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Landscape archaeology and remote sensing in southern Madagascar

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Abstract. This paper demonstrates how remote sensing can be used to aid the general approach of landscape archaeology. The methodology and results of a project attempting to elucidate links and controls between environmental change and long-term social change in southern Madagascar are outlined. Multi-seasonal Landsat TM images, SPOT panchromatic and ERS-1 SAR images are used to produce a number of outputs. These include a general landcover map, a detailed map of forest extent and type (split into primary, secondary, and regenerative), field pattern maps, and predictions of archaeological site locations based on spectral properties of known sites. From these maps it has been possible to predict possible former settlements, archaeological sites, and forests of sacred significance.

1. Introduction

This paper aims to demonstrate how remote sensing can be used to aid the general approach of landscape archaeology using a case study which attempts to elucidate the links and controls between environmental and social change in southern Madagascar.

Landscape archaeology is a geographical approach whereby a region is investigated in an integrated manner, studying sites and artefacts not in isolation, but as aspects of living societies that once occupied the landscape (e.g., Tilley 1995). To do this it is necessary to collect and analyse archaeological and environmental data over large areas. Satellite imagery can be utilised to derive information about the contemporary landscape, and under certain circumstances it is possible to make inferences regarding former changes in the environment. As southern Madagascar is poorly mapped, remote sensing data can provide useful environmental information, and be used as a base map in its own right. Information covering large areas can be acquired at a fraction of the effort that would be required by field survey.

During initial field surveys a SPOT multispectral image (16 August 1989) was acquired as hardcopy prints at a scale of 1 : 100 000 which were used primarily as a navigation aid. Further remotely-sensed data was acquired, in digital format (table 1), to enable investigation of the following objectives;

1. Identification of primary and regenerated forest, including possible further subdivision in terms of age, which is relevant to anthropogenic phases of forest clearance and settlement patterns.
2. Production of maps showing field patterns, for use in assessing relative chronology of development.
3. Assessing the potential for mapping stone-cleared fields and settlement sites indicated by pottery scatters.

Table 1. Remotely-sensed data. The wet season generally lasts from October to March.

Sensor	ID Scene	Date	Season
Landsat-TM	path 159 row 77	25 June 1984	Dry
Landsat-TM	path 159 row 77	19 January 1985	Wet
Landsat-TM	path 159 row 78	19 January 1985	Wet
SPOT Pan	168-400	16 August 1989	Dry
ERS-1 SAR	orbit 15314 frame 4113	20 June 1994	Dry

4. Production of image maps for use in subsequent fieldwork, to be used for navigation and as base maps.

2. Archaeological and anthropological context

The study area in southern Madagascar is known as Androy, the home of the Antandroy people, which extends from the Mandrare River in the east to the Menarandra River in the west, a distance of 200 km, and from the sea to 150 km inland (figure 1). The low southern plains are sandy and occasionally covered in dense dry forest. The northern part is a hilly upland of Precambrian basement (Battistini 1964).

Since 1991, archaeological and anthropological research has been exploring relations between people and environment during the last two millennia. The focus being an investigation of the origins, development and social context of monumental tomb building, which since the nineteenth century have become an element of elaborate funerary traditions characteristic of Antandroy culture (Parker Pearson 1992, Parker Pearson *et al.* 1994).

A subsidiary aspect of the research is to investigate causes of extinction of *Aepyornis maximus*, or the Elephant Bird, the largest bird that ever lived. This extinction may relate to climatic change or human predation, although human predation of *Aepyornis* eggs is the favoured theory, being typically 30 cm in length they are likely to have made excellent food. Concentrations of *Aepyornis* eggshell located in a variety of coastal settlements, dating from the last 1000 years, appear to be the remains of nesting sites. No sites have yet yielded unequivocal evidence of predation. Nevertheless, there are large areas of eroding dunes where stratigraphic sections can be found that record evidence of *Aepyornis* and human occupation. The location from remote sensing and analysis of such sections is a priority.

Fieldwork reconnaissance, conducted in 1991, 1993 and 1995 (see figure 1), discovered and recorded over four hundred archaeological sites, compiled information on contemporary villages, tombs, cemeteries, vegetation and natural features and recorded oral history held by the local people (Parker Pearson 1992, Parker Pearson *et al.* 1994).

3. Integration of data in a GIS

In order to be able to use information derived from remotely-sensed images in conjunction with maps, aerial photographs, and field-derived information, the data were geometrically corrected and projected to the local map projection for use in a GIS. Data were stored as either raster or vector format as appropriate, and analysed using Erdas Imagine software. The remotely sensed data is listed in table 1. In addition limited aerial photographic coverage was available at a scale of 1:25 000.

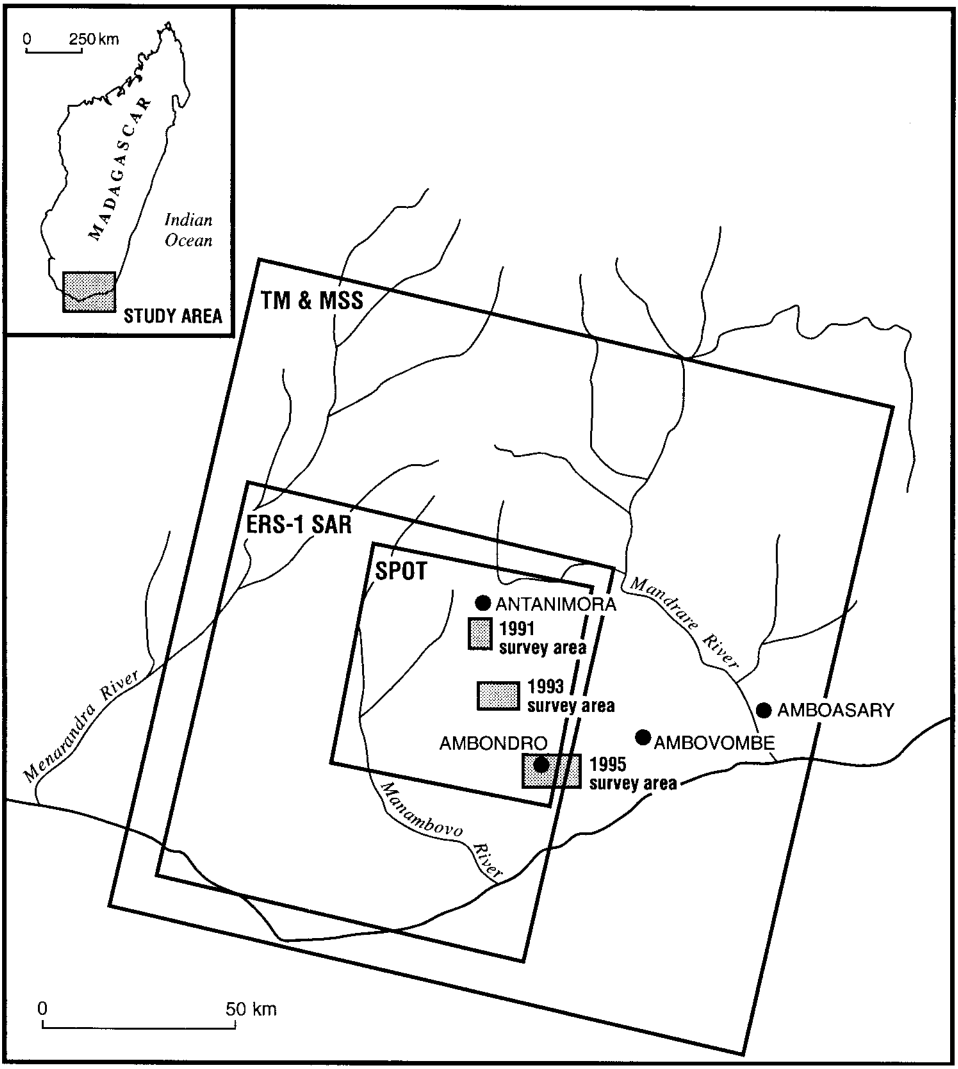

Figure 1. Location of study area showing extent of imagery utilised, principal areas of field survey, major towns and rivers.

All optical images were geometrically corrected to the Laborde Oblique Mercator Projection using maps at a scale of 1 : 100 000 for reference.

The 1 : 100 000 scale maps, derived from 1950s aerial photography, were scanned, geo-referenced and combined to create a single digital map mosaic. Forest cover information was extracted from this mosaic by recoding pixels to a value of one for those colours relating to forests whilst the others were set to zero, thus creating a thematic data layer displaying forest cover in the 1950s. A 3 by 3 majority filter reduced the inaccuracies resulting from the annotation in the original maps and inconsistencies in the scanning process.

Information acquired during the 1991 field survey was compiled as a large map showing locations of archaeological sites, monumental tombs, modern villages, field systems, and rivers. This had been produced by plotting sites onto aerial photographs and tracing these directly onto an overlay. The relative locations therefore contained considerable geometric distortion arising from the radial displacement inherent in aerial photographs. The map was scanned in blocks approximating to the extent of each aerial photograph and geometrically corrected to the georeferenced Landsat TM image. The river network provided control points for a second order transformation. The resulting georeferenced blocks, stitched together, formed the background for on-screen digitising of the archaeological sites and monumental tombs. As the sites had been dated from the pottery recovered during the survey, this enabled separate data layers to be constructed for each historical phase. Five data layers were produced, with a total of 132 sites and an additional layer with 99 tomb locations.

Locations of sites recorded during the 1993 field survey had been acquired using a global positioning system (GPS). These locations, in latitude/longitude, were converted to Laborde co-ordinates and manually plotted on a 1 : 12 500 hard copy of a SPOT/TM merged image. Some of the site locations were adrift by up to 150 m due to inaccuracies in the GPS. This was easily corrected from field notes and sketches as the field boundaries were clearly visible on the image. The corrected plot of sites, tombs, villages and water sources were scanned and as with the 1991 area, data layers relating to historical phases were created.

It would have been desirable to include a digital elevation model (DEM) in the GIS so that analysis of slope and elevation could be conducted. Unfortunately the only digital data available was at a spatial resolution of about 1 km which was inadequate. Contours displayed on the scanned map mosaic were used as a compromise.

4. Forest cover

Previous investigations of Madagascar's forests using satellite imagery has concentrated mainly on identifying the extent and progress of deforestation (e.g., Green and Sussman 1990). Central Androy is unusual as, in addition to deforested areas, there are large stretches of forest that have regenerated. This has been revealed during archaeological field survey and by the Antandroy oral histories. Settlements and field systems, some dating back to the eleventh century, have been located within forests, thus demonstrating that reforestation episodes occurred subsequent to the abandonment of these sites (Parker Pearson 1992, Heurtebize 1986). Oral evidence has identified forests that have been regenerating for as little as two or three decades and others that have never been exploited, suggesting they are primary forest. The latter are those regarded by the Antandroy as having sacred significance. These forests are typically roughly circular, about three or four hundred metres in diameter and often contain tombs. These are not monumental tombs, but part of an older burial tradition still in use today that consists of internment in wooden palisade tombs. Due to taboos about entering these forests little is known concerning their antiquity and contents.

It is implicit in the above discussion that our model of forest development is as follows:

(*a*) Using the climatic climax concept we regard primary forest to be the natural vegetation cover for the soils and climate of the region. Such forests may have taken many millennia to develop.

(*b*) Disturbance of the forest by anthropogenic or other means laid sections bare.

This permitted the ecological process of succession to take place, whereby grasses give way to shrubs and on to trees. We categorise these as secondary forests, which are characterised by mature tree stands but may have different species composition and densities to the primary forests.

(*c*) The progression from primary to secondary, via the act of disturbance, may take many decades to centuries. For cases where disturbance has been recent, ecological succession may still be in process with juvenile trees and shrubs in evidence. We call these regenerating forests.

Identifying primary forest is important as this represents undisturbed areas that have been devoid of settlement for some time, possibly several millennia, whereas other areas can be considered as potential settlement foci in the past. The contrast between disturbed and undisturbed forest regions can be used as a guide to previous land use. Additionally areas of sacred significance may be identified by sub-circular remnents of primary forests. The identification of secondary and regenerating forests in conjunction with dated archaeological sites may provide information on phases of deforestation and reforestation.

4.1. *Multi-spectral classification of forest cover*

The aim was to subdivide the image into forest and non-forest elements and then to further subdivide the forest into primary, secondary and regenerating categories if possible.

Unsupervised classification using the ISODATA algorithm was performed on the wet season (January 1985) TM scene to create 100 statistically based clusters, which were used in a maximum likelihood classification to produce this number of classes. By comparison with maps, aerial photographs, known field sites and colour composite images, this output was recoded to produce a non-forest mask which was used to remove all pixels which were not mapped as forest. The remaining image data could now be investigated to examine the degree of spectral variation within forest cover. Figure 2 demonstrates that there is considerable spectral variation amongst forest pixels. Such variation is likely to be an amalgam of many factors including biophysical factors that relate to trees in addition to the spectral properties of the background soil or understorey, and complications that arise from variable reflectance as a result of topography. Recently deforested areas should proceed along a spectral trajectory in accordance with structural and compositional changes that arise from the process of succession from grasses through shrubs to trees and to mature forest. Tree size, density and species composition might be the main controls (Cohen *et al.* 1995), which leads to a hypothesis that the spectral variation is some function of forest age. Investigation of spectra for forests referred to in oral histories and field surveys indicate a clear spectral distinction between primary, secondary and regenerating forest. Since secondary forests have been demonstrated by archaeological evidence to have an antiquity of up 700 years, differences between primary and secondary forests are unlikely to be due to age factors such as tree size or density. More likely it is species composition that accounts for the differences in the spectral response.

Spectral divergence analysis was conducted in order to determine which band combinations produced the greatest spectral variation of forest pixels, the best choice being a four band input comprising TM-3, -4, -5 and -7. Training samples were chosen from areas observed from fieldwork and taken from the forest mapping of

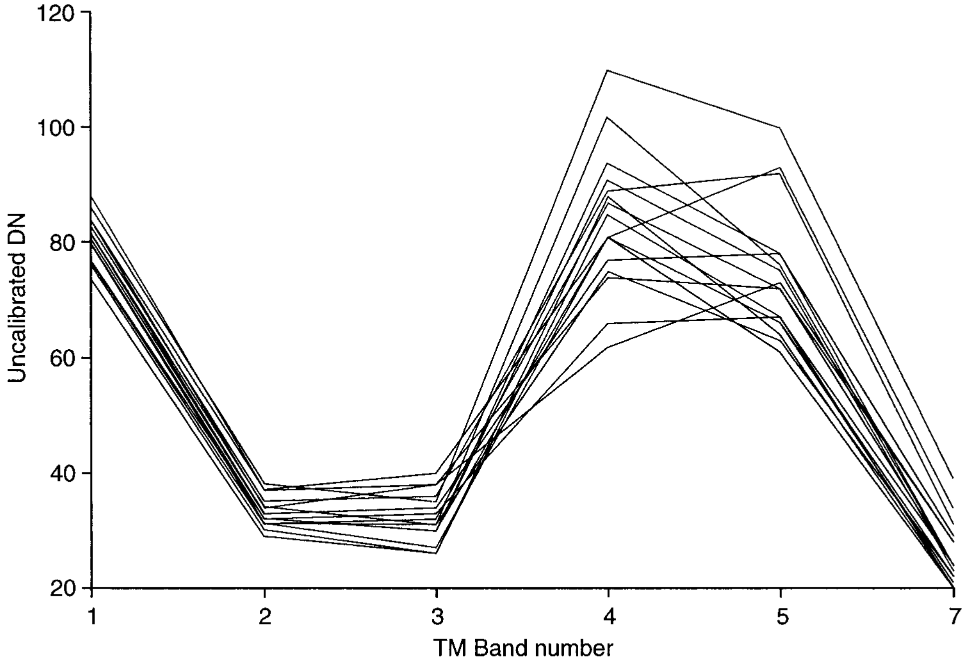

Figure 2. Spectral variation of forests in TM bands-1, -2, -3, -4, -5, and -7.

Heurtebize (1986). A maximum likelihood decision rule was applied. Of the resulting 25 classes, nine could be shown to be forest, four possible forests, five scrub, three agricultural vegetation and four undefined vegetation. The forest classes could be further subdivided as follows: three represent primary forest, one coincides with an unhealthy forest type, and another one is forest that has been regenerating over the previous two or three decades. The remaining classes are secondary forests.

An assessment of the classification by comparison with maps and field surveys revealed two problems; inaccuracies in areal extent, and confusion between a few areas of suspected secondary and primary forests. Experimentation with a variety of tasselled cap and principal component analysis bands was made but only minor improvements were detected. Nelson and Horning (1993) also highlight the problems of delineating the forests in this region.

To exploit spectral variations in forestry between seasons, a dry season TM scene (25 June 1984) was introduced into the classification along with the wet season image. If, as suspected, species composition distinguishes primary from secondary forests then differing seasonal variations of individual species should separate these forest types. Additionally the seasonal variations may reduce confusion between forest and non-forest cover types that has led to the problems outlined above.

Figure 3 shows a comparison between the mapped forests of Heurtebize (1986) and our classification results for the area. It is clear that there is a good correspondence between the two, and that the remotely sensed data is now able to produce maps of primary, secondary and regenerating forest of sufficient reliability. As the purpose of this exercise is to derive approximate information about forest type to be used in reconstructing former societies we have not considered it necessary to conduct a strict classification accuracy assessment (e.g., Congalton 1991). If our

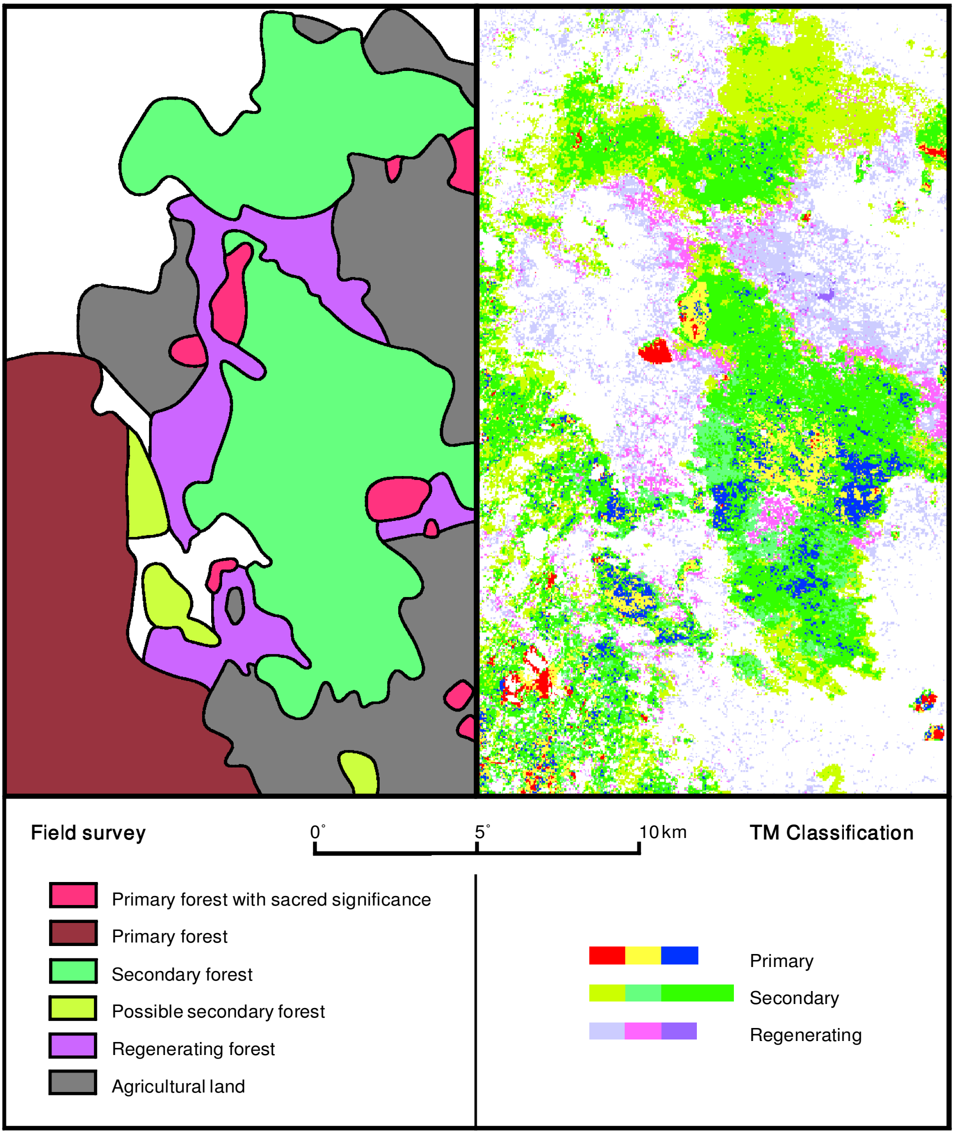

Figure 3. Comparison between field mapped forests (after Heurtebize 1986) and our multi-seasonal TM classification, displaying a good general correspondence. The distinction Heurtebize draws between primary and secondary forests is the presence of ancient fields within the latter. As this is not a biological criterion this may be the reason for the discrepancy in the south west of the area. The primary forests with sacred significance are those areas containing tombs. The various colours within each class of the TM classification represent spectral variation within each class.

classification is of the order of accuracy that many classifications are capable of achieving (e.g., 70–80 per cent) this is more than sufficient as it far exceeds the level of information otherwise available.

One of the original objectives was to examine the extent to which secondary forests could be placed into a sequence of regeneration. The spatial distribution of spectral classes relating to secondary forest does not give any clear indication that this is possible. Some classes appear to be more closely related to primary forest and are located deeper within forests, whilst others can be seen closer to unforested areas. An example of this can be seen in the northern part of the TM classification illustrated in figure 3. It may be that this type of forest can be crudely divided into two groups according to regenerative state. However an equally likely explanation is that some forests are more easily accessible and therefore less dense due to small-scale resource exploitation. Geo-referenced hardcopy images have been produced so that these key areas can be visited during the next field survey. It is hoped that these tentative age interpretations of the classification results can be confirmed by field examination and oral evidence.

4.2. *ERS-1 SAR data*

It was originally intended to utilise the ERS-1 SAR image (20 June 1994) in the classification exercise in order to provide information that may relate to canopy structure and texture. This proved impossible to achieve as without access to digital elevation models we were not able to execute a terrain correction to permit the merging of the SAR data with Landsat. It was clear however that the SAR image contained useful forest information and so it was analysed on its own. Rather than engaging in experimental modelling to try and relate backscatter to forest canopies, we chose a simple image analysis approach as it was obvious from visual investigation that forested areas were distinguishable.

The image was geometrically registered to the Laborde projection using corner co-ordinates. Although inaccuracies of up to 150 m in some areas were evident this was considered accurate enough as no registration with other imagery was intended. Following the recommendations of Vencatasawmy *et al.* (1997), the image was speckle reduced using a Lee-Sigma filter followed by resampling to 25 m spatial resolution. Linear conversion from 16- to 8-bit data was performed between the minimum value and a value of 650, the latter value obtained from examination of the original histogram.

Visual examination of the image demonstrated accordance with the forested area as shown on the 1 : 100 000 scale maps. Forested areas had higher backscatter and greater spatial variability. Image thresholding (density slicing) was not capable of producing a forest map as too much confusion with other cover types resulted. In order to exploit textural as well as tonal differences a texture image was produced by using a 9 by 9 filter that replaced the central pixel with the variance of its neighbours, followed by eight applications of a 5 by 5 low pass filter to smooth the result. An unsupervised classification was performed using the original and the texture image producing 4 statistically-based clusters. Finally a 3 by 3 median filter was used to tidy the image by removing individual or very small clusters of pixels.

Comparison with maps demonstrates that two of the classes correspond closely to areas of forest, one class represents cleared areas and the remaining class probably represents areas of scrub or regenerating forest. Figure 4 displays part of the final SAR-derived forest map centred around the 1993 survey area. The SAR image and the results of the multi-seasonal TM classification are shown for comparison purposes.

An accuracy assessment of this classification can at present only be subjective as the maps and other imagery used for comparisons are at least ten years older than the SAR image. It is clear that there is a general agreement between the locations and extent of forestry derived from the SAR and the TM images. However, the SAR

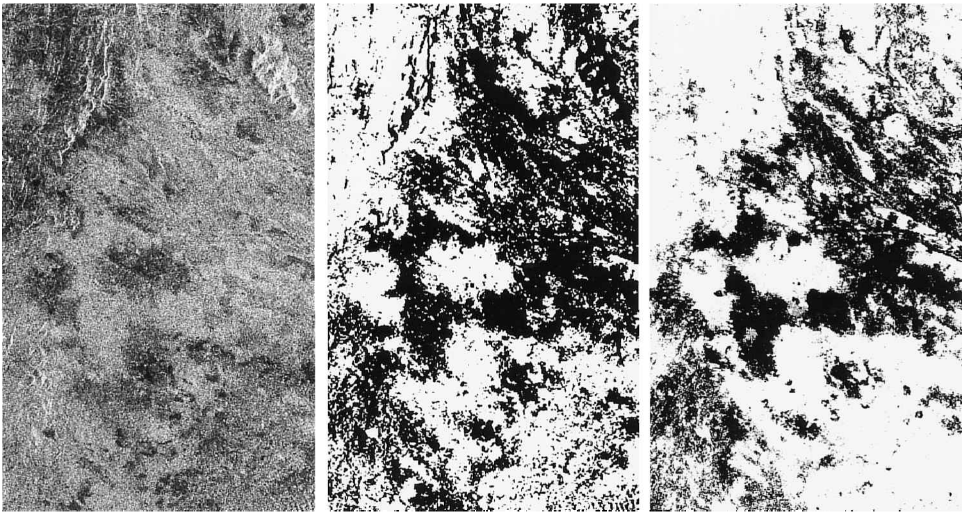

Figure 4. Comparison between SAR scene, SAR derived classification and multi-seasonal TM classification. Note the good correspondence except in the more rugged terrain in the north-west and north-east of the image. Each image is 32 km across.

derived classification suffers from inaccuracies at a detailed level, especially in the more hilly areas, where some slopes facing the sensor have a higher backscatter and have been misclassified as forest. This has prevented its use in change detection analysis.

There are obvious advantages of using SAR data to produce forest classifications, in terms of cost, spatial resolution and cloud penetration. The advantage of the methodology described here is that is relatively simple and is faster than multi-spectral classification. This may have applications where a lower level of accuracy is acceptable.

4.3. *Red soils*

When the wet season TM image is displayed as a simulated true colour composite (TM-3, -2, -1 as RGB) many areas appear as brownish-red indicating a relatively high reflectance in visible red wavelengths. Information from field survey indicates that these are areas of bare red soil. Figure 5 illustrates the spatial distribution of this spectral class. It is evident that there is an association between these areas and forestry, that leads us to hypothesise that the red soils may record former locations of forest. Indeed a comparison of red soil areas with forest cover as portrayed on the 1950s maps shows that some of these areas were formerly forested, and have been cleared since the 1950s. The red soils are often located around the edges of forests or within clearings, which supports this. If this hypothesis is correct it permits further information to be derived about changes in the former landscape. A major nineteenth century settlement at Ambaro was found on these red soils, which dates the deforestation to over a century ago. This permits us to map areas of deforestation, as marked by red soils, presumed to have occurred over 100 years ago.

It is common in semi-arid environments to observe red hematitic soils. Whilst it seems that the red soils are indicators of areas of recent deforestation we are uncertain about the mechanism that reduces the redness over time. A possible reaction dis-

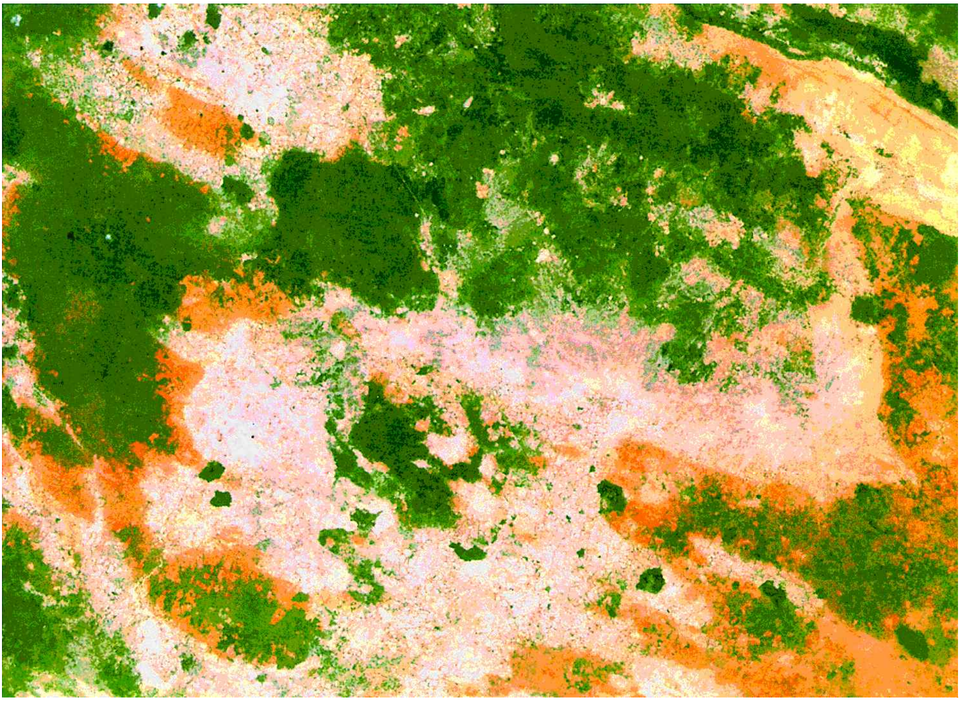

Figure 5. Simulated true colour composite of the wet season TM scene. Note the spatial association of red soils (seen as orange in colour) to forests (green). The image is 29 km across.

solving the hermatite by iron reduction is outlined by Schwertmann (1971) and Pye (1983). This may have been facilitated by cultivation allowing increased organic incorporation in the soil.

4.5. *Landscape reconstruction based on forest change*

A key feature of landscape archaeology is to recognise that the contemporary landscape is merely a palimpsest of successive changing relationships between people and their environment. Each stage of Androy's history has resulted in changes in these relationships, such as in settlement structure, land use pattern and exploitation of natural resources. All these processes will have affected the modern landscape seen in remotely sensed images. By using information on distribution and type of forest we may begin to unravel these sequences of change and assist in the archaeological investigation of Antandroy society.

To use the remote sensing products effectively it is necessary to consider what is already known of Androy's history. The earliest written descriptions of Androy society date from the mid seventeenth century. The most notable of these early texts, published in 1729, describes the years of slavery of a shipwrecked sailor amongst the Antandroy. This text describes the existence of a capital ruled by a king and a series of regional centres ruled by princes (Drury 1729). These centralised nucleated settlements and the power of the royal clan seem to have waned by the late nineteenth century. What we have attempted to do with our forest record is to suggest likely locations for major settlement foci. Figure 6 shows the distribution of primary and secondary forests and the red soils discussed in the preceding section. The capital has already been located in the 1993 survey area (figure 6: area 9). A clearing of these dimensions serves as a template for the identification of similar locations. Eight possible settlement areas have been identified that are worthy of further field investigation. One of these (figure 6: area 1), approximately 10 km to the south of the capital, may consist of three such areas. This is suggested by its size, and the distribution of forests and soils. The primary forest at the centre is significant since some of the earliest Antandroy kings are buried here. This makes the investigation of this area a priority for future fieldwork. Other possible settlement foci have been identified (figure 6: areas 2–7). Area 7 has already been surveyed by Heurtebize (1986), who discovered large numbers of tombs and relict field systems. This is the ancestral land of the Renivave group of clans, who moved here around 1850. Area 8 is the major town of Tsihombe where survey in 1995 identified major eighteenth and nineteenth century villages pre-dating the town, founded in 1901.

Another application of the forest record has been the identification of sacred forests. These are subcircular remnants of primary forests that have survived deforestation because of this sacred significance such as location of tombs. Most are isolated and are easy to identify on the imagery. On the basis of spectral signatures

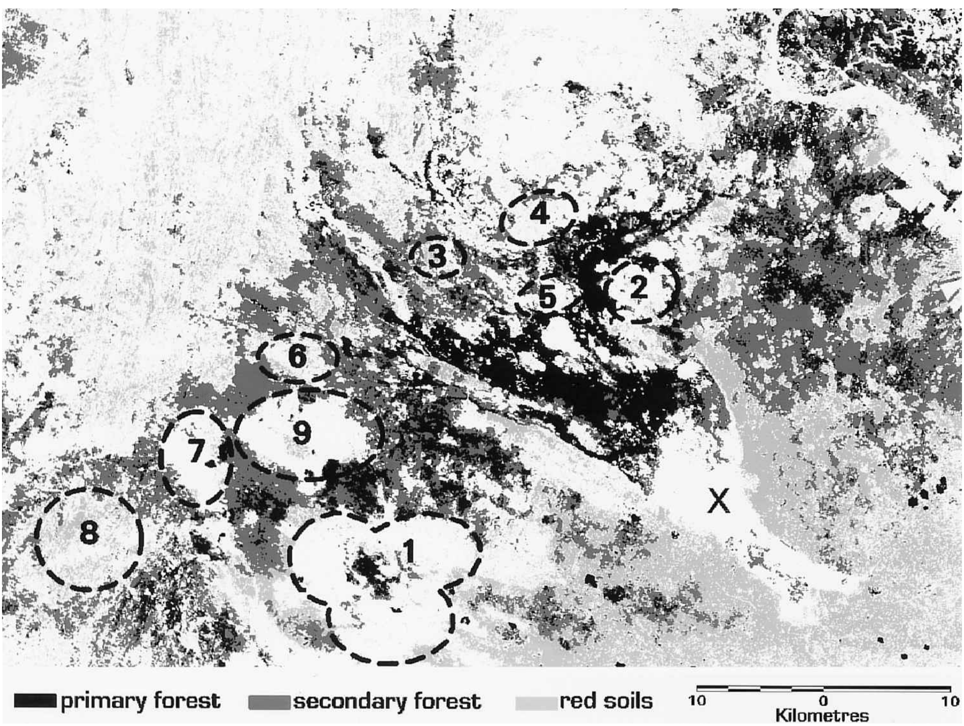

Figure 6. Map of red soils, primary and secondary forests. Possible settlement zones are indicated as numbered ellipses. Areas of non-red soils (white areas) within primary forest immediately to the south of zone 5 are natural depressions into which water percolates. A larger natural depression (indicated by an X) is probably a former lake. The formerly unexploited area, discussed in §4·5, is indicated by red soils in the south-east corner of the image. Zone 9 corresponds to the 1993 survey area as marked in figure 1.

it is also possible to locate sacred forests that have since been surrounded by secondary forests. Figure 7 illustrates the distribution of sacred forests. The majority are located towards the coast and have been divided into groups (figure 7: areas 1 to 5) based on their spatial arrangement. Three of these relate to the present distribution of the royal clan (areas 2, 4 and 5). These areas are worthy of investigation as they may contain tombs or be of other significance.

The remote sensing products have also suggested the intriguing possibility that an area towards the coast can be identified as being unexploited until the eighteenth century. There are two separate lines of evidence to support this conclusion. We find sacred forests which can be taken to be the remains of an expanse of primary forest which subsequently underwent dissection. Since these remnants have survived due to special significance afforded to them by the Antandroy, this demonstrates that there was no major deforestation of this area before migration to Androy by this ethnic group. Archaeological evidence has suggested that this occurred 300 years ago. Also, the area considered here is indicated by red soils (see figure 6). In previous discussion it has been suggested that these soils may indicate that deforestation occurred relatively recently. This conclusion has been supported by subsequent field survey in the southern part of this zone which located no settlements dating to before the eighteenth century.

5. Field pattern mapping

Field patterns can contain information about their chronological development and territorial and social organisation of the landscape. It is sometimes possible to phase them according to age and to detect influences controlling their layout. In various locations across the British landscape, for example, most notably on Dartmoor (Fleming 1988), field systems were laid out during the Bronze Age on

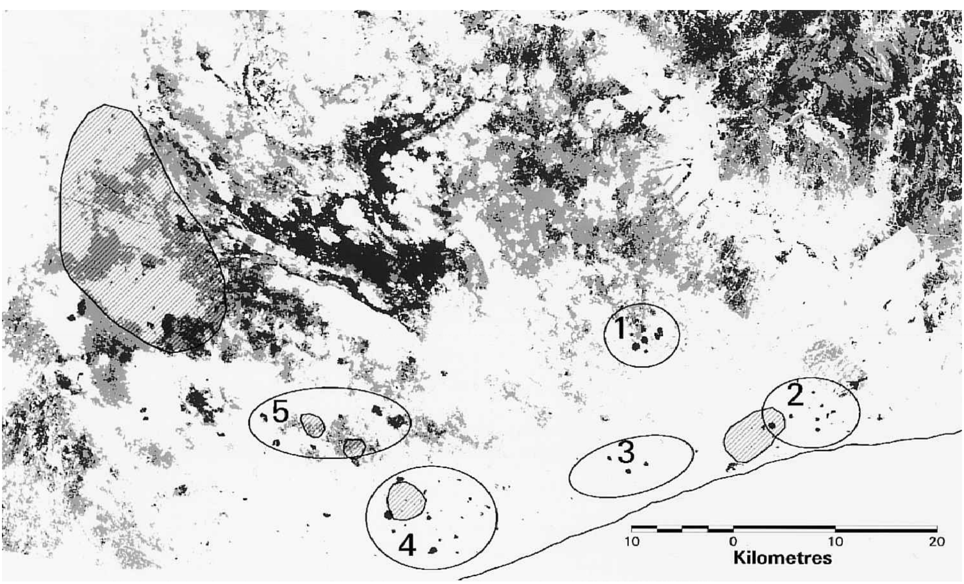

Figure 7. Map of primary (black) and secondary forests (grey). The present distribution of the royal clan is indicated as shaded areas. Possible tomb groups are suggested by numbered ellipses (see §4·5) with individual sacred forests visible within these.

single alignments with a regular pattern. This indicates organised land management probably by a single controlling influence. Also, Williamson (1987) found pre-Roman field systems fossilised in modern East Anglian fields.

Field boundaries in the Androy region of Madagascar consist of thick hedges primarily composed of cactus. A spatial resolution of 10 m, permitted by a SPOT panchromatic image, was therefore adequate to detect these linear features. To increase the utility of this imagery it was merged with a TM scene. Field boundaries could then be distinguished from other linear features and agricultural areas from uncultivated areas. We found the best method of merging was by principal components analysis of the first four TM bands, inclusion of the SPOT Pan band (as PC-1) and PCA inversion thus allowing the merged image to be displayed as a simulated true colour or false colour IR composite. Edge enhancement was performed by applying a Sobel filter to the SPOT image prior to merging. The fields were manually plotted using 1 : 12 500 hard copy.

Archaeological sites represented by pottery scatters were compared to the field pattern map. Figure 8 demonstrates two hypothetical models of the relation between field patterns and settlements. Comparing these models to the actual data (figure 9) it can be seen that the field patterns cannot be contemporary with the ancient settlement (model *a*) and show a clear radiating relationship with the modern settlement (model *b*). From this we conclude that field patterns relate to modern rather than ancient settlements.

The youngest of the archaeological sites is nineteenth century and therefore the

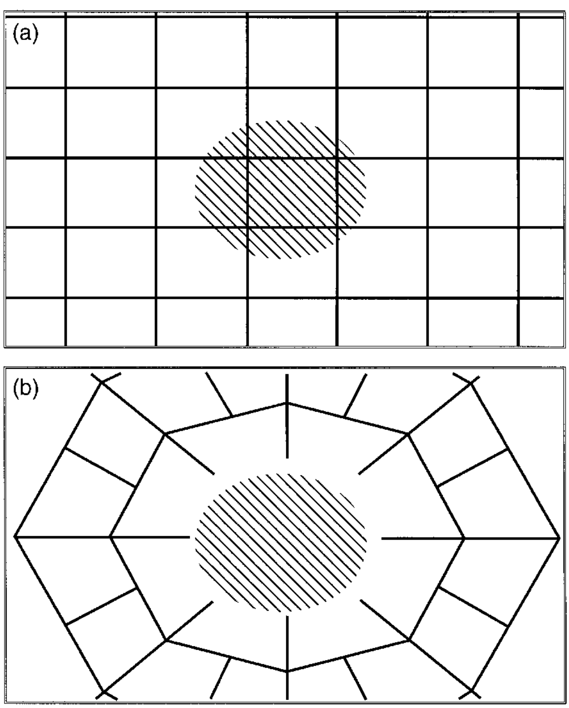

Figure 8. Hypothetical models of pattern and age relations between a settlement site and field patterns. Model A demonstrates field patterns not contemporary with settlement, and therefore the field system must post-date abandonment of the settlement. Model B demonstrates a field pattern contemporary with settlement.

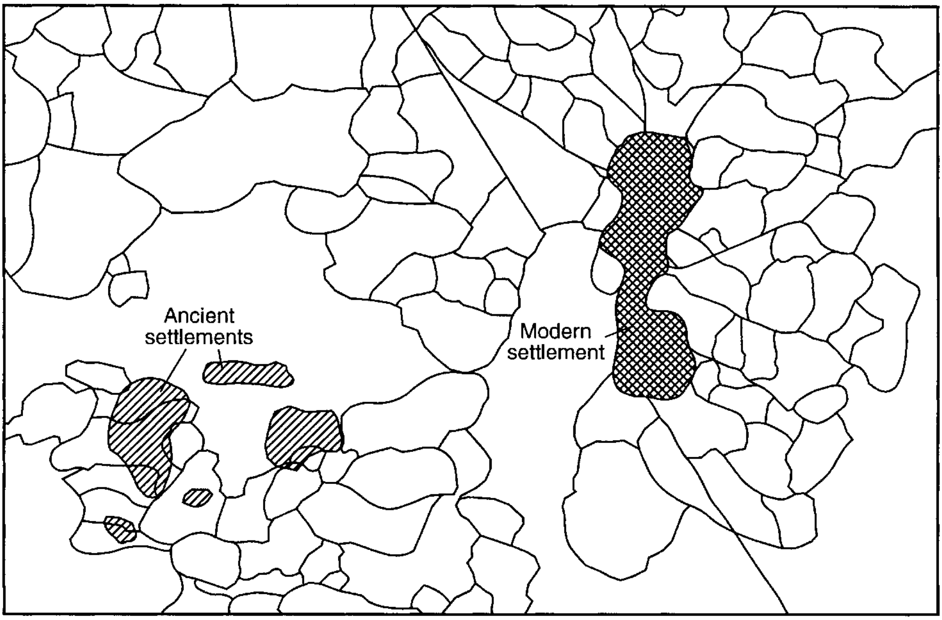

Figure 9. An example of field patterns mapped from the SPOT/TM merged image for part of the 1993 field survey area (see figure 1). These are plotted against known ancient settlements (from pottery scatters) and a modern settlement in order to establish the relative age of settlement and field development (see figure 8 and text).

field boundaries must have been set out after this date. It is thought that they may date to the 1930s when the French colonial authorities introduced the cochineal beetle to the region which destroyed the cactus then being used for field boundaries. Fields existing today have been established ignoring any previous layout. Field patterning shows that there was no overall plan to this layout which suggests a lack of deliberate and controlled reorganisation of the landscape. Instead we see fields added to others, suggesting gradual expansion. It was hoped that it would be possible to phase some of these fields according to their date. Owing to their relatively recent age this has so far not been possible.

6. Palaeodunes

Whilst active dune systems are known to exist along the coastal hinterland, examination of the TM imagery reveals an extensive pattern of parabolic dune formations. These are of the classic hairpin shape usually associated with a semi-arid environment. Figure 10 illustrates the pattern and extent of these dunes. They cover an area of about 600 km^2 between the Manambovo and Mandrare rivers and stretch inland for up to 15 km and to an elevation of 200 m. Individual dune forms are of the order of 10 by 3 km in size.

The imagery demonstrates that the dunes possess a cover of vegetation, and fieldwork observations support this. It has been discovered that sacred forests comprising the primary forest assemblage exist within the dune area, thus demonstrating that the dunes must have developed prior to the establishment of the forests, i.e., probably well over a millennium ago. It is of interest to establish a date for this dune development as this will record a period in time for which a semi-arid climate

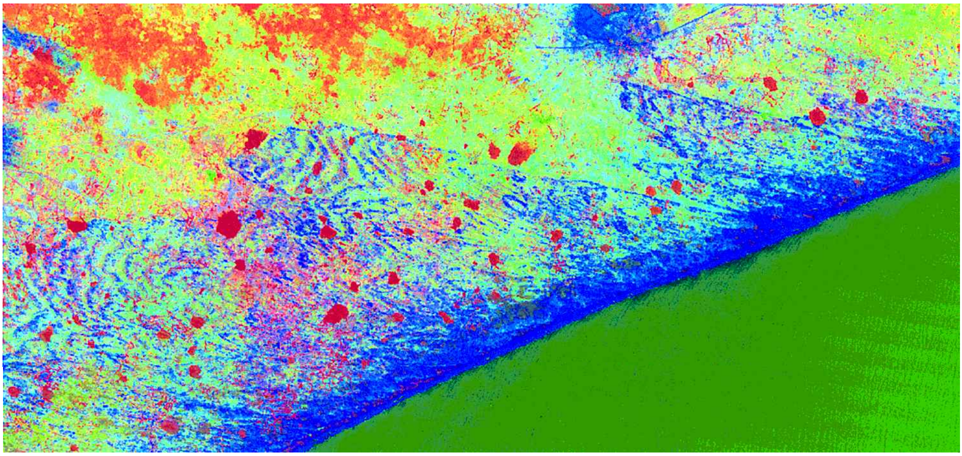

Figure 10. Distribution and pattern of hitherto undiscovered palaeodunes (blue) emanating from the coastal sand source. Sub-circular sacred forests are visible as small red patches. Image is 38 km across, and is a colour composite comprising PC-2, PC-3, TM-3 as RGB.

can be inferred. It may relate to the shift from a wet to dry climate between 3000 and 2000 years BP that has been reconstructed from evidence of dwarf hippopotami, giant lemurs, elephant birds and crocodiles, and from palynological evidence (Burney 1993). The aridity may alternatively, relate to climate change of much greater age, of the order of tens to hundreds of thousands of years related to the glacial–interglacial cycles that the Earth experienced, the most likely time being at the last glacial maximum (ca. 18 000 BP). Future fieldwork will collect buried sand samples so that the dune development can be accurately dated by means of optically stimulated luminescence (OSL) dating.

7. Directing future fieldwork

As satellite imagery is able to provide information covering much larger areas than is practical to visit by fieldwork, an important objective in this project was for it to be used to identify areas worthy of further field investigation. The most significant effort at directing fieldwork has already been discussed: the location of probable settlement sites by reconstruction of forest change. In addition two further approaches have been adopted.

The possibility of using the imagery to find actual archaeological sites was investigated. It had been noted on previous field visits that in the hilly, rocky and more sparsely vegetated areas archaeological sites were characterised by a reduced density of loose stones. These stone-cleared sites were large and distinctive enough to be visible from a considerable distance, and so it was conjectured that Landsat TM or SPOT data might be able to identify such sites. With *a priori* knowledge of the location of these sites it was possible to locate four of them on the TM imagery. These were used as training sites in a supervised multi-spectral classification to produce predictions of where other stone-cleared sites may be found. There are many factors that may cause spectral confusion between stone-cleared sites and other cover types, and there may be many areas that have low stone cover for natural reasons, and so this kind of approach can only realistically be used as a reconnaissance tool to direct fieldwork. These sites will be visited in the next fieldwork campaign. In other less rocky areas it had been noted that occupation debris from former settlement sites was of such a density as to change the appearance of the soil colour over areas of many hectares. Utilising TM images, the spectra of known occupation areas were compared with surrounding soils and it became apparent that due to the high natural variability of soil colour it was not possible to use this approach.

As outlined in § 2, exposures in the coastal dunes sometimes reveal shell fragments of the extinct Elephant Bird. As there are unanswered questions relating to the reasons for the extinction of these birds, it is important that further sites are located, analysed and dated. The coastal dunes are easily detected on the TM and prominent blow-outs can be located as light-coloured areas stretching inland by up to a kilometre. These represent promising areas to visit, as exposures will be present within the blow-outs. An image map has been produced and latitude-longitude co-ordinates extracted to assist in guiding the next fieldwork expedition to these areas.

8. Summary and conclusions

Satellite imagery has been used to assist in a landscape archaeological approach that aims to reconstruct the history of the Antandroy people. It has been particularly effective in providing maps of forest extent and regenetive state. Utilising multi-seasonal TM scenes it was possible to derive maps that indicate forest type as primary, secondary or regenerative. The spatial pattern that these forest types display have permitted the identification of nine former settlement zones, some of which are already known and some that require future field investigation. Small patches of primary forest that have remained untouched for sacred reasons have been identified and form an important part of the reconstruction.

An image comprising SPOT panchromatic data merged with a TM image (19 January 1985) allowed the detailed mapping of field patterns. These suggest a lack of overall planning, rather a simple expansion away from the settlement foci. Although cactus has been used for hedges since the eighteenth century, today's fields all date from since the 1930s. Little evidence could be found for the relative ages of their development phases.

Evidence of a former much more arid climate was found. An extensive and inactive parabolic dune field was discovered covering an area of about 600 km^2. The significance of this dry phase cannot be assessed until material can be collected for use in providing reliable dates. It is likely however that the dry phase may correspond either to the known wet to dry change at 3000 to 2000 BP or to the last glacial maximum at about 18 000 BP.

A major part of the research effort has been to use remote sensing to direct future fieldwork expeditions. At the simplest level this has resulted in carefully processed SPOT panchromatic/TM image maps which have been overlaid with the local map co-ordinate system and printed on a high quality printer as maps of A4 size. These, together with a GPS, are to be used as base maps and navigational aids during fieldwork. The forest type classifications have been used to predict the location of former settlement sites. Further predictions have been made based on the spectral identification of stone-cleared areas, which may represent archaeological sites. It has been possible to identify major blow-outs in the coastal dune systems, which have been mapped as promising sites at which to search for evidence relating to the extinction of the Elephant Bird.

In addition to the archaeological and anthropological results that have been reported it is hoped that this paper may serve as a demonstration as to how remote sensing can be used in a project such as this to provide useful information on landscape change over a wide area that is poorly known.

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