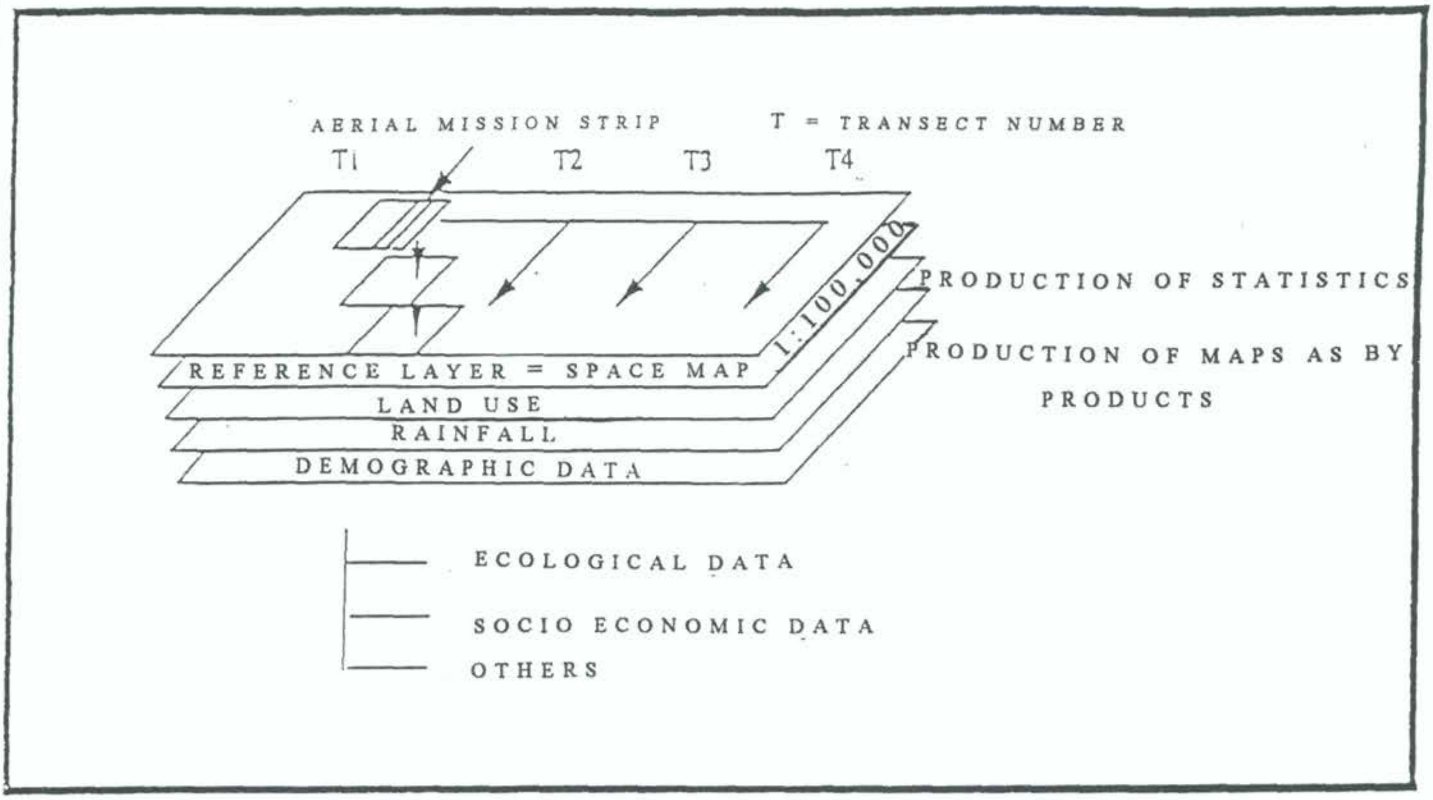
A land use cartographic coverage in 3 or 4 themes would be enough to allow for a sound choice of the images where the test-plots could be chosen. A more detailed study (combining visual and automated classifications) could be conducted on the selected images only.

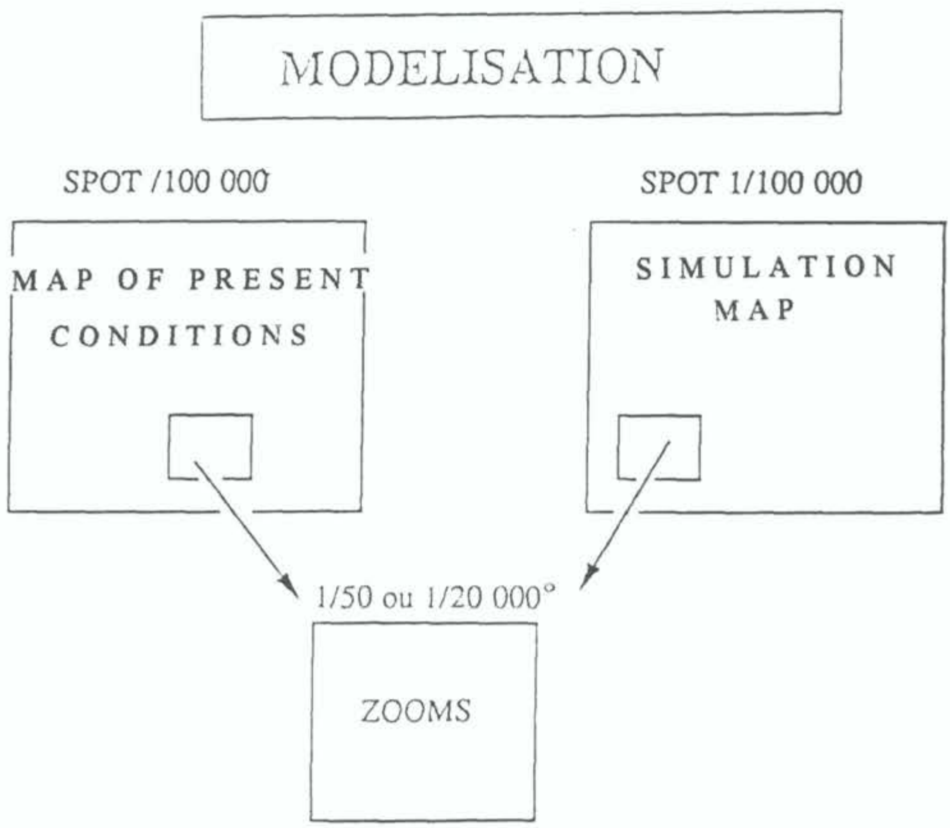
Economic point of view

Satellites images are a tool which give quick access to some (limited) information. They allow for a regular monitoring of large areas at an acceptable cost and provide information easy to integrate in a G.I.S. In the long term, after integrating a large amount of existing data or data to be collected, which concerns different physical or socio-economic parametres, the G.I.S. would be able to predict the influence of a probable environmental evolution in the area in question like climatic, demographic changes, etc.

A desertification G.I.S. would provide the means allowing a feasible management of the Sahelian environment. The drawing on the following page (cf. figure 15) schematizes the proposed idea.

FIGURE 15: DIAGRAM PRESENTING DESERTIFICATION G.I.S.





HELP TO DECISION MAKERS

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REPORT OF THE INTERNATIONAL EXPERT PANEL TO ASSESS PROCEDURES FOR MEASURING AND MONITORING DESERTIFICATON PROCESSES ON A WORLD WIDE BASIS

Nairobi 6 - 9 December 1993

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GOAL: To assess the existing Institut Geographie National-France International (IGN-FI) report on uses of remote sensing for desertification assessment and to propose further developments based on Remote Sensing and Geographic Information System (GIS) technology.

OBJECTIVES:

1. To evaluate the IGN-FI procedure for assessing land cover change in the Sahel using aerial photography and remotely sensed data in photographic and digital form.
2. To provide conclusions and recommendations to United Nations Environment Programme/Desertification Control-Programme Activity Center (UNEP/DC-PAC) on the capability of the IGN-FI procedure for assessment of desertification status.

The discussions focused on three general areas. These were:

1) land cover determination using aerial photography from the 1950s and the 1980s,
2) land cover determination using SPOT imagery and digital data,
3) problems of interpreting land cover change to determine rate of and status of dryland degradation.

The following issues were discussed:

I. LAND COVER DETERMINATION FROM AERIAL PHOTOGRAPHY

a) Appropriateness of the Data

1. Photography was available at 1:50,000 scale. Land cover classes were determined by API (Air Photo Interpretation). While this method produces useable results, there was no indication of the level of error and the impact of interpreter subjectivity. This restricts the ability to detect real trends over time when there are only two sets of aerial photography.

2. Land cover types were based on an accepted Sahelian classification system. However, while some land cover types could be determined unambiguously, others could not. This limits accuracy and the ability to detect trend especially if those classes are ecologically significant. It was also not clear how well the cover classes could be used as indicators of ecological status. There is some concern that the timing of aerial photograph acquisition may not have been optimal for land cover discrimination. However, it was recognized that no otehr photographic data was available.

b) **Accuracy issues, techniques and statistical evaluations.**

3. The ultimate purpose of the data analysis is to establish change over a 30-year period. This cannot be done unless the amount of error about each land cover determination is known. It was not clear how the interpreters calibrated themselves against ground data. There was also no statistical evaluation of interpreter error.

4. While it was recognized that the results were produced by highly skilled interpreters, it would be useful to have a more detailed and explicit description of the procedures used. This would enable other users to apply the same procedures making them more transferable.

c) **Sampling design (mode of assessment)**

5. IGN-FI used a transect based approach with subsequent selection of individual aerial photographs for interpretation. We consider that the use of aerial photography along environmental gradients is a valid approach. However, it was not clear that the selection of individual photographs was sufficiently representative of ecosystem variability. More information on the distribution of ecosystems and the extent to which ecosystems were sampled would have been useful.

6. We recognize the necessity to acquire new photographic data at the same time of year as the 1950s coverage. In the future, photographs should be acquired, if possible, at times when the land cover characteristics of interest are discriminated to the maximum extent, e.g. when the phenology of certain key species is optimal for identification and measurement. It would have been useful to know such key times if API is to be used again. We recognize, however, that the timing of aerial photography is always a compromise.

d) **Operational capability**

7. We endorse the IGN-FI approach for using aerial photography as a verification tool for remotely sensed data subject to the points raised above. API is a relatively simple technique and training manuals and standards are readily available. It is therefore highly transferable. However, we do not regard it as a cost effective technology for land cover determination over large regions. In the future high resolution digital technologies such as multispectral airborne videography should be considered to improve analysis and interpretation of results.

II. LAND COVER DETERMINATIONS FROM SATELLITE REMOTE SENSING

a) **Appropriateness of the data**

8. IGN-FI used SPOT data and digital classification procedures for the determination of land cover. We endorse this basic objective approach but recognize that results may vary with the classification procedures and algorithms used. There are many such procedures and it is possible that other approaches may provide better results than those used. We are not in a position to evaluate this. We agree that one classification appraoch should be used to assure repeatibility for change detection. It would,

however, have been helpful if the authors had carried out a detailed literature review to justify their choice of procedures.

9. The IGN-FI cover classes may be used to provide a baseline for assessment of future change. Therefore it is important that the raw data be made available as well as the classified data and the results.

10. SPOT is a relatively high per unit area cost data source. Use of SPOT might be justified in the case of agricultural land use but may be less important for natural vegetation which is the dominant cover type in most areas of the world where land degradation is to be measured.

11. SPOT is an appropriate sensor if comparisons are to be made between air photos and satellite imagery for change detection. Based on cost, the methodology used and from an operational point of view, SPOT may not be the best data source if comparisons are being made between multiple satellite images over time as part of a desertification monitoring system. We are seeking statistical differences between classes rather than changes at a particular location. Such an approach would preclude the need for exact planimetric location. However, this can easily be generated in the future using Geographic Positioning Systems.

b) Accuracy issues/techniques and statistical evaluation.

12. The basic approach used by the IGN-FI for 'truthing' cover classes (API) determined from satellite data is sound. However, the errors associated with API must be recognized because the resultant cover classes are not necessarily 'true.'. It is also important to have an adequate ecological understanding when labeling cover classes.

13. Classification which leads to categorical results is appropriate for cover classes which are clearly differentiated from their neighbors. In natural vegetation variations may be gradational, in which case classification may introduce artificial differences. Classification accuracies reviewed by the expert panel, especially those used primarily for natural vegetation and recorded by IGN-FI, may have lacked precision partly from reliance on a semi-supervised classification approach and partly due to a lack of discrimination of those classes on aerial photographs. It will be useful to develope a confusion matrix between the classification results and the ground reference data. Also a widely accepted measurement of accuracy should be used.

c) Mode of assessment

14. IGN-FI have used SPOT paths to create transects along rainfall gradients representing a variety of ecological systems. This is a realistic sampling approach for dealing with the variability of the Sahel. If the methodology is to be used in the study of a larger region it will be necessary to select future transects on a systematic basis and based on an adequate ecological understanding of the landscapes.

15. In the future when selecting satellite scenes it is essential to attempt to acquire data at times when key land cover types are spectrally most distinct. The IGN-FI report indicated that some cover types could not be clearly discriminated at certain times of

the year. Consideration should also be given to using short-term or seasonal spectral differences as an additional cover discriminant.

d) Operational issues

16. The SPOT data provides a useful digital baseline for future assessments. It should, however, be made possible to reassess the basic data using new classification methods along with some reliance on aerial photography or videography as alternative ground data sources. This is a way to fully utilize the existing data sets and at the same time, take advantage of future developments in image processing.

17. It is not entirely clear that the relatively expensive SPOT imagery is essential for these analyses. Consideration should be given to the use of imagery from other sensors. In making decisions about the type of data to be used, consideration should be given to the likely future supply, the existing archive and the relative costs. Also differences in spectral and spatial resolution must be taken into account.

18. One problem which the IGN-FI team encountered was the need for good ecological information when interpreting their data. As this information becomes more available, it is likely that classification accuracy and cover class discrimination could be improved.

19. If the methodology is to be implemented elsewhere, ready access to the appropriate technology is essential. PC-based image processing systems are widely available and are now highly sophisticated. It should be relatively simple to obtain this capacity. Some of these software packages were used by IGN-FI

III. CONSIDERATIONS FOR THE FUTURE

20. Since the IGN-FI study was started in 1987 there has been rapid progress in sensors, image processing algorithms and ecological understanding of the patterns observed on satellite imagery, both in space and time. These include such things as new vegetation indices based on dynamics, mixture modelling, contextual classification and integration with other information types in a Geographic Information Systems. If the method is applied elsewhere it could be modified to take advantage of these developments.

21. It should also be possible to define the types of ecosystem behavior necessary to interpret change in cover as a degradation process as opposed to the effects of rainfall variation or increasing intensification of land use. *A priori* models to allow such interpretation are now becoming available. Further progress in this area would be a real advantage. An example of ecosystem behavior might be examination of changes in plant growth rates on cultivated land with distance from settlements which might be correlated with loss of productivity. The potential for identifying settlements from high resolution satellite data such as the SPOT panchromatic band already exists. Growth rates can also be assessed from multitemporal imagery given rainfall data.

IV. CONCLUSIONS AND RECOMMENDATIONS

22. Determination of cover from remotely sensed data has the potential to allow measurement of land degradation. The present approach (IGN-FI), while representing a beginning, did not measure the extent of land degradation. However, it did provide a measure of land cover change. No approaches currently existing have this capability, except those develped for certain specific ecosystems and land uses.

23. Quantitative assessments of the extent of land degradation are complicated by changes due to rainfall variability and legitimate use of the land. Quantitative assessments can be made in a few ecosystems where changes in pattern or successional status can be related to land degradation. Our suggestion is that these approaches be applied in case studies of representative ecosystems to extend and test their utility. Until these studies have yielded results, global assessment of 'desertification' is likely to be impractical.