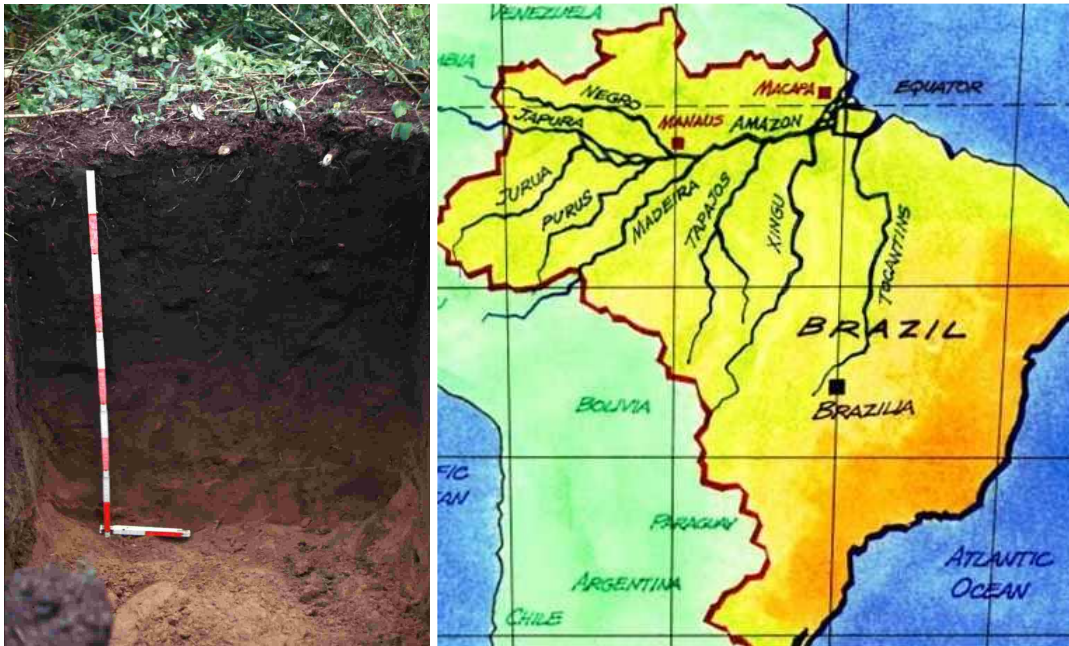


Possibilities of mapping Amazonian Dark Earths using remote sensing techniques



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Preface

This study was conducted within the scope of an INREF¹ Seed Money Project research. This seed money project research is undertaken on 'Terra Preta de Indio'. In particular, the project aims at designing research proposals for large integrated programs in the field of Amazonian Dark Earth (ADE)².

Within the INREF project 4 main areas of scientific interest have been set out:

- 1) The archeological and historical anthropological origins of ADE. How did the indigenous people form and maintain ADE? (Archeology, Paleo-Botany and Historical Anthropology)
- 2) What does ADE consist off? What are the soil components and processes involved? (Soil Quality, Micromorphology and Microbiology)
- 3) What are the (agricultural) possibilities of ADE? Possibilities for carbon sequestration and agronomic use (Agronomy and Ecology)
- 4) Where can ADE be found? What is the spatial distribution of ADE? (RS and GIS)

For the last 'work package' an initial investigation is done, dealing with; '*which research is needed to find out where Terra Preta can be found in the Amazonian basin*'. At the moment estimates are made that only 10% of ADE have been mapped. Within research on ADE there is a high need for finding out the spatial distribution of ADE. Remote sensing has been proposed as the major tool in achieving this aim (Erickson, 2003).

¹ Interdisciplinary Research and Education Fund van Wageningen UR

² The terms Terra Preta and Amazonian Dark Earth are used both for the same phenomenon. Terra Preta refers to the local (Brazilian) naming, ADE to the scientific classification.

Contents

1. Introduction	4
1.1 Amazonian Dark Earths	4
1.2 Research objectives	4
2. Literature review	5
2.1 Distribution of ADE	5
2.2 Characteristics of ADE	6
2.3 Possibilities of remote sensing	7
2.4 Prospects	9
3. Material and Methods	10
3.1 Materials	10
3.2 Data analyses	11
4. Results	11
5. Discussion	13
6. Conclusions	13
References	14

Figures

Figure 1: Known distribution of ADE sites (source: Universität Bayreuth, 2005).

Figure 2: Map of the distribution of archaeological sites in the region of the Trombetas river (Pará State) (source: Hilbert 1990, in: Kern et al 2003)

Figure 3: Map of the distribution of archeological sites in the region of the Madeira river (Amazônas State) (source: Simões and Lopez 1987, in: Kern et al 2003)

Figure 4: Masked Landsat Thematic Mapper band 4 image of the region of the Trombetas river and the distribution of the ADE sites. Darker blue indicates higher reflection in band 4 and red indicates the highest values in band 4 (above 80 dn value)

Figure 5: Masked Landsat Thematic Mapper band 4 image of the region of the Madeira river. Darker blue indicates higher reflection in band 4 and red indicates the highest values in band 4 (above 80 dn value).

Figure 6: Average reflectance values of the ADE sites and the whole masked image of the region of the Trombetas River

Figure 7: Average reflectance values of the ADE sites and the whole masked image of the region of the Madeira River.

Tables

Table 1: Characteristics of possible sensors to be used for mapping ADE.

Table 2: Details of the gathered images per region.

Source front page images:

Terra Preta; <http://www.laputanlogic.com>, 2005.

Map of Brazil; http://members.tripod.com/~bore_encyclopedia, 2005.

1. Introduction

Historically, the strategy of agricultural practice in the Amazon consisted of slash and burn agriculture. The common practice was that new farmland is colonized and is being used for 2-3 years until crop yields declines and /or the growth of weeds is too excessive to utilize the land (Erickson, 2003).

However, there is strong evidence for a different agricultural practice covering most of the Amazon Basin and further. Permanent or semi-permanent agriculture from the indigenous people (until around 1500) could have created sustainable fertile soils, these are known as Terra Preta or Amazonian Dark Earths (ADE) (Glaser et al, 2001).

1.1 *Amazonian Dark Earths*

Terra Preta or Amazonian Dark Earths are most commonly understood as ancient remnants of Amazonian civilizations that inhabited the area before the coming of the Europeans. After the colonization of (Northern and) Southern America, the indigenous population nearly got extinct and with them the knowledge on ADE. Recently large remains have been found and investigations have started (e.g. Denevan, 1996; Heckenberger et al, 2003 and Lehmann, 2003).

ADE were made between 500 BC and 1500 AD and are thought to have originated from disposal of organic waste and incomplete burning, creating charcoal (slash and char) (Mann, 2002). The anthropogenic A-horizon of the ADE have greater depths (on average 30-60cm) than the typical rainforest soils (on average 10-20 cm) (Kern, 2003 and Erickson, 2003).

ADE are found on all soil types in the Amazon watershed and are normally located on bluffs near rivers, but also farther away in the inner land. Apart from Terra Preta, also Terra Mulata have been identified. These soils have increased levels of organic matter but not as high as Terra Preta. Terra Mulata (also classified under ADE) are the transitional soils between Terra Preta, which are most commonly adjacent to the former settlements, and the primary rainforest on the Terra Firme (generally Ferralsols). Terra Mulata show a lower level of organic waste and human artifacts (e.g. shells, pottery etc.), but it is believed that they were cleared in the same way as the Terra Preta (slash and char). No clear criteria have been set to precisely define these types of soils (Erickson, 2003) and in this study Amazonian Dark Earth (ADE) will refer only to Terra Preta.

After the indigenous population left, most ADE have been covered by dense (secondary) rainforest. Many sites have been found (Kern et al, 2003) and some are archaeologically investigated but many still are undiscovered. The total extent of the ADE is not known (Erickson, 2003) and estimations of the extent of these ADE differ from 10% (Mann, 2002) to 0.1%-0.3% (Sombroek et al, 2005) of the total area of the Amazon basin. Scientists take interest in a description of basin-wide patterns and variability of these soils (Erickson, 2003; German, 2003).

1.2 *Research objectives*

With this Capita Selecta an investigation is undertaken to describe several possibilities using remote sensing techniques to retrieve these ADE under rainforest canopies (late secondary tropical rainforest). First, a limited literature study is conducted to discover possible biophysical and spatial indicators for mapping ADE and indicators to map these ADE are compared in relation to the feasibility of mapping ADE. Second, two maps with known ADE sites (obtained from Kern et al 2003) were digitized and Landsat Thematic Mapper images and DEM images were overlaid to investigate the characteristics of the known sites.

2. Literature review

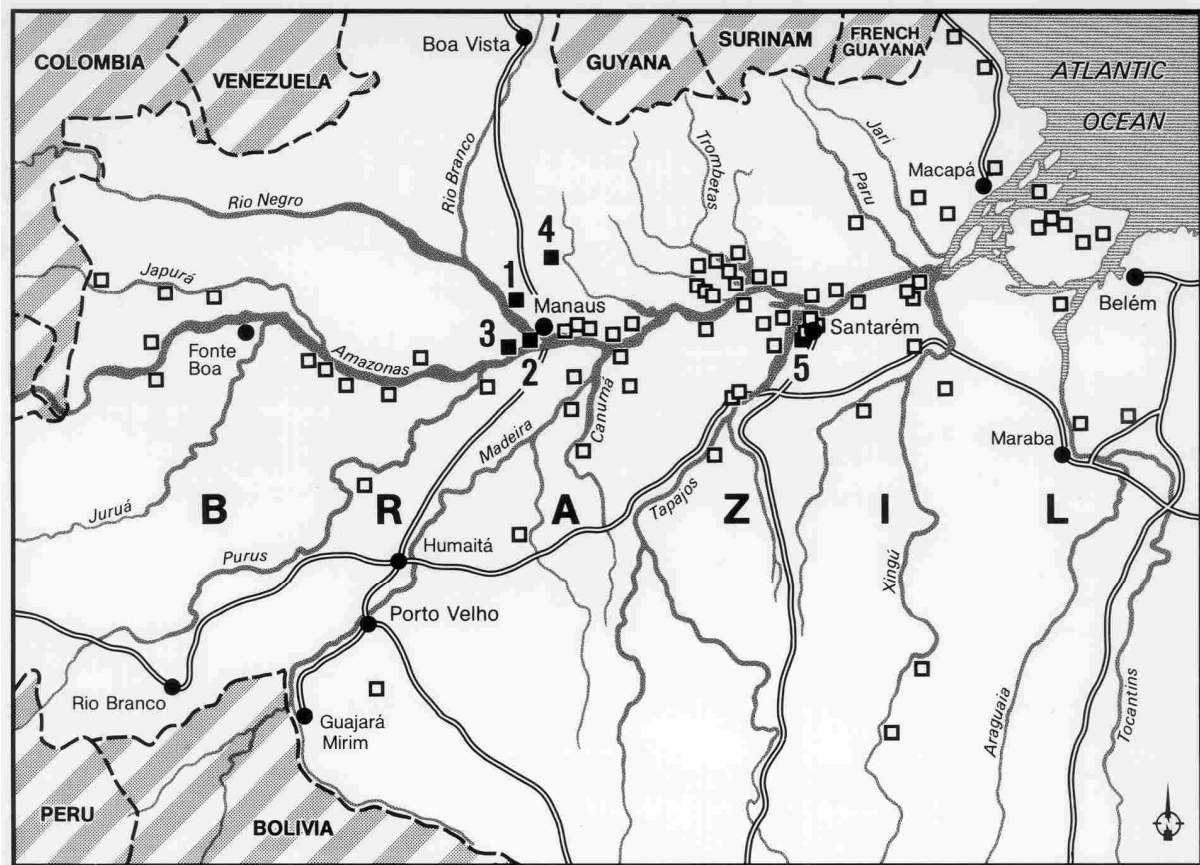
2.1 Distribution of ADE

Ecotypes and Rivers

Brazil is divided into 33 eco-regions and the Amazon Basin includes 17 main landscapes of these (Kern et al, 2003). The Amazon can be divided into three types of classified river systems, namely white, clear and black waters. ADE's are widely spread and are found in all river systems, but mainly in white water river systems (Kern et al, 2003). The ADE found on the black water systems (rich in humic acids) are usually small, probably because of a decreased number of inhabitants due to unsuitable exploitation of food in these rivers.

Most sites are located in the surrounding of Manaus, and further downstream (figure 1). The pattern that ADE sites are situated relatively close to present settlements is obvious. When moving away from habited areas, sites are less likely to be found because of the low accessibility of the rainforest.

Figure 1: Known distribution of ADE sites (source; Universität Bayreuth, 2005).



Landscape

The height of the former settlements in the landscape being ADE, is at least over two meter (99% of the cases) above the river water level and 45% of the cases were found between 5 and 25 meter. Only 4% was above 40 meter from the river level (Kern et al, 2003). In general, sites with ADE are situated on strategic places and far enough from the floodplain to be secure for flooding. These sites are mainly on the edges of the plateaus and on elevated plateaus in the riverbed. Apart from that, the presence of a little stream close to the elevated settlements was a necessity for the inhabitants' water demand.

Size and spatial pattern

Individual ADE sites are variable in size and range from a fraction of one ha to over 300 ha. Kern et al (2003) report that 80% of the documented sites are less than 2 ha in size, but there are at least over 100 sites found which are larger than 2 ha.

The spatial pattern of the ADE sites is hypothetically described in the report of Erickson (2003) and he poses several possibilities of evolution. Some sites have a clear elongated form, but there exist much variability between sites. When mapping ADE patterns of the former settlements, it is important to be able to detect these on a larger scale map.

Size and pattern of the ADE sites is an important factor to take into account, when reviewing possibilities for remote sensing. The possibility of provable difference is highly dependent on the spatial extent of the individual pixel values. If pixels are by definition mixed (e.g. rain forest on ADE and on adjacent soils in one pixel), the level of possible statistical differences is less and the identification of ADE sites becomes more complex.

2.2 Characteristics of ADE

Relevant literature was studied to retrieve indications towards possible biophysical parameters, which can be used analysing remote sensing data. These possible indicators were derived from a broad range of literature including anthropological reports (German, 2003), soil physical reports (Glaser et al, 2001; Glaser et al, 2002) and historical reports (Devevan, 1996; Erickson 2003).

Soil properties

ADE contain higher concentrations of nutrients, including nitrogen, phosphorus and calcium and have a greater and more stable organic matter (Glaser et al, 2001). This has been extensively investigated (Glaser, 2002; Kern, 2003) and the soil is seen as a phenomenon, where ancient cultures were able to improve soils instead of depleting them over years and centuries.

Frequent findings of charcoal indicate the former slash and char culture. The slash and char culture is the key factor in the persistence of these soils due to slow decomposition of charcoal. The soils have a high CEC (Cation Exchange Capacity) and improved physical characteristics than common soils in the region. According to local farmers, productivity on the soils is much higher (German, 2003; Glaser et al, 2001) and the soils are therefore preferred over surrounding soils on Terra Firme.

Vegetation composition

Local residents observe differences in vegetation composition and structure on ADE (German, 2003). German (2003) listed several distinct host species, which may be found on ADE. These 'indicator species' are generally associated with old fallow or mature forest.

Classification of vegetation types via unique vegetative reflectance has been done in forest monocultures and in clearly defined vegetation transitions (e.g. wetland vegetation) (Hirona et al, 2003). But the lack of relevant literature of mapping tropical rainforests via specific reflectances suggests that mapping patches (here: late secondary forests on highly fertile soil) is not yet achievable with present data gathering techniques.

Although mapping via unique reflectances is likely not achievable, efforts could concentrate on the specific reflectance of forest structure and the corresponding characteristics of the canopy heterogeneity.

Biomass

ADE are perceived to be distinctive from adjacent soils in terms of nutrient dynamics. Due to the increased fertility, there are several indications that also the above ground biomass is

increased on the ADE. German (2003) found that local farmers think that biomass accumulation is about two times higher on ADE than on adjacent Terra Firme. Estimation of the elevated levels of above ground biomass on these soils still has to be done, but Glaser et al (2001) state that “enhanced biomass production at these sites may still result in larger carbon input in the topsoil”. Some studies on plant growth, crop yields and natural generation showed that charcoal can increase the aboveground biomass (Chidumayo, 1994; Kishimoto & Sugiura, 1985 in: Glaser et al, 2002).

For mapping biomass with remote sensing techniques it may be interesting to note that:

- 1) German (2001, pers. observation) found a lower overall average of girth of the present mature tree species on Terra Preta;
- 2) Biomass accumulation on Terra Preta soils is in the late successional stages slower than on Ferralsols (German, 2003, local farmers). Note that the total biomass is not mentioned, but the biomass production in the later stages of the vegetation succession.

Structure

Canopy and lower layers of the vegetation structure of the re-grown rainforest on ADE are more complex. Due to increased fertility more plants have the ability to survive under closed canopies. This includes more vegetative layers in general and in particular, more vines and thorny vegetation, a closed understory and a lower overall canopy (German, 2003).

In line with the occurrence of different flora species (see *vegetation paragraph*) the structure and vegetative layers are assumed to be different on ADE, compared to surrounding rainforest. This can be of interest, especially because of the ability to investigate vegetation structure by radar remote sensing (Santos et al. 2003).

2.3 Possibilities of remote sensing

During the past decade the use of remote sensing for tropical rainforests has had increased attention due to the ability of monitoring large-scale vegetation changes. Much focus, in Brazil and other countries in South America, is on deforestation and possibilities of remotely sensed data for mapping primary and early-secondary rain forest (Lu et al, 2005; Moran et al, 2000; Santos et al, 2003).

In order to investigate ADE, I elaborate on several findings of articles and describe the possible uses when mapping ADE.

Resolution and site dimension

A minimum detectable size of 2 ha is a requisite to have sufficient possibilities for mapping ADE, but enhanced spatial resolution would improve the localisation of the many smaller patches. In table 1 several sensors are enlisted with their spatial resolution and their corresponding spectral resolution, indicating the possible use and number of hypothetically pure pixels when investigating a site of 2 ha. When detecting these sites the elongated shape can be of special interest, because software filters have possibilities to stress horizontal or vertical entities in images.

Collection method	Sensor	Spatial resolution	Spectral resolution	Nr. of possible pure pixels of 2 ha site
SAR (SB)	ERS-AMI	30m	C-band	11
	JERS-1	18m	L-band	62
	Radarsat	variable	C-band	Variable
SAR (AB)	SIR-C	15-45	X, C, L, -bands	89-5
	AeS-1	1.5m (variable)	P-band	8889
Multispectral	TM4-TM5	30m ¹	7 bands	11
	SPOT-5	5-10-20m	5 bands	400-100-25
Hyperspectral (SB)	EOS-MODIS	250-1000m	36 bands	0.16-0.01
Hyperspectral (AB)	AVIS-2	1.5m (variable)	Variable	8889

Table 1: Characteristics (spatial and spectral resolution) of possible sensors to be used for mapping ADE. (source: Lillesand & Kiefer, 2000). SB: Spaceborne, AB: Airborne.

¹TM band 6 (thermal band) has a spatial resolution of 120m.

Landsat Thematic Mapper

The Landsat Thematic Mapper (TM) is a sensor which has a very broad range of uses. The sensor of TM mainly captures mixed information over vegetation cover: green leaves, canopy, shadows stems and branches (Lu et al, 2005). The use of TM images for mapping the ADE site has limited opportunities, but because of the completeness of the dataset (covering whole Brazil) and the relatively low cost it can be useful to initially evaluate its possibilities of mapping ADE.

Lu et al (2005) investigated the relationship between aboveground biomass of tropical forests using TM reflectance data and found that the TM4 band was most sensitive for detecting aboveground biomass. Hereby it must be noted that the relationship and thus the sensitivity decreased rapidly when the aboveground biomass of the forest stands was above 11 kg/m² (mainly primary forests). This implies that there is saturation of reflectance due to the complex structures of rainforests (Lu et al, 2005).

Other opportunities with the TM are the ability to map rivers, streams and old fallow and mature forest. In this way, a general idea of the possible locations in the landscape of the sites can be obtained.

Radar

Synthetic Aperture Radar (SAR) has proved to be an effective tool to analyse the humid tropics, because of the ability to peer through clouds (Lillesand & Kiefer, 2000; Santos et al, 2003). In general, the shorter wavelengths (C-band) backscatter from tree leaves, whereas longer wavelengths (L- and P-bands) are best for sensing tree trunks and limbs (Lillesand & Kiefer, 2000).

Studies (Lu et al, 2005; Moran et al. 2000; Santos et al, 2003) using remote sensing data for identification of primary and secondary rain forest are common. Investigation of aboveground biomass on tropical rainforest using P-band airborne SAR (Santos et al, 2003) showed the capability of detecting secondary forest and to a lesser extent primary forest. The P-band has significant correlation with the aboveground biomass, but it must be noted that saturation of backscattered radiation occurs. Imhof (1995, in: Santos et al, 2003) examined the C-, L- and P- band saturation levels for two forests (including a tropical rainforest). The saturation levels for both forests were; 20 ton/ha for C-band, 40 ton/ha for L-band and 100 ton/ha for P-band. Where biomass levels of primary forest on moderate fertile soils is about 200 ton/ha there are some difficulties to overcome to get good estimations of rainforest on fertile soil.

L-band has been proposed to be able to estimate vegetation structure. As noted above, there are clear indications that the canopy and vegetative layers on undisturbed ADE are more

complex and therefore possibly detectable. The saturation level forms a complicating factor but the possibility to combine radar images and other data can be sufficient to map ADE.

Vegetation classification

The complexity of vegetation type classification of tropical rainforests is extremely difficult, despite the increased availability of spatial data. Biomass and structure have been proposed to be able to partly overcome these problems (see 2.2). Characteristics of spectral reflectance of emergent trees could still be of interest, especially when these emergent trees have an increased abundance on more fertile soils. Simple vegetation indices (NDVI or SAVI) or more complex indices could improve prediction of occurrence of the ADE.

DEM and buffering

When taking the patterns described in Denevan's bluff model (1996) into account, it might be sufficient, or at least rewarding, to investigate the position of the edges on the Terra Firme. In general, the model describes a pattern of settlements, which are situated, on the edge of the raised Terra Firme adjacent to the floodplains (Várzea) of the Amazon river system. Localisation of these strips along the rim of the floodplains could downsize the area of interest and improve mapping of ADE. A set of spatial explicit rules (buffering) in combination with a Digital Elevation Model (DEM) could be used as a technique to focus on areas of interest.

2.4 Prospects

In general efforts on mapping of these soils will mainly concern identification of patches of variable sizes (1 ha to 350 ha) of 500-years-old successional rainforests on increased fertile soils. In recent literature characteristics of ADE with regards to soil differences and the corresponding vegetation are described, and remote sensing has opportunities to localize these soils. Despite extensive physical descriptions and archaeological meaning of these soils there an information gap remains on 'untouched' ADE sites. Although clear differences exist, many characteristics (e.g. biomass, forest structure) have to be translated into measurable values in order to be able to predict occurrences of ADE sites in the field. If the mapping is to be successful, efforts should be taken to translate characteristics of 'untouched' soils. Hereafter possible future projects are described.

Vegetation

A field study could be conducted to estimate the increased presence of aboveground biomass on ADE and this should be compared to the aboveground biomass on the surrounding soils. Depending on the variation different methods can be chosen to predict the location of ADE through remotely sensed data. In the same field, work objectives to investigate species composition in relation to canopy structure, vertical structure and emergent trees should be taken into account.

Images

Depending on available images, resources, cost and benefits, a choice for a sensor should be made. Depending on the kind of sensor, further methods in the field of data processing can be chosen. Ideally airborne radar images should be made from the complete Amazon basin, but this is very costly. It might be sufficient to localize the ADE when the field work and the biophysical parameter estimation is combined with lower resolution images.

3. Materials and methods

3.1 Materials

All the figures from Kern et al (2003) displaying known distributions of ADE sites were investigated. The areas of interest to investigate the possibilities of mapping ADE are chosen in such a way that the Landsat Thematic Mapper images show a closed forest canopy and a relatively low influence of human activities in the surroundings, in order to be able to investigate the naturally overgrown ADE sites. On the above described criteria two maps were chosen (figures 2 & 3) to continue the analyses.

Figure 2: Map of the distribution of archaeological sites in the region of the Trombetas river (Pará State) (source: Hilbert, 1990 in: Kern et al, 2003)

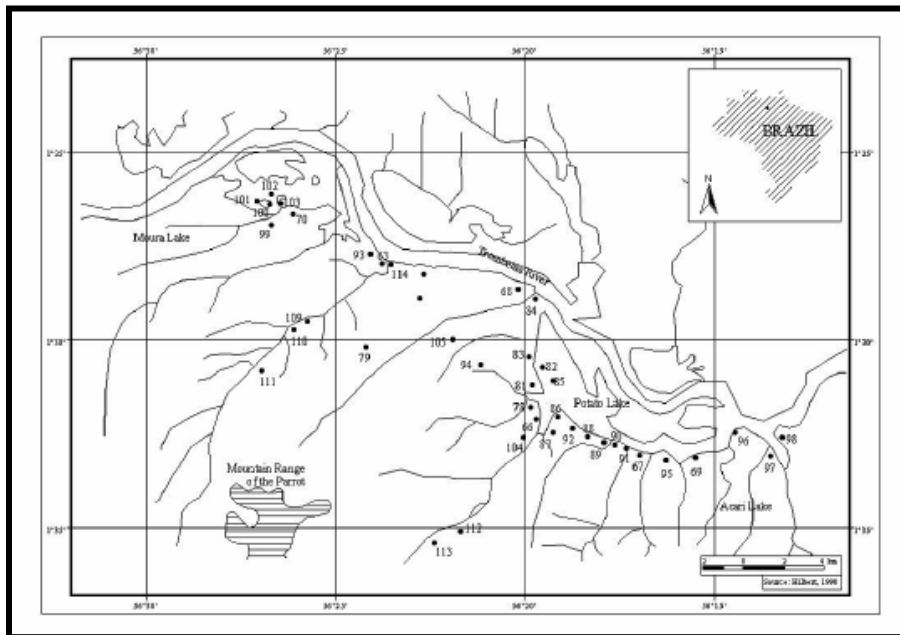
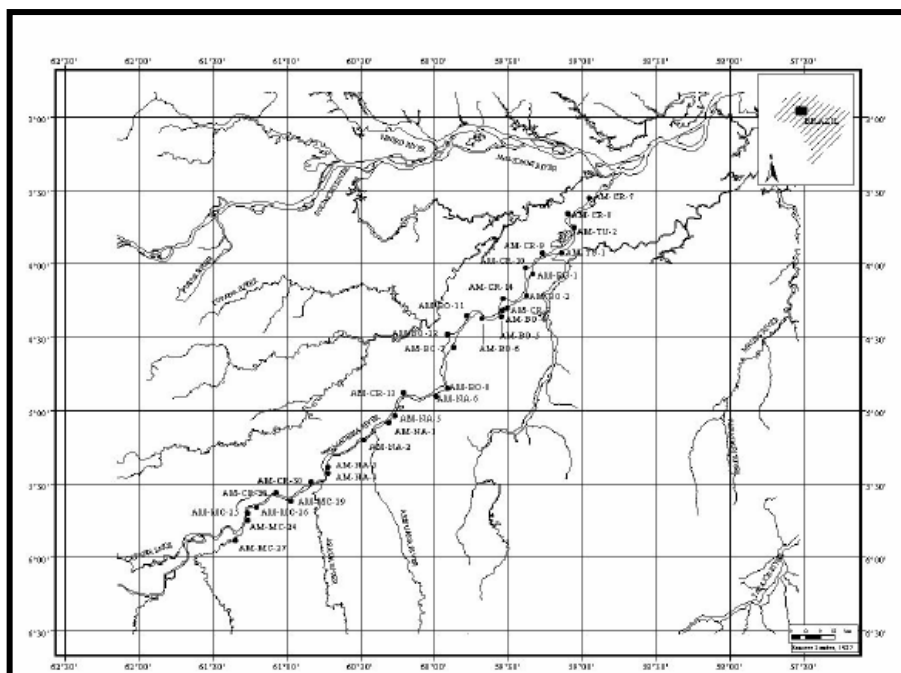


Figure 3: Map of the distribution of archaeological sites in the region of the Madeira river (Amazônia State) (source: Simões and Lopez 1987, in: Kern et al, 2003).



Two Landsat Thematic Mapper images and two corresponding STRM DEMS images (for details see table 2) were downloaded from Earth Science Data Interface (ESDI). None of the Thematic Mapper images had clouds and the images were already pre-processed and geo-referenced in UTM 84 coordinates.

For image analyses a combination of the software packages ENVI, ERDAS IMAGINE and ArcGIS was used to geo-reference, overlay, mask and generate statistics of the areas of interest in the images.

<i>Region</i>	<i>Path / Row</i>	Landsat Thematic Mapper		STRM DEM	
		<i>Resolution</i>	<i>Acquisition date</i>	<i>Resolution</i>	<i>Acquisition date</i>
Trombetas river region	228 / 61	30m / band6 60m	06-09-1992	90 m	Feb 2000
Madeira river region	230 / 63	30m / band6 60m	24-06-1992	90 m	Feb 2000

Table 2: Details of the gathered images per region.

3.2 Data analyses

For the two locations a mask was build using the STRM DEM and all water and all land above 40m was excluded. Efforts were done to see how many ADE sites would fall into the selected area and how many would fall in the outside the 40 meter elevation limit, Kern et al. (2003) reported that 4% of all sites would be located above 40m. Also a percentage of the sites below the water level was calculated to get an estimate of how many sites are flooded and thus causing difficulties to localize with general remote sensing assumptions because of altered abiotic conditions.

Secondly, the generated mask was put on the band 4 image of the Landsat Thematic Mapper images and stretched according to increasing digital values (0-133 digital number (DN)) representing darker blue and the highest values of TM band 4 displayed in red.

The distribution of the Terra Preta sites of the maps obtained from Kern et al (2003) (figures 2 & 3) were digitized and overlaid on the stretched and masked Thematic Mapper band 4 image. The digital values of the ADE sites in the Thematic Mapper band 4 images were averaged and compared to the averaged values of the total masked map to see if the locations showed an increase in TM band 4.

4. Results

The percentage of ADE occurring below an elevation of 40 meters above river level were 11.4% (4 out of 35 sites) for the Trombetas river region and 0% for the Madeira river region (0 out of 12 sites), combined: 8.5%. The percentage is higher than the reported 4% of all sites, but is the difference still within reach of the 4%. The percentage of ADE sites occurring in the water or in the riverbed was 14.3% for the Trombetas river region (5 sites out of 35 sites) and 0% for the Madeira river region (0 out of 12 sites).

In figure 4 the digitized distribution of the ADE sites of the Trombetas river region is shown. The sites located at the lower right of the image are clearly at or close to high values of the TM band 4. More north the sites show no clear relationship with TM band 4 values.

In figure 5 the distribution of ADE of the Madeira river region is shown. All ADE sites are occurring at or very close to high TM band 4 values, implicating that a high value of TM band 4 could be a good indicator for the occurrence of ADE sites.

Figure 4: Masked Landsat Thematic Mapper band 4 image of the region of the Trombetas river and the distribution of the ADE sites. Darker blue indicates higher reflection in band 4 and red indicates the highest values in band 4 (above 80 dn value).

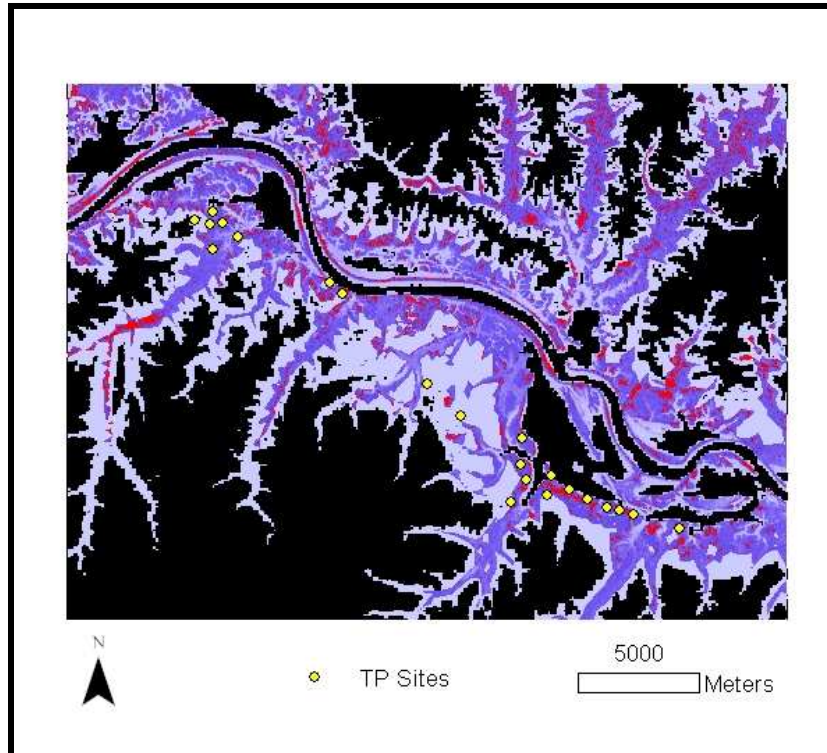
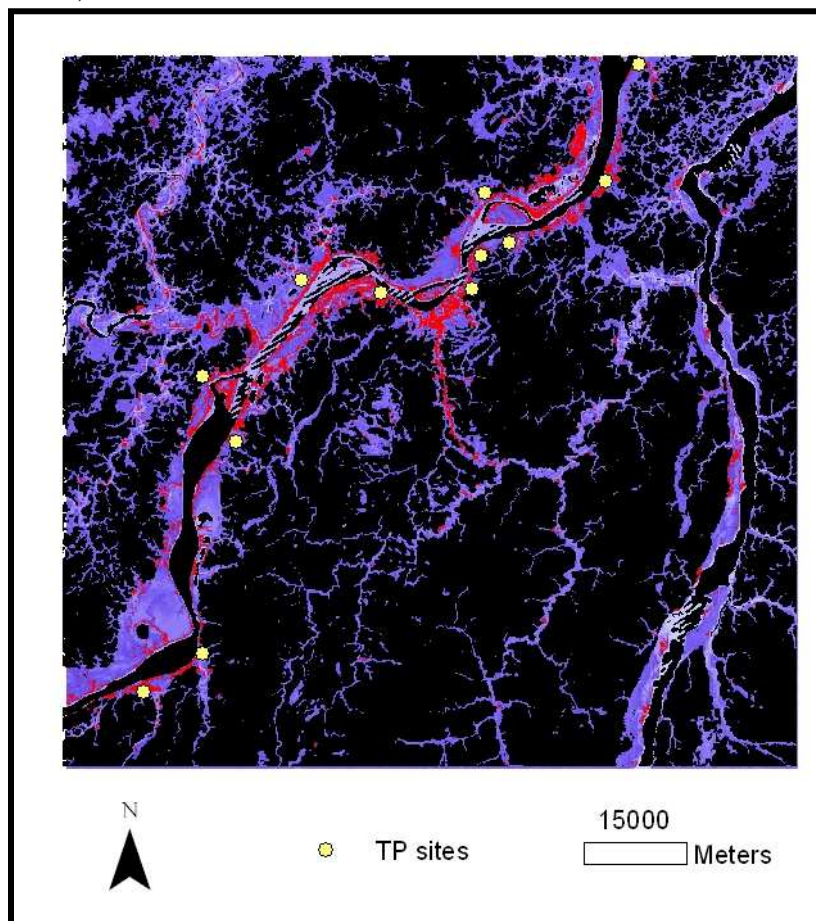


Figure 5: Masked Landsat Thematic Mapper band 4 image of the region of the Madeira river. Darker blue indicates higher reflection in band 4 and red indicates the highest values in band 4 (above 80 dn value).



Other locations have increased values of TM band 4 as well and TM band 4 will therefore not only be able to predict ADE locations.

In figure 6 and 7 the digital values of TM band 4 (0.76-0.90 μm) are shown for the locations of the digitized ADE sites compared to the whole image. The band 4 DN average values (with a maximum DN value of 133) of the pixels on the TP sites and for all pixels values are 80.52 (sd = 8.53) and 63.70 (sd = 24.14) respectively, for the Trombetas region. The band 4 DN average values of the pixels on the TP sites and all pixels are 60.17 (sd = 15.57) and 54.9 (sd = 11.67) respectively, for the Madeira region. Due to the great number of pixel values, it was impossible to introduce all values to a statistical software package, but visual interpretation shows increased values of band 4 in and around the ADE sites.

Figure 6: Average reflectance values of the ADE sites and the whole masked image of the region of the Trombetas river.

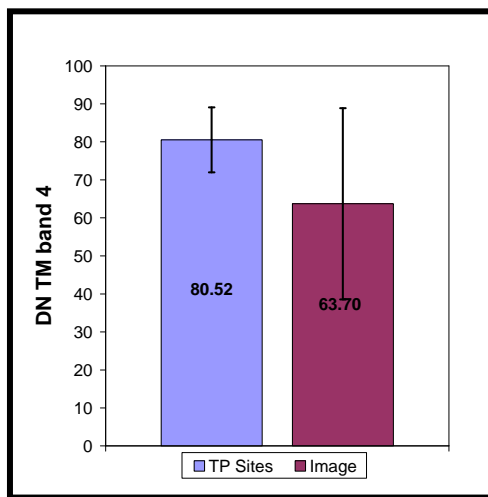
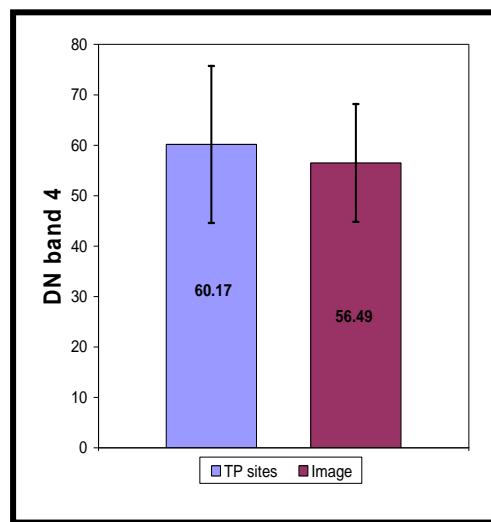


Figure 7: Average reflectance values of the ADE sites and the whole masked image of the region of the Madeira river.



5. Discussion

From the figures 4 and 5, patterns are recognisable and one can predict where ADE sites could occur. Sites generally have a long and narrow shape (Erickson, 2003) and in the manipulated maps, high values of NIR reflection along the riverbeds are visible as the expected form of the ADE sites. More accuracy about sizes, forms and borders of the ADE sites and higher spatial resolution could significantly improve the results and the localization of ADE. The location of the sites on maps from Kern et al (2003) were presented as point features and digitized manually, making estimation of the exact location very hard.

Despite the increased values in TM band 4 nearby the ADE sites, other regions had also increased values in TM band 4. More fieldwork should be conducted in order to get insight whether saturation, vegetation structure or other factors play a role in the increased reflection. Because of the restrictions of the reflective properties of flooded sites, variation between sites and human influence some sites will be missed out in this kind of analysis. Therefore remote sensing techniques should be deployed to retrieve the majority of the ADE sites but can not be used to retrieve all ADE sites.

6. Conclusion

The ADE patterns described in the literature as well as the biotic and abiotic characteristics of the sites form stepping stones for remotely locating ADE. The results show that a combination of STRM DEM and Band 4 of TM constitutes a possible tool to narrow down the possible occurrences of ADE sites. Field studies combined with more advanced sensors will have much potential to map ADE sites, and here I show that with free available images with a low spatial and spectral resolution a pattern is recognisable. Areas of interest where ADE sites will be searched in future projects could be narrowed down using probability maps derived from TM images and DEMs.

When future projects would have to make consideration which tool would be likely to yield the best results, SAR has the best opportunities to map the structural differences on the ADE sites and thus predict locations best.

Merging data of images of different sensors (such as hyperspectral, DEMs and Landsat TM images) with different spatial resolutions has also great potential to accomplish good prediction of location of ADE sites over larger areas.

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