

# **The Use of Landsat Thematic Mapper and ERS-1 SAR Data for Mapping Vegetation in the Manáus Region of Brazil**

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## **Declaration**

This is to declare that this dissertation is my own work and has not been previously submitted for any other degree in any other university.

## Acknowledgements

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## Abstract

The work described in this dissertation has looked at measures that can be taken to improve the accuracy of satellite-based land cover mapping in the humid tropics. The project region was the region of Manaus in the central Brazilian Amazon. The study has used Landsat TM and ERS-1 SAR data.

A vegetation classification system has been proposed that integrates the capabilities and limitations of mapping from current 'high resolution' satellite data (visible / infrared spectrum) into the definition of vegetation formations. The system defines vegetation formations based on local environmental characteristics and the structure of the vegetation. The floristic composition of the vegetation characterises the occurrence of a vegetation formation in a particular location. However, floristic composition does not contribute to the definition of that vegetation formation. Thus, the system provides a basis for the mapping and floristic comparison of vegetation in distant locations.

It has been shown that radiometric distortions of considerable magnitude may exist in Landsat TM data. View angle dependent radiometric distortions and level shift banding were identified as the main distortions present in the dataset used for this project. Software tools for the correction of these distortions were implemented. These tools enabled a considerable reduction of the distortions encountered. It was demonstrated that the corrections performed significantly improved the spectral separability of vegetation types in subsequent land cover classifications.

A strategy for the exact co-registration and georeferencing of spatial datasets based on modelling the spatial distribution of ground control point x- and y-residuals with respect to the datasets has been described. The strategy allows for the reliable detection of inaccurate control points and the identification of the required order of polynomial coordinate transformation function. It also allows for the quantification of registration accuracy.

A technique to model the spatial distribution of the 'reliability' of satellite-derived land cover maps based on the spectral distance information derived during the classification process has been described. The utility of the resulting 'reliability map' for highlighting incorrectly classified areas on land cover maps has been demonstrated by field verification.

A spectral separability analysis showed that Landsat TM data did not allow for the spectral separation of all vegetation types. However, the vegetation types of each of the three geo-ecological formations 'terra firme', 'whitewater floodplains', and 'blackwater floodplains' could be separated spectrally. Therefore, the boundary between these formations was visually interpreted from ERS-1 SAR and Landsat TM data. Each of the resulting image regions was subsequently classified with the corresponding subset of classes. This enabled the mapping of the project region at a high level of thematic resolution while avoiding the misclassification of pixels between spectrally similar vegetation types.

In agreement with the results reported by other researchers, the utility of ERS-1 SAR data for general vegetation mapping was found to be rather limited. However, ERS-1 SAR data appeared to be suitable for the updating of existing vegetation maps for further forest clearing. The data were also found useful for the visual interpretation of the floodplain boundary from geomorphological features.



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## **Publications**

Corves, C. and Place, C.J. (1994): Mapping the reliability of satellite-derived landcover maps - an example from the Central Brazilian Amazon Basin. International Journal of Remote Sensing, Vol. 15, No. 6, pp. 1283-1294.



Chapter 1

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# **1. The use of satellite data for the study of vegetation distribution and dynamics in the humid tropics.**

Even though increasing attention has been paid to tropical<sup>1</sup> forests in recent years, large gaps remain in our knowledge on the spatial distribution and temporal evolution of vegetation formations and environmental conditions in tropical lowland regions. This information is of high interest both to vegetation science and resource management. The designation of protected areas as well as the planning of colonisation projects in the Amazon region often had to be undertaken without accurate information on the spatial distribution of vegetation formations and other important environmental factors, such as the occurrence of seasonal flooding. Satellites provide data for the analysis and mapping of tropical vegetation at local to global scales (for an overview see Sader et al., 1990). While much work on satellite-based vegetation mapping in the humid tropics has focused on continental and global scale mapping of the forest / non-forest boundary from low resolution AVHRR data, the development and standardisation of techniques to use high spatial resolution satellite data at semi-detailed scales<sup>2</sup> for ecological studies, regional planning, and resource management in the humid tropics is lagging far behind. This lack of progress may have been caused to a large extent by the failure to bridge the gap between traditional field-based vegetation science and satellite-based mapping of Earth surface features (section 3.1.1).

The aim of the research reported in this thesis was to investigate the applications of satellite remotely sensed data for the mapping of vegetation distribution in the humid tropics and for the monitoring of changes in such distributions over time. Satellites provide the most comprehensive and up-to-date data for the study of sub-regional size<sup>3</sup> areas at semi-detailed scales<sup>4</sup>. The use of satellite data for the study of vegetation required work on both ecological aspects and technical aspects related to data processing.

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1 if 'tropical' is used without further qualification, it refers to 'humid tropical'

2'semi-detailed' refers to scales of 1:50,000 - 1:250,000

3 'Sub-regional size' refers to areas of the size of a few thousand to some tens of thousands of square kilometres, i.e. areas covered by one or a few Landsat TM or SPOT scenes.

4 Air photographs would provide a higher spatial resolution at, however, much higher cost for data acquisition and interpretation. Furthermore, in humid tropical regions, such as Amazonia, air photography is frequently out of date.

Before defining the specific objectives of the work reported in this thesis (section 1.3), section 1.1 discusses the conceptual basis of mapping vegetation from satellite data. Section 1.2 provides an analysis of some of the work published on remote sensing of humid tropical vegetation. Strengths and weaknesses of different data types and interpretation techniques are highlighted. Gaps in the current knowledge are identified. Drawing on this discussion of the 'state of the art', section 1.3 defines the objectives of the work reported in this thesis. Section 1.4 explains the reasons for basing this study primarily on Landsat TM data and section 1.5 explains why the Manaus region has been chosen for this study.

## **1.1 Mapping vegetation from satellite data.**

Information on vegetation distribution can be extracted from satellite data in several ways. The commonly used techniques can be grouped into two main categories:

- (a) Image enhancement techniques that do not involve the classification of the image into categories.
- (b) Classification of the image into land cover categories.

Classification of an image into categories can be achieved by digital classification or through visual interpretation of the data. Before exploring some of the theoretical issues underlying the concept of digitally classifying satellite images, some key differences between human image recognition and computer-based image classification need to be highlighted.

### **1.1.1 Human image recognition versus digital image classification**

The information in a (single) image can be imagined as being encoded by several mechanisms:

- \* shape
- \* spatial context of objects with reference to other objects
- \* spectral information
- \* texture of surfaces

Shape and spatial context are probably the most important features for human image

recognition. The human vision system is still able to recognise and interpret images if colour is removed (e.g. black and white photographs or television), and in many instances even if only the silhouette of an object is shown (grey levels and texture removed). In contrast, digital image classification algorithms in most of today's commercially available image processing software mostly make use of spectral information. Attempts to measure and quantify image texture have been made over the past two decades (e.g. the Haralick measures, Haralick et al., 1973; Haralick 1979), however progress in this field has been limited. Progress has been even slower for the computer-based recognition of shapes in (multi-band) grey level images and the automated interpretation of the spatial context of objects.

Today and for a number of years to come, satellite remote sensing in the visible and infrared spectrum will be based on data from sensors comparable to Landsat TM or SPOT HRV. This means that the spectral information is limited to 7 or less channels at 8 bit resolution. Of the maximum 8 bit dynamic range much less than 256 grey levels is occupied by vegetation in any scene. Green vegetation often has a dynamic range of 50 or less grey levels in TM bands 4 or 5, and significantly less in bands 1, 2, 3 and 7. For many targets (e.g. green vegetation) the information in visible and infrared bands is correlated, so that for mapping vegetation from Landsat TM data, only approximately 3 independent spectral channels exist (see section 6.2.1). The superior capacity of computers to analyse a large number of spectral channels can therefore not be expected to provide a decisive advantage over the human vision system in the interpretation of visible / infrared wavelength satellite images at present, as far as the recognition / classification of objects is concerned. Whereas currently the human image recognition system appears to be still superior to computer-based techniques as far as image classification is concerned, digital image processing techniques have been found to be very powerful for the enhancement of spectral features (e.g. principal components analysis, mixture modelling).

The following section establishes under which conditions of study area characteristics and study objectives digital classifications are likely to provide reliable land cover maps.

### **1.1.2 The conceptual basis of image classification**

Image analysts like to regard the task of classifying a satellite image into a vegetation

map similar to mathematical problems that allow only one true solution given a set of initial parameters. Reality, unfortunately, is not that simple. In order to identify the roots of error in satellite-based vegetation mapping we have to explore which conditions would need to be satisfied if image classifications were to approximate the situation of solving a mathematical problem. Any deviation from these idealised conditions would highlight potential sources of error and elements of subjectivity, which would then render the results non-reproducible, and possibly, unreliable.

The following paragraphs will examine the idealised conditions for solving the 'classification equation'.

**Condition 1:                    Distinct types of vegetation exist on the ground.**

Fundamental to the idea of categorising objects into classes is the fact that distinct objects do exist. In terms of mapping vegetation this means that the units of vegetation that exist on the ground form some natural and distinct clusters. This assumption may hold true to some extent for agricultural environments where fields are relatively homogeneous and sharp boundaries between fields of different crop types exist. It does not, however, represent the situation that is encountered when mapping natural vegetation. Formations of natural vegetation tend to display spatial patterns that are characterised by the existence of ecotones. While some environments are dominated by vegetation of relatively homogeneous types, others are characterised by transition zones occupying a large percentage of the total area. The concept of classifying vegetation into categories would be more applicable in the former case but less in the latter one.

**Condition 2:                    Spatial, spectral, and temporal properties of the satellite data do allow for the detection of the vegetation units.**

The spatial resolution of the data, in comparison to the size of vegetation units on the ground, introduces a further element to be considered. 'Distinctness' of vegetation units can only be defined in spatial, spectral, and temporal terms with reference to a specific sensor and data type. Seasonality can be an important characteristic for vegetation discrimination if multi-temporal datasets are available and the vegetation exhibits seasonal change. The use of multi-temporal high spatial resolution satellite data for mapping vegetation in the humid tropics has been very limited due to cloud

cover prohibiting the acquisition of suitable imagery, and the high cost of imagery. This situation is different for low resolution data, where multi-temporal datasets have been the basis to compensate for the relatively poor spectral resolution of the data in regional and continental scale land cover mapping projects (e.g. AVHRR).

**Condition 3: All vegetation classes on the ground are known.**

If the image analyst has an incomplete knowledge of the project region, i.e. does not know the full set of land cover types that exist, error in the classification is likely to occur. It will, however, be difficult to detect. In areas of restricted access to the field, such as large parts of the humid tropics, it is not a trivial task to ensure that all land cover types that occur in the project region are known. The problem is aggravated if the area to be mapped is large. Furthermore, the problem is circular in its nature. If not all classes are known, a sample-based accuracy assessment will not be able to detect the misassignment of pixels to classes, particularly if the field verification of sample points is replaced by the interpretation of air photographs (see section 5.2).

**Condition 4: The vegetation classification system must define vegetation classes in a way that is equally understood by different users.**

Any type of information reduction by categorisation is based on the definition of a system of classes. The definition of such a system and the unequivocal characterisation of the classes may present a problem in itself. The definition of classes in agricultural environments (e.g. 'wheat') may be trivial. However, the definition of classes of natural vegetation in a way that ensures that this definition is understood equally by different users can be a complicated task.

In the development of a vegetation classification system and the definition of the individual classes particular importance must be given to proper field verification. As Lunetta et al. (1991) state:

"Thematic data layers created using remote sensing data generally require the use of some type of classification system(s) to facilitate categorisation of the data for subsequent GIS spatial data analysis. When dealing with mixed pixels or polygons and transition zones or dynamic systems, labelling inconsistencies will occur with all classification systems. This introduces an element of error which is particularly

difficult to quantify. (...) In mixed, transition, or dynamic process situations, it is particularly important that detailed field verification data be collected to adequately describe the variation and minimise classification system related error."

**Condition 5:                   The system of ground classes accounts for all spectral information provided by the satellite sensor.**

It is known that the information provided in satellite images is often difficult to match with the human perception of the land cover of a particular project region. This can entail two problems. On the one hand, certain classes which have been established for mapping may not be detectable on a certain type of imagery. On the other hand, the satellite image may exhibit spectral classes that have not been included in the ground-based classification scheme (e.g. spectral variation within vegetation classes due to differences in soil characteristics or hydrological regime). Again, the problem is complicated if the area which is surveyed is large, complex, or inaccessible (Kalliola and Syrjänen, 1991).

### **1.1.3           Conclusions**

Several conclusions can be drawn at this stage:

- (1) Visual interpretation is likely to produce more reliable land cover maps than the digital classification of satellite data because human image recognition is much more efficient than computers / software in using non-spectral information in an image (shape, spatial context, texture).
- (2) Categorisation is commonly used in traditional thematic mapping, but categorisation is not really adequate for the representation of continua and gradients in natural vegetation.
- (3) Image classification cannot be expected to provide reliable results if ground classes are not distinct (in terms of the data and methodology used for the classification). The more an area is covered by transition zones, the less classification can be expected to provide 'objective', reproducible, and reliable results. Image enhancement techniques that do not involve the classification of the data (e.g. mixture modelling, principal components analysis) may be the preferable option.



- (4) The importance of effort in field verification and thorough definition of the classification system rises with the complexity of the environment.

The following review will demonstrate how these issues have affected satellite-based vegetation mapping in the humid tropics.

## **1.2 Review of data sources and applications: identification of key issues.**

Data from the following spaceborne sensors have been used in vegetation mapping in the humid tropics (the most commonly used sensors are shown in bold):

### Visible and infrared data

- (1) Low resolution data: **AVHRR**, GOES-VAS
- (2) High resolution<sup>5</sup> data: **Landsat TM, Landsat MSS, SPOT**, Indiasat
- (3) Very high resolution data: KFA-1000

### Radar data

- (1) High resolution data: **ERS-1 SAR**, JERS-1 SAR, ALMAZ, SIR-A/B/C

### **1.2.1 Low resolution visible and infrared data.**

Even though AVHRR and other low resolution satellite data are not suitable for mapping at semi-detailed scales, they can provide important information in multi-scale and multi-sensor mapping and monitoring programmes. A brief review is included to highlight how AVHRR data have been used for global and continental scale mapping and monitoring of tropical vegetation. AVHRR data have mainly been used in three ways for the study of tropical vegetation:

- (a) Fire detection
- (b) General land cover mapping
- (c) Mapping the forest / non-forest boundary

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<sup>5</sup>'high resolution' refers to high **spatial** resolution



#### **1.2.1.1 Fire detection**

Riggan et al. (1993) provide a recent review of the use of AVHRR data for monitoring tropical forest fires. AVHRR data provide indications of regions and times at which fires are extensive at a continental scale. The 3.55 - 3.93  $\mu\text{m}$  channel of the AVHRR is sensitive to fire radiant emissions (Matson and Holben 1987), even though small fires can be unambiguously discriminated only at night (Riggan et al. 1993). The 3.55 - 3.93  $\mu\text{m}$  channel is routinely used by the Brazilian Space Agency INPE to detect fires across Brazil. During 1991, for example, over 500,000 fires were inferred (Riggan et al. 1993).

#### **1.2.1.2 Large area land cover studies**

AVHRR data have been widely used for studying vegetation over large areas (see, for example, Achard and Blasco 1990; Hayes 1985; Justice et al. 1985; Townshend and Tucker 1984). Detailed vegetation mapping from AVHRR data requires multi-temporal datasets in order to balance the low spectral resolution with additional information on seasonal characteristics of the vegetation. Continental scale vegetation maps have been prepared for South America (Stone et al. 1994; Townshend et al. 1987). NDVI seasonality of different land cover types has been studied for Mexico (Turcotte et al. 1989), Africa (Millington et al. 1992; Townshend and Justice 1986), and Asia (Malingreau 1986) during the 1980s. A recurrent problem has been the verification of mapping results over such large areas. In the TREES project, AVHRR-derived forest maps are being validated against TM-derived vegetation maps. However, as Malingreau et al. state, "a major difficulty which must be mentioned in this respect is that correct vegetation classification is difficult on mono-temporal high resolution datasets" (Malingreau et al. 1993).

#### **1.2.1.3 Mapping the forest / non-forest boundary**

Because of the AVHRR sensor's limited capacity for vegetation discrimination, much AVHRR-related work has focused on mapping the forest / non-forest boundary (see, for example, Cross et al. 1991; Malingreau et al. 1993; Malingreau et al. 1989; Malingreau and Tucker 1990; Nelson et al. 1987; Nelson and Holben 1986; Shimabukuro et al. 1994; Tucker et al. 1984). Much of the early work in the 1980s was undertaken by NASA groups. Currently, the UK's TIGER project and the

European TREES initiative both focus on the production of continental to global scale maps of tropical forests.

Interestingly, after a 1980s 'euphoria' for AVHRR data, NASA decided to base their global tropical forest mapping project ('Pathfinder') on Landsat TM data. From the results presented at the First TREES Conference (October 1993) it was not entirely clear whether forest maps prepared from AVHRR data will be of sufficient accuracy as to allow the detection of changes in this boundary in analysis to be carried out in coming years. The TREES project has recognised this problem and regions of active deforestation detected on AVHRR data will be mapped and monitored with high spatial resolution optical and radar data (SPOT, Landsat TM, ERS-1).

AVHRR data have been applied to global and continental scale vegetation studies not because the data are ideal for this purpose, but because better data have not been available. In their review of the utilisation of AVHRR data for global land cover mapping Townshend et al. (1991) conclude that although some encouraging results have been obtained, 'operational provision of global land cover information will require better datasets in terms of spectral, radiometric, temporal, and spatial properties'. Such data will be provided by new satellite sensors in the near future. These include the ATSR-II sensor on board ERS-2, the vegetation instrument on the coming generation of SPOT satellites, and the MODIS-N (Moderate Resolution Imaging Spectrometer) sensor of the EOS (Earth Observing System) (Townshend et al. 1991).

Vegetation maps produced from low resolution satellite data are of only limited use to regional planning and resource management because of the insufficient spatial resolution of the data (1 km for AVHRR). Of some interest for monitoring large areas with low population densities and little infrastructure could be the fire detection capability of AVHRR data. However, mapping and monitoring tropical vegetation at semi-detailed scales require satellite data from high spatial resolution sensors.

### **1.2.2 High spatial resolution visible and infrared data (Landsat MSS, TM, SPOT XS)**

High spatial resolution satellite data for Earth observation became widely available with the Landsat MSS satellite in 1972. Spatial, geometrical, and radiometric

resolution were significantly enhanced with the launch of Landsat-4 and its TM sensor in 1984. A further increase in geometric resolution (even though at lower spectral resolution than the TM sensor) was provided by the SPOT satellite launched in 1989.

Improvements in spectral and spatial resolution increase the volume of data to be stored and processed. This is reflected in a widespread tendency to use relatively small datasets. Studies based on TM data published to date have often used small areas: Garcia and Alvarez (1994) used a test area of 900 km<sup>2</sup>; King used several test areas of 512 by 512 pixels (King 1994); Paradella et al. (1994) used a test area of 230 km<sup>2</sup>; Saxena et al. (1992) used a 1024 by 860 pixels test area. Any of these extracts represents less than 5 percent of a full TM scene. Image classification over entire scenes may encounter problems that have not been detected in such small scale studies.

A common feature of many publications that report studies on the use of Landsat TM data in digital vegetation mapping is the lack of information given on (a) the correction level of the acquired data, (b) an assessment of residual radiometric distortions in the data, and (c) steps that have been taken to reduce such residual radiometric distortions should they have been discovered (see, for example, Garcia and Alvarez 1994; King 1994; Lozano-Garcia and Hoffer 1993; Paradella et al. 1994). It is possible that the importance of data quality for digital image classifications has not been fully appreciated in some occasions.

Through their pointable and programmable optics, the SPOT satellites have a significant advantage over the TM sensor for operational mapping: the repeat cycle can be decreased from a nominal 26 days to a few days only. As Rosenholm (1993) points out, this can be a decisive advantage, particularly in the humid tropics with their high frequency of cloud coverage.

An advantage of SPOT HRV and SPOT panchromatic data over TM data is the increased geometric resolution which gives a better representation of ground texture. This can be an important criterion for the differentiation of land cover types in visual interpretations. Rosenholm (1993) reported that texture has been extremely valuable for separating different forest classes and distinguishing open forest from bush or scrub in several large scale mapping projects in the humid tropics. However, from a

comparison of TM and SPOT data for mapping land systems in Belize, King (1994) concluded that the higher spectral resolution of TM data was more important for the demarcation of land systems than the higher spatial resolution of SPOT data. Although recognising the superior geometric resolution of TM data, in their study of western Amazon vegetation Tuomisto et al. (1994) reported that all major vegetation patterns that were visible on TM data could spectrally be identified on MSS data. They stressed the advantage of MSS data in terms of much lower cost and lower data volume per unit area, as compared with TM data.

An advantage of the SPOT system is its capability to provide stereopairs for stereoscopic interpretation. The acquisition of suitable images can, however, be a problem in areas of frequent cloud cover. King (1994) concluded that stereoscopic resolution was more important for demarcating land use systems in Belize than spectral range or high spatial resolution.

Landsat MSS data have been successfully used for digitally mapping the forest / non-forest boundary in many instances (see, for example, Nelson et al. 1987; Sader 1987). While this proved possible with high accuracy, digital classification of MSS data has repeatedly been found unable to discriminate the required vegetation classes in general land cover mapping (see, for example, Bayley and Moreira 1978; Ringrose et al. 1988; Singh 1987). In particular, the spectral separation of forest types has proved impossible in digital classifications of MSS data (Bayley and Moreira 1978; Sader et al. 1990).

Although TM data provide higher spatial and spectral resolution than MSS data, the digital classification of vegetation formations, in particular the differentiation of forest types, has sometimes been found unsatisfactory. In a study of migratory bird habitats in Costa Rica, Sader et al. (1990) were not able to distinguish old secondary forest from disturbed primary forest, nor early successional stages from secondary growth forest and regions of mixed crops.

Many studies (see, for example, King 1994; Rasch 1994; Ringrose et al. 1988; Rosenholm 1993; Tuomisto et al. 1994) agree that for vegetation and land use mapping the visual interpretation of high resolution visible / infrared data provides much more reliable results than digital classification. Rosenholm (1993) summarises the experience of the Swedish Space Corporation from several large tropical

vegetation mapping projects:

"Our experience in the use of digital classification for complicated thematic mapping is consistently negative compared with manual methods".

Tuomisto et al. (1994) compared visual interpretation of MSS data with digital classification for mapping extensive areas of floodplain vegetation in the Western Amazon. They concluded that (a) digital classifications were not able to differentiate even major forest classes and the "results were practically useless"; (b) forest could usually be distinguished from non-forest in digital classification; (c) when attempting to distinguish vegetation types within the primary rain forest, the proportion of misclassified pixels became unacceptable; (d) the pixel-by-pixel classification procedures may be suitable for such homogeneous surfaces as water and wheat fields, but they are not adequate for tropical rain forest.

These results confirm the severe limitations of currently used pixel-by-pixel classification algorithms. As Rosenholm (1993) states:

"Most digital classification methods are extremely primitive mathematically and undeveloped algorithmically".

Great progress in the development of satellite sensors made during the past three decades has not been matched by comparable progress in digital techniques to extract information from the increasing avalanche of available imagery.

### **1.2.3 High resolution radar data**

Airborne radar data have been increasingly used for mapping tropical regions since the 1970s. It is the capability of radar to obtain images of areas under cloud cover that make it so attractive for tropical forest monitoring.

The capacity of radar to detect vegetation formations depends on system parameters (e.g. wavelength, polarisation, incidence angle) as well as target characteristics (surface roughness; water content and dielectricity constant; vegetation structure) (Hoekman 1990). Radar radiation backscattered from a target contains several types of exploitable information: amplitude, phase, and polarisation. The processing level of radar data determines which of these types of information can be extracted (for

example, ERS-1 PRI data provide only amplitude information, while ERS-1 SLC data enable also the extraction of phase information). The exact mechanisms of interaction between radar radiation and vegetation targets are still not fully understood. However, some general conclusions can be drawn that facilitate the interpretation of amplitude images as undertaken in this study:

- (1) The longer the wavelength, the deeper is the penetration of the radiation into the vegetation canopy. While X-band radar is largely reflected at the canopy surface, backscatter in C-band results from volume scattering in the top 50-200 centimetres of the forest canopy. L-band, and even more P-band, radar penetrates still deeper into the vegetation and the backscatter may have important components from the soil surface (or water surface in case of flooded forests) and undergrowth (Hoekman 1990; Pope et al. 1994).
- (2) If the water content of a target (vegetation, soil) rises, the amplitude of backscatter is increased. As a result, the amplitude of backscatter from grassland tends to be higher in the rainy season than in the dry season<sup>6</sup>.

The airborne radar surveys of the 1970s, such as the Projeto Radambrasil, used mostly X-band radar (see, for example, Furley 1986). They demonstrated the usefulness of radar for reconnaissance level baseline studies of natural resources. While airborne radar systems and experimental space-borne systems flown on the Space Shuttle have reached a high level of sophistication (multi-band, multi-polarisation, high geometric resolution), currently operational satellites provide radar data with much more restricted characteristics. The ERS-1 radar, for example, is limited to one wavelength (C-band) and one polarisation (VV). Satellite-borne radar data for much of the humid tropics are currently available only from the ERS-1 satellite. L-band radar data have been acquired during several Shuttle Imaging Radar missions and the few months of the Seasat satellite operation, while the JERS-1 satellite's SAR instrument has, unfortunately, been plagued by problems since its launch.

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<sup>6</sup> For details refer to the results reported for ongoing experiments in: Proceedings of the Second ERS-1 Symposium. Space at the Service of our Environment. 11-14 October 1993, Hamburg, Germany. European Space Agency, Paris, France, ESA SP-361, 1994. Volume 1: section on agriculture (pp. 49-110), Volume 2: section on soil moisture (pp. 837-894).



Some studies have compared the suitability of different frequencies and polarizations of radar for forestry applications. From their study of airborne SAR remote sensing of Corsican Pine stands in the Thetford Forest (UK), Baker et al. (1994) concluded that (a) P-band HV-polarization would be the most useful SAR combination for estimating stand volume and biomass, and (b) the L-band / HH-polarization combination of the JERS-1 SAR would most likely be much more useful for such applications than the C-band / VV-polarisation combination of ERS-1. The shorter radar wavelengths (X-band, C-band) reflect strongly the morphology of the forest canopy (Hoekman 1990). Canopies of different morphology (e.g. primary forest with large gaps and emergents versus secondary forest with a 'smooth' canopy) can be distinguished if the spatial resolution of the radar is sufficiently high, as is the case for airborne radar systems (Wooding and Attema 1993; Wooding and Attema 1994).

Pope et al. (1994) analysed the use of fully polarimetric P-band (68 cm wavelength), L-band (24 cm wavelength), and C-band (5.7 cm wavelength) AIRSAR imagery for the study of forest, wetland, and agricultural ecosystems in Northern Belize. Four biophysical indices were calculated for each band. Pope et al. concluded that (a) all four indices and three bands were needed to characterise the landscape; (b) this finding did not appear to vary with spatial scale; (c) when only level surfaces were considered, variability in biomass was secondary to upper canopy spatial variability, such as canopy closure and homogeneity. The experiments showed that multi-polarisation and multi-wavelength airborne radar can provide a wealth of information on the physiognomy of vegetation formations (e.g. relative importance of vertical versus horizontal woody elements; green biomass versus woody biomass; canopy closure, and others). The large wavelengths (i.e. P-band and L-band) also provided information on the environmental conditions of a site, e.g. sub-canopy flooding. With respect to the C-band / VV-polarisation of ERS-1, Pope et al. concluded that this combination proved to be one of the least suitable for the study of vegetation. Information from this combination described primarily topography and the presence or absence of vegetation. They concluded that the best application of ERS-1 configuration radar in the tropics might be in studies of geomorphology and deforestation. They added that the potential to use multi-date imagery might prove to be the most advantageous aspect of current spaceborne radar systems (Pope et al. 1994).

Even though the ERS-1 SAR parameters of C-band / VV-polarisation, and a spatial

resolution around 30 metres are not the most suitable ones for vegetation and, in particular, forest type mapping, ERS-1 SAR presents the only source of radar data currently available for most of the humid tropics and will remain so for the next few years. The ERS-2 satellite, to be launched in 1995, will have the same configuration, while the Canadian Radarsat will have C-band with HH-polarization.

The SAREX-92 campaign has compared airborne X-band (3 cm wavelength) and C-band (5 cm wavelength) data with spaceborne C-band ERS-1 data. Only minor differences were found between X-band and C-band and airborne C-band data of VV or HH polarisation. The results suggest that the C-HH configuration of the future Radarsat satellite will show a sensitivity to land surface features that is very similar to the C-VV configuration of the ERS-1 SAR (Wooding et al. 1993). The results of the SAREX-92 campaign, with respect to ERS-1 SAR data (Ahern et al. 1993; Wooding and Attema 1994; Wooding and Attema, 1993), have highlighted the following aspects:

- \* Because C-band radar does not penetrate deeply into woody vegetation, different types of woody vegetation can rarely be differentiated by tone. Woody vegetation appears generally with high backscatter values on ERS-1 SAR imagery. Backscatter components from the forest floor (soil or water, if flooded) are negligible. The amplitude of backscatter from areas of grassland is low, with the lowest values occurring during the dry season. During the rainy season, soil moisture is increased and backscatter from grassland is generally higher than in the dry season.
- \* There is little difference in tone between primary forest, incompletely cleared areas, and areas of early natural regeneration. Only those clearings that are actively used for pasture or crops are detected. This leads to a systematic underestimation of cleared areas.
- \* The spatial resolution of ERS-1 data is not sufficient to detect the characteristic differences in texture between primary rainforest, secondary forests, and pasture, that is visible on airborne radar imagery.
- \* ERS-1 SAR is a useful dataset to map geology and landforms by visual interpretation. The steep incidence angle of the ERS-1 SAR enhances subtle



differences in topography.

- \* Topography causes pronounced distortions in radar backscatter which render digital classifications of land cover difficult or impossible. The correction of these distortions based on digital terrain models and the use of imagery from ascending and descending orbits has made significant progress in recent years. However, digital terrain models at sufficient resolution are not available for most of the humid tropics.

While it has been recognised that the information content of mono-temporal ERS-1 SAR data for forest mapping is relatively low, the ERS-1 system offers the potential of multi-temporal, largely weather-independent image acquisition. Leysen et al. (1993) demonstrated the potential of exploiting multi-temporal ERS-1 SAR coverage for the differentiation of land cover types in Western Africa. These and other studies highlighted the importance of selecting the most suitable dates for image acquisition for maximising the potential to discriminate land cover types.

Several authors report studies on forest mapping using combined Shuttle Imaging Radar data (SIR-B) and either Landsat TM or SPOT data (Lozano-Garcia and Hoffer 1993; Nezry et al. 1993). Leckie (1990) reported on a similar experiment using airborne radar and visible / infrared data. All authors agree on the synergistic effect of using combined optical and visible / infrared data. The accuracy of digital classifications was consistently higher for combined optical and radar data than for optical data alone in all three studies .

A number of recent studies on forest test sites in Europe has found that the phase information in ERS-1 raw data contains information for the discrimination of forest from other land cover types. Coherence between multi-temporal datasets is lower for forest canopies than for grassland. The phase information has also successfully been used to estimate tree height of forest stands to less than a metre accuracy (see Proceedings of the MAESTRO 1 Airborne Polarimetric SAR Campaign published in the International Journal of Remote Sensing Vol. 15, No. 14, 1994).

#### **1.2.4 Conclusions**

Two main conclusions can be drawn with respect to the suitability of different data

types for mapping tropical vegetation:

- (1) ERS-1 SAR data are unlikely to provide much information for mapping vegetation at more detail than the woody vegetation / grassland differentiation.
- (2) Landsat TM and SPOT HRV provide data that are suitable for mapping vegetation and land use at semi-detailed scales.

### **1.3 Thesis objectives and organisation**

The use of high resolution satellite data for the study of vegetation is a rapidly evolving area of research. Certain issues are equally encountered in applications in the humid tropics and in other climatic regions. This refers, for example, to the urgent need to develop classification algorithms that utilise non-spectral information in the images. Other aspects are more specifically related to work in the humid tropics.

This study has focused on issues that are related to improving the accuracy and reliability of satellite-derived land cover maps in the humid tropics. The application of satellite remote sensing to the study of vegetation distribution necessitated that both ecological issues and problems of a more technical nature related to processing the satellite data were dealt with. However, ecological issues have not been dealt with per se but only with reference to extracting meaningful information from the satellite data.

#### **A. Ecological objectives**

- (1) To define a system of categorising vegetation for satellite-based land cover mapping

Traditional botanical systems of categorising vegetation do not take into account the characteristics of spatial data and information extraction techniques used in land cover mapping. The use of such systems in satellite-based vegetation mapping leads to a mismatch between vegetation classes and mapping capabilities. This is a potential source of low map reliability.

A system for categorising the vegetation of the Manáus region has been designed that strikes a compromise between the definition of classes by botanists and ecologists, and the capabilities of mapping vegetation from current high resolution satellite data. The vegetation types of the Manáus region have been described based on this system (chapter 3).

- (2) To investigate the separability of vegetation formations in Landsat TM spectral space

The spectral separability of the vegetation formations of the Manáus region in Landsat TM spectral space has been investigated (section 6.2).

- (3) To map the vegetation of the Manáus region using digital satellite imagery

The vegetation of the Manáus region has been mapped based on a hybrid approach that combines the visual interpretation of geology and landforms from ERS-1 SAR data with the digital classification of Landsat TM spectral classes (section 6.3). This part of the thesis provides a synthesis of the methodology developed in the data processing oriented chapters (chapters 4 and 5). However, rather than suggesting that a definitive solution to the problem of mapping the vegetation of the Manaus region has been achieved, chapter 6 attempts to highlight shortcomings in three main areas: (a) current image processing technology for land cover mapping, (b) verification of map accuracy over relatively large areas, and (c) the limits imposed by ecotones on the accuracy of categorical maps in natural environments.

- (4) To investigate the potential of ERS-1 SAR data for mapping and monitoring vegetation in the Manáus region

The literature review presented in section 1.2.3 suggested that C-band radar data (of the characteristics of the ERS-1 satellite) do not have a high potential for discriminating woody vegetation types. However, the capacity of radar to penetrate clouds makes ERS-1 SAR data a product of interest for the study of humid tropical regions where visible / infrared data are not available due to almost permanent cloud cover. To date, relatively few studies have been undertaken in which the potential of using multi-temporal ERS-1 SAR data for

mapping and monitoring humid tropical regions has been investigated.

This project provided a suitable framework for the assessment of the utility of ERS-1 SAR imagery. The potential of multi-temporal ERS-1 SAR data to discriminate the vegetation types encountered both on terra firme<sup>7</sup> and on the floodplains of the Manáus region has been evaluated. The availability of multi-temporal ERS-1 SAR data also allowed an assessment of the utility of these data for updating existing vegetation maps for monitoring ongoing deforestation (section 6.1).

#### B. Image data pre-processing objectives

The data processing oriented work aimed at providing a methodology that would contribute to the production of maps with the highest possible thematic and geodetic accuracy. To a large extent this meant the identification and reduction of possible sources of error. The following issues have been dealt with:

- (5) To investigate the effects of and correct for residual radiometric distortions

Residual radiometric distortions exist to varying degrees in digital satellite data. Such distortions can severely degrade the spectral separability of land cover types. The review of the literature suggests that the importance of this factor for the thematic accuracy that can be achieved in digital classifications may not have been fully recognised in past studies.

The Landsat TM data used for this study have been assessed in detail with respect to the existence of residual radiometric distortions. Software has been implemented to quantify and correct the most severe distortions (chapter 4). The impact of the corrections on the spectral separability of vegetation types has been assessed (section 6.2.3).

- (6) To improve techniques for the co-registration and georeferencing of spatial datasets from remote regions

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<sup>7</sup>'terra firme' is an expression locally used in the Manáus region for those areas that do not undergo seasonal inundation

Satellite-based vegetation mapping increasingly has to integrate spatial datasets from a variety of satellite sensors and other sources. The accurate co-registration and georeferencing of these datasets present specific problems in rainforest regions because of the lack of location-invariant features and often poor map quality.

A simple and systematic approach has been identified to (a) identify inaccurate ground control points, and (b) select the appropriate order of polynomial function for coordinate transformation (section 5.1).

- (7) To map and investigate unreliably classified regions in satellite-derived land cover maps

Traditional sample-based methods of assessing the accuracy of land cover maps have a series of shortcomings. Most importantly, they fail to identify where unreliably classified regions are located. A technique has been identified to map unreliable regions in satellite-derived land cover maps. The utility of the 'reliability maps' has been evaluated in the field (section 5.2).

## **1.4 Choice of data**

This study has focused on the use of Landsat TM data. Several arguments spoke in favour of TM data instead of SPOT HRV data:

- (1) The mid infrared bands of the TM sensor make the data more independent of atmospheric haze than SPOT HRV. In addition, earlier work based on principal components analysis (Corves, unpublished results) had shown that band 5 of the TM sensor contained useful information for forest type discrimination. The SPOT XS sensor has no comparable wavelength band.
- (2) TM data have been acquired by the Brazilian receiving station on a regular basis since 1984. Landsat data are the standard data product used by many Brazilian organisations, while SPOT data are rarely encountered.
- (3) TM data are significantly cheaper per unit area than SPOT HRV, particularly if bought in Brazil.

ERS-1 SAR data have been included because they represent the only radar data available for most of the humid tropics. The data used in this study are described in more detail in section 4.1.1.

## **1.5 Choice of the project region**

Considering the resources available for this project, it was essential to select a project region where a certain infrastructure existed for field verification, and where results from studies carried out by other researchers could be integrated into the analysis. These considerations lead to the selection of the Manáus region as the study area (Figure 1.1). Compared with other parts of the Amazon, the region has a reasonable road infrastructure. Public transport allowed for many places in the vicinity of Manáus to be reached at low cost. Manáus has an airport where small planes can be hired for the acquisition of oblique air photography. The variety of vegetation and land use types in the immediate vicinity of Manáus is high due to the presence of both large floodplains and terra firme regions belonging to different geological formations. The National Amazon Research Institute of Brazil (INPA), as well as a variety of other federal and state research institutions are located in Manáus. A much larger number of studies on environment and vegetation is available for the Manáus region than for many other parts of the Amazon. All these factors provided good reason for the choice of the Manáus region.

Figure 1.2 shows a false colour composite<sup>8</sup> of the 8 August 1991 Landsat TM image of the Manáus region (full scene of 185\*185 square kilometres). Figure 1.3 shows the project region of this study in more detail. It comprises an area of approximately 4000 square kilometres on the confluence of the Rio Negro and the Rio Solimões. The geographical coordinates of the project region are given in Table 1.1.

The following chapter will provide an analysis of the environmental framework of the project region. This information will be used in chapter 3 for the definition of vegetation formations.

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<sup>8</sup> all false colour composites of TM data shown in this thesis use the following assignment of bands to colour guns: red - band 4; green - band 5; blue - band 3



# Chapter 2

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## **2. The environmental framework: geology, geomorphology, climate, hydrology, and soils**

Chapter 2 provides an introduction to environmental factors, such as geology, geomorphology, soils, climatic, and hydrological conditions, that are determinants of the spatial pattern of vegetation in the study area. Drawing on this analysis, a classification system for satellite-based mapping of vegetation in the Manáus region will be suggested in chapter 3. This classification system is based on vegetation structure and on the environmental conditions under which vegetation formations occur.

### **2.1. Geology and Geomorphology of the Amazon Basin**

Knowledge of the geological evolution of the Amazon basin is still incomplete and different authors disagree even on major elements of its geological history. The following brief discussion attempts to identify only those aspects that appear central to the understanding of the spatial patterns of vegetation. Drawing heavily on the work of Putzer (1984), Bigarella and Ferreira (1985), Fittkau (1974), and Irion (1989), a brief overview of the geology and geomorphology of the Amazon basin as a whole and the Manáus region in particular will be provided as a framework for the discussion of soils and vegetation patterns in the Manáus region.

According to Irion (1989), the catchment of the Amazon river may be divided into three main geological formations: (1) the Andean arc which emerged through collision of the Nazca and South American plates since the Miocene; (2) the old Precambrian shields north (Guyana Shield) and south (Central Brazilian Shield) of the Amazon basin; (3) the Amazon basin proper ('Amazon lowlands'). Large parts of the Amazon lowlands are characterised by Tertiary sedimentary deposits reaching thicknesses of more than 1000 metres. In the western Amazon basin the sediments have been deposited predominantly by fluvial processes and are derived from erosion in the Andes since the Miocene (Salo and Räsänen 1989). In the central and lower Amazon basin the sediments have accumulated since the Palaeozoic mostly from the erosion of quartz-rich parent materials of the Precambrian rocks of the Guyana and Central Brazilian shields (Irion 1989; Putzer 1984).

Large parts of the upper and middle Amazon basin do not exceed elevations of more



than 100 metres above recent mean sea level. West of Santarem, the 100 metre contour line encloses an area of 1.3 million square kilometres. Even as far east as Iquitos, 3600 km from the Atlantic Ocean, the level of the Amazon river is only about 80 metres above present mean sea level (Irion 1989).

The Quaternary history of the Andean lowlands is characterised by the influence of glaciations on global sea levels. During glacial advances, the sea level was lowered, while in interglacial epochs, the sea level rose again. During the glacial periods of the Pleistocene, the sea level dropped more than 100 metres below the present mean sea level (Irion 1989). During those periods the river beds of the large rivers together with the sediments deposited earlier during interglacials, were subject to strong fluvial erosion. The sea levels during interglacial epochs are the subject of controversy, but it is assumed that maxima of at least some tens of metres above recent mean sea level occurred (Irion 1989). During high sea levels the ocean dammed up the waters of the Amazon drainage system, thereby causing the formation of large fresh water lakes that trapped the fluvial sediments of mostly Andean origin. After sufficient sediments were deposited, new water ways developed with their characteristic pattern of ridges, swales and levees. Such former floodplains are easily discernible on the radar images of the Projeto Radam survey (MME/DNPM 1978). It is, however, assumed that by far the largest part of the five million square kilometres of Amazon lowlands have not been affected by the Pleistocene fresh water lakes. This unaffected area has been named the 'Quaternary Terra Firme' (Irion 1989).

## **2.2. Geology and Geomorphology of the Manaus Region**

The preceding section has shown that the central Amazon basin and the Manaus region are characterised by Tertiary and Quaternary sedimentary deposits. Klammer (1984) assumes that a maximum sea level of about 180 m above recent mean sea level was reached in the late Pliocene (2-2.5 million years B.P.). Since then, the sea level has fallen, undergoing a series of fluctuations related to the Quaternary glacial and interglacial periods. Due to the above mentioned damming of the Amazon by high sea levels, large parts of the central Amazon lowlands are assumed to have undergone successive periods of ponding and sedimentation at high sea levels, and erosion at low sea levels. With maximum sea levels prevailing in the late Pliocene, progressively older sedimentary plains occur at higher elevations (Klammer 1984). The terra firme land above recent flood levels therefore consists of a stepped series

of depositional plains, the altitude of these plains corresponding to high sea levels of interglacial epochs. This hypothesis is supported by both geomorphologic evidence and analysis of minerals indicating a higher degree of weathering and a greater age for depositional surfaces at higher elevations (Fittkau 1974; Klammer 1984). The degree of dissection reflects the age of the terra firme deposits (Klammer 1984) and has been used for mapping the extent of sedimentary formations from radar imagery in the Projeto Radam (MME/DNPM 1978).

Three main sedimentary formations are distinguished in the Manáus region: (1) the Barreiras Formation, (2) the Solimões Formation, and (3) Quaternary alluvial deposits (MME/DNPM 1978):

Formation	Period	Age (million years)
Alluvial Deposits	Holocene	1 - today
Solimões Formation	Pleistocene	1
	Pliocene	13
Barreiras Formation	Miocene	25
	Upper Cretaceous	70
Trombetas Formation	Palaeozoic	70 - 470

(adapted from MME/DNPM 1978)

Figure 2.1 shows the distribution of these formations in the Manáus region according to the interpretation of radar imagery in the Projeto Radam survey (MME/DNPM 1978). The main properties of these formations will be briefly outlined in order to facilitate understanding of the soil properties described later.

### **2.2.1. Tertiary Deposits**

#### **(a) Barreiras Formation**

No complete agreement exists amongst geologists on the age of the Barreiras Formation. This is largely due to the lack of dateable fossil records in these sedimentary deposits. While Putzer (1984) dates the Barreiras Formation to the Cretaceous, other authors date it to the early Tertiary (MME/DNPM 1978).

According to Chauvel et al. (1987), the Barreiras sediments are characterised by the products of long in situ weathering, the main constituents being quartz and kaolinites. The sediments are very poor in nutrients (i.e. phosphorus, calcium, potassium) (Chauvel et al. 1987).

#### **(b) Solimões Formation**

The whole late Tertiary sequence of sands and clays in the middle Amazon basin has been named 'Solimões' Formation. While Putzer (1984) considers the Solimões Formation to represent Eocene, Oligocene, and Miocene deposits, a more recent origin (middle Pliocene to Pleistocene) is assumed by MME/DNPM (1978).

The Tertiary deposits of the Barreiras Formation and the Solimões Formation form today's 'terra firme' areas. These areas do not undergo regular seasonal flooding. Terra firme soils have been deeply weathered and the nutrients have been strongly leached (MME/DNPM 1978). Although local variations exist, most terra firme areas are characterised by oligotrophic soils of low pH.

### **2.2.2. Quaternary Deposits**

The evolution of the modern Amazon drainage system is assumed to have taken place in the late Tertiary or early Pleistocene (Irion 1989). As pointed out above, the genesis of the contemporary floodplains in the Manáus region was strongly influenced by eustatic sea level changes during the Quaternary (Junk 1984). It is assumed that the sea level fell to 130 m below today's level during the last maximum glacial advance, about 18,000 years ago. During this period, the large Amazonian rivers cut deep and very broad valleys into the Tertiary sediments of Central

Amazonia. When the water rose, the valleys started to be filled up again by sediments deposited mainly along the whitewater rivers (carrying a high suspended load). Blackwater rivers, having low sediment loads, have yet to fill their valleys. Their lower courses are very broad and sometimes deep, forming the so-called 'Ria-Lakes'. The floodplains along blackwater rivers (frequently called 'igapo') cover much smaller areas than those along whitewater rivers (frequently called 'várzea'). Sediment transport in whitewater rivers is of considerable importance, allowing deposition of sediment layers of > 1 metre depth per year. Dynamic islands of several square kilometres may appear and disappear within a few decades (Junk 1984).

This brief review of the geological evolution of the Amazon region, and the Manáus region in particular, yields some important conclusions:

- \* The Manáus region serves as an example of geological conditions that are encountered over large areas of the Central Amazon lowlands.
- \* The main geological formations in the Manáus region are Tertiary sediments forming today's terra firme regions, and secondly, the Quaternary and recent deposits forming today's floodplains.

The following paragraphs will focus on climatic and hydrologic factors that both directly and indirectly influence the spatial distribution of vegetation types through their impact on soil evolution.

### **2.3. Climate and hydrology**

The Amazon basin is characterised by a hot and humid climate. Daily fluctuations in temperature are greater than seasonal variations. Precipitation varies between 2000 mm per year in the northern and southern parts of the basin and 4000 mm per year on the slopes of the Andes (Figure 2.2). However, average precipitation in large parts of the basin is between 2000 mm and 3000 mm per year (Junk and Furch 1985). The distribution of rainfall over the year is not constant, exhibiting a more or less pronounced division into a dry season and a rainy season (Figure 2.3) (Salati 1985; Salati and Marques 1984). In Manáus, the rainy season lasts from November to May (Figure 2.4).

Differences in precipitation rates between the wet and dry seasons affect the water levels of the rivers. Whereas small rivers respond to local rainfall, the water levels of large rivers integrate rainfall in the entire catchment and may not correspond to local rainfall patterns. All large rivers undergo pronounced seasonal fluctuations in water level. The flood pattern normally shows one maximum and one minimum per year. The Amazon river at Manaus reaches its maximum in May/June. The annual difference between highest and lowest water levels at Manaus can reach up to 15 m; normally it is 8-10 m (Figure 2.4). Maximum and minimum flood levels of the large rivers vary strongly between years (Figure 2.5). This leads to large differences in the areal extent of inundation, particularly in the floodplains of whitewater rivers, between consecutive years.

According to the colour of their waters, Sioli (1965) classified Amazonian rivers into three groups: whitewater, blackwater and clearwater rivers (only whitewater and blackwater rivers occur in the Manaus region). Whitewater rivers are characterised by sediment-rich, 'muddy' water. They frequently have their origin in the Andes or in the pre-Andean region where intensive erosion occurs. A typical representative of whitewater rivers is the Rio Solimões. Sediments transported by whitewater rivers have their origin in geologically 'young' formations. The alluvial deposits tend to be comparatively nutrient-rich and, consequently, the soils of whitewater floodplains are fertile with intermediate pH levels. The dark colour of blackwater rivers is caused by dissolved organic substances such as fulvic and humic acids. Blackwater rivers are low in sediments. They frequently originate in areas of sandy podzols or with swampy conditions. Such areas are commonly encountered in Central Amazonia and in the northern periphery of the Amazon basin (Junk and Furch 1985). A typical representative of blackwater rivers is the Rio Negro. Blackwater floodplains are characterised by nutrient-poor soils of low pH.

The annual change of several months of inundation with dry periods ('monomodal floodpulse') is a major determinant of plant, animal, and human life in the floodplains. The occurrence of this flood pattern over many thousands if not millions of years has enabled the evolution of a variety of plants and animals that are unique to the floodplains. The marked differences in water chemistry between whitewater and blackwater rivers have lead to further specific adaptations as will be described in chapter 3.

Beyond the direct influence on evolution and adaptation of lifeforms, climatic and hydrologic factors have determined the evolution of the major soil types from different geological parent materials.

## **2.4. Soils of the Amazon region**

The current state of knowledge on the spatial distribution of soils in the Brazilian Amazon depends to a large extent on the Projeto Radam reconnaissance surveys executed in the late 1970s and early 1980s. A tentative soil map of the Brazilian Amazon is shown in Figure 2.6. The present state of knowledge suggests that the largest part of the Amazon lowlands is occupied by nutrient-poor, acid Oxisols and Ultisols. While these soils occur in terra firme areas, Entisols are found in periodically inundated floodplains. Figure 2.6 indicates that the soil types encountered in the vicinity of Manaus are typical of the much wider central Amazon lowland region.

## **2.5. Soils of the Manaus Region**

The soils of terra firme and floodplain areas are very different and will therefore be treated separately.

### **2.5.1. Soils of the Terra Firme Regions**

We have seen that in the Tertiary, sediments were eroded from the Precambrian shields and deposited in the central Amazon basin, forming the so-called 'Amazon Planalto'. The surface of the Planalto consists of a layer of kaolinitic clays of 10-20 m thickness. Kaolinite is one of the most highly weathered secondary minerals and lacks both nutrients and the capacity to retain the nutrients necessary for plant growth (Jordan 1985). The generally low fertility of terra firme soils is due to the effects of weathering and leaching (high temperatures, heavy rains) over millions of years. Most soils have a low cation exchange capacity and low retention of base plant nutrients (such as Ca, K, Mg). Furthermore, much of the exchange capacity is taken up by Al and H, leading to generally infertile soils. These soils are typical of the Oxisol soil order (Soil Taxonomy 1975). The ecosystems have developed a variety of adaptations to the inability of the soils to retain and supply nutrients, such as concentration of roots near the surface of the soil, reduced leaf fall, mycorrhizae and



many other mechanisms leading to a nearly closed cycling of mineral nutrients.

Even though the Amazon basin is frequently thought of as a homogeneous 'tropical rainforest', slight differences in soil quality (nutrients, soil hydrological regime, etc.) are reflected in pronounced variations of the floristic composition of the vegetation. In the following paragraphs, the major soil types of terra firme areas in the Manáus region will be examined briefly based on information given in the Projeto Radam survey. Only major features will be reported here, while further details on individual soil profiles are available in the original literature (MME/DNPM 1978). The descriptions are based on the Brazilian soil classification system, but the equivalent names of the American Soil Taxonomy (1975) are indicated according to MME/DNPM (1978) and Furley (personal communication, 1993).

#### **2.5.1.1 Latossolo Amarelo Alíco (Allic Yellow Latosol)**

- \* Allic Haplorthox
- \* Allic Acrustox
- \* Allic Acrorthox

These highly weathered soils have developed from the Tertiary sediments of the Barreiras Formation. They are mostly well drained. The cation exchange capacity (CEC) is low as is the base saturation. The  $Al^{3+}$  saturation is higher than 50 %. The clay content is high, but the clay fraction largely consists of kaolinite with minor percentages of iron oxides. The soils are typically very deep ( $\geq 200$  cm). Such soils are found on plateaux and gentle slopes to the northwest and north of Manáus. The vegetation ranges from dense forest (on predominantly clayey soils) to campinarana forest<sup>1</sup> (on sites with a higher percentage of sand).

#### **2.5.1.2 Podzólico Vermelho Amarelo Alíco (Allic Red-Yellow Podzol)**

- \* Allic Paleudult
- \* Allic Paleustult
- \* Allic Orthoxic Tropudult
- \* Allic Othoxic Dystropeptic Tropudult
- \* Allic Ustoxic Palelurmult

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<sup>1</sup> See chapter 3 for detailed information of vegetation types.



These soils have developed from the Tertiary sediments of the Solimões Formation. They are moderately to well drained. Podzolization has taken place to varying degrees with A, B, and C horizons being clearly discernible. The base saturation is low; the CEC is moderate to low. The  $Al^{3+}$  concentration is higher than 50 %. These soils are marginally less oligotrophic than the soils of the Latosol/Oxisol group (personal communication P.A. Furley, 1993). They are typical of plateaux and gentle slopes to the southwest and south of Manáus. The vegetation consists of dense to open forest formations.

#### **2.5.1.3 Laterita Hidromorfica Alica (Allic Hydromorphic Laterite)**

- \* Allic Plinthudult
- \* Allic Superic Plinthaquox

These soils represent former river beds in the Manáus region (personal communication G. Prance, 1994). They have formed over sediments of the Solimões Formation. They are encountered in the depressions and valley bottoms between the plateaux. The vegetation consists of dense to open forest cover. The soils are shallow, the pH is low. The soils exhibit a high clay content, are rich in sesquioxides, and poor in humus. Soils of the depressions and valley bottoms undergo prolonged periods of water saturation, causing oxygen deficiency in the root zone. Base saturation and CEC are low, the  $Al^{3+}$  concentration is high.

#### **2.5.1.4 Podzol Hidromorfico**

- \* Aeris Arenic Tropaquod

These soils occur in level or gently sloping terrain. In the vicinity of Manáus, they occupy only small areas that are mostly vegetated by campina and campinarana vegetation. The soils are sandy and very acid. Both base saturation and CEC are very low. The  $Al^{3+}$  concentration is very high. Periods of moderate to bad drainage change with times of good drainage, allowing podzolization to occur.

Chemically, the terra firme soils described above are very poor, due to the low base saturation and the low cation exchange capacity of the clay fraction. Most of the available plant nutrients are linked with the organic matter in the topsoil (Furley

1990; MME/DNPM 1978; Sombroek 1984).

### **2.5.2. Soils of the Floodplains**

According to Sombroek (1984), floodplain soils vary considerably in their internal drainage condition, their texture, organic matter content, acidity, and clay mineralogy, depending on local flooding conditions and the source of the sediments. Relatively elevated parts ('levees', restingas) have soils with sedimentary stratification and free internal drainage. Low stretches (backswamps, lake basins, and swales between levees) have predominantly clayey soils with restricted internal drainage. In the floodplains of the rivers that originate in the Andes and that carry a high sediment load (whitewater rivers, e.g. the Rio Solimões), the hydromorphic soils are non-acidic (locally even calcareous) with a high activity mineral assemblage of illite/montmorillonite (Sombroek 1984). The rivers that originate in the Precambrian Shields or in the sedimentary basin itself carry little or no sediments and may contain high percentages of humic acids (blackwater rivers, e.g. the Rio Negro). The floodplain soils of blackwater rivers are acid, have clay minerals of low activity and are generally less fertile than the soils of whitewater floodplains. In the following paragraphs, the major soil types of floodplain areas in the Manaus region will be examined based on the Projeto Radam survey. Only major features will be reported here while information on individual soil profiles is available in the original literature (MME/DNPM 1978).

#### **2.5.2.1 Gley Pouco Humico Eutrofico (Slightly Humic Eutrophic Gley)**

- \* Eutric Tropaquept
- \* Eutric Aeric Tropaquept

These soils are typical of the more stable parts of the floodplains of the whitewater rivers such as the Rio Solimões. They have been formed from Quaternary sediments. Soil horizons are little developed. The structure is clayey to sandy. Drainage is moderate to poor as inundated periods alternate with dry periods (seasonal inundation). The base saturation is high. The CEC depends on the parent material but tends to be intermediate to high. The natural fertility of the soils is frequently high. The areas are important for riverine agriculture of short-cycle vegetables and fruits (e.g. jute, manioc, maize, water melon, tomato, rice, and beans).

### **2.5.2.2 Solos Aluviais Eutroficos (Eutrophic Alluvial Soils)**

- \* Eutric Tropic Fluvaquent
- \* Eutric Aquic Tropofluvent

These soils represent recently deposited sediments. Many are very young with little to no differentiation of horizons. They are mostly composed of fine sands and silt. Larger particles settle near to the river shores, forming the levees. Finer particles remain longer in suspension and settle in areas of reduced water currents such as backswamp areas away from the river shores. Typical areas of such soils are found along the shores of the Rio Solimões. The natural soil fertility is high due to the annual deposition of sediments. Such areas are partly used for riverine agriculture.

### **2.5.2.3 Gley Pouco Humico Allico (Allic Slightly Humic Gley)**

- \* Allic Oxid Tropaquept

These soils are typical of the more stable parts of the floodplains of blackwater rivers (e.g. the Rio Negro). They are formed from Quaternary sediments which have their areas of origin in regions of hydromorphic podzols or on the Precambrian Guyana Shield. The soils are very acid, of low base saturation, and of low cation exchange capacity. The fertility, consequently, is very low. Such soils are typically found under different types of igapo forest.

## **2.6. Summary and Conclusions**

The main geological formations in the middle Amazon and in the Manaus region in particular are (a) deeply weathered Tertiary sediments of the Barreiras and Solimões Formations (forming today's terra firme), and (b) the floodplains of the large rivers, formed by Quaternary and recent fluvial deposits. The floodplains of large rivers are inundated by an annual flood pulse. In the case of sediment-rich whitewater rivers (i.e. Rio Solimões), this causes an annual 'fertilisation' of floodplain soils. In contrast, the floodplains of sediment-poor, low pH blackwater rivers (i.e. Rio Negro), represent nutrient-impoverished environments, as do most of the highly leached, acidic terra firme soils. The relative stability of climatic, hydrological and other environmental conditions over millions of years in the Amazon region as a whole has

favoured the evolution of specific adaptations in all lifeforms. Plants in the floodplains have adapted to seasonal flooding, resulting in marked differences in species composition between upland and floodplain plant communities. Differences in soil chemical and physical properties lead to marked differences in the vegetation composition on terra firme. The following chapter will show how the conditions of the physical environment are reflected by the spatial pattern of vegetation and land use.

# Chapter 3

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### **3. The Vegetation of the Manaus Region**

Chapter 3 is divided into two parts. Part 1 (section 3.1) defines a vegetation classification system that is adapted to mapping vegetation from current high spatial resolution visible / infrared satellite data. Based on this system, the vegetation formations of the Manaus region have been described in detail in part 2 (sections 3.2, 3.3, and 3.4).

The botanical families of all plant species mentioned in the text are indicated in the Appendix to this chapter.

#### **3.1 A vegetation classification system for mapping humid tropical vegetation from high resolution satellite data.**

##### **3.1.1 Mapping vegetation from satellite data.**

Satellite remote sensing has become a major tool for mapping tropical vegetation. Often these inventories have been carried out without a detailed botanical knowledge, and the resulting vegetation data were unsatisfactory for biologists (Kalliola and Syrjänen, 1991). The potential of satellite data for the study of vegetation has not been fully exploited due to a failure to bridge the gap between image analysis and vegetation science. This gap results from a profound difference in the tools and scale of analysis: space-based observation versus field data collection. The lack of collaboration between the two disciplines has caused a lack of progress in several areas. Image analysts still do not fully understand the physical basis of reflectance from vegetation canopies. Vegetation classification systems developed by image analysts for satellite-based mapping projects often can not be matched with traditional vegetation classification systems. This may have contributed to a rejection of satellite based mapping by vegetation scientists. On the other hand, ecologists have not fully recognised the unique potential offered by satellite data to study vegetation patterns and dynamics at landscape, regional, continental, and global scales. The dislike of traditional ecologists for satellite data arises in part from the often perceived low accuracy of satellite-derived vegetation maps, when compared with detailed field study (see, for example, Kalliola and Syrjänen, 1991). It certainly also reflects the difficulty to match the satellite sensor's view of the Earth surface with human perception (see below).

Satellite-based vegetation mapping is characterised by a lack of standards in the vegetation classification systems. Consequently, the results obtained in different studies are often of little comparable value. This chapter takes a more systematic and more unified approach to defining a classification system for use in satellite-based vegetation mapping. It is hoped that the approach satisfies the needs of the ecological community, while considering technical constraints imposed by the data and the method of interpretation.

### **3.1.2 Characteristics of traditional vegetation classification systems**

Vegetation classification systems have been based on several types of information:

- (a) Geographical context: Information on climate, topography, geology, and geomorphology is used to define major phytogeographical regions. This type of classification tends to be used for global and regional studies.
- (b) Physiognomic or structural: The description is based on external morphology, life form, stratification and size of the species present. Physiognomic and structural methods have been used primarily for the classification of vegetation at regional or global scales. Frequently, classification systems make use of both structural data and information on geographical context. One such classification systems was proposed by Veloso et al. (1991) for Brazil (see below).
- (c) Floristic: the species present in the study area are identified and their presence/absence or abundance is recorded. Floristic analysis has been applied to mapping at large scales (Kent and Coker, 1992).

While traditional vegetation classification systems have been based on climatic, environmental, physiognomic, and floristic data, classification systems for vegetation mapping must also consider the spatial data and information extraction techniques to be used:

- (1) The system must be adapted to the satellite data to be used in terms of both spectral and spatial resolution (and temporal resolution in the case of multi-temporal data).



- (2) The system must consider how information is going to be extracted from the data. For example, digital classification is mostly limited to spectral information, while visual interpretation can use features such as shape, the spatial context of objects, or their texture.
- (3) The system must define classes of vegetation that make sense to the map user and that can be identified on the ground (e.g. vegetation structure / physiognomy, floristic composition, environmental characteristics).
- (4) The system must be complete, i.e. it must allow for all vegetation units that occur in the project area to be categorised.
- (5) A vegetation classification system developed for mapping in a particular area should be upwards compatible with systems developed for mapping larger regions or entire continents.

If the characteristics of the spatial data and the information extraction techniques on which vegetation mapping will be based are not considered at the moment of designing the classification system, there is a high risk of defining classes that cannot be mapped or not making the fullest use of the potential of the data. This characterises the situation of employing traditional botanical systems of vegetation classification in satellite-based mapping projects.

### **3.1.3 Brazilian vegetation classification systems**

#### **3.1.3.1 Projeto Radambrasil**

The most detailed vegetation maps currently available for most parts of the Brazilian Amazon have been produced by the Projeto Radambrasil survey. The Radambrasil project was based on the visual interpretation of airborne X-band radar data, supported by air photography and field verification. With an initial map scale of 1:250,000 and later generalisation to 1:1,000,000 the project presented a reconnaissance survey. Vegetation formations were defined according to climatic factors, uniform geomorphological regions (in the central Amazon based on relief and drainage), and the visual interpretation of basic vegetation types (savannah, dense forest, open forest, semi-deciduous forest) using image grey tone and texture

(Furley, 1986). The structural type of the vegetation was verified through airphoto interpretation and field surveys. Table 3.1 shows the vegetation classes that Projeto Radam defined for the Manáus region.

The vegetation classification system was optimised for the visual interpretation of SLAR X-band data. The heavy reliance on the photo interpretation of geomorphological features (i.e. dissection patterns) makes it difficult to use this classification system with visible and infrared wavelength satellite data where the information used is rather of a spectral than of structural nature.

X-band radar data provide only a rather limited amount of information on vegetation because radar of this wavelength does almost not penetrate into the vegetation. The vegetation classification system used in Projeto Radam therefore, had to infer vegetation characteristics from the visual interpretation of geomorphological patterns. The high level of geomorphological detail visible on the X-band SLAR imagery led to the designation of an excessive number of vegetation classes. Furthermore, the Radam vegetation classification system made little use of available phytogeographical data. As a result, although the number of vegetation classes is too high, these classes mostly reflect geomorphological differences. The actual number of vegetation classes without the subdivision based on geomorphology is relatively low. Consequently, the system does not provide the level of detail that can be achieved with high resolution multi-spectral satellite data.

### **3.1.3.2 Classification of the Brazilian Vegetation (Veloso et al. 1991)**

Another system for the classification of Brazil's vegetation has been suggested by Veloso et al. (1991). The system has been designed to support vegetation mapping from remotely sensed data at regional and reconnaissance level scales (1:10,000,000 - 1:250,000). It is based on the structure of the dominant life forms, climatic factors (primarily the water deficit arising during the dry season), the altitude of the terrain, and the physiognomy of the vegetation. Details are shown in Table 3.2. Because of its design for mapping at scales smaller than 1:250,000 the system does not provide sufficient detail for the current project. Also, the system uses parameters which are difficult to determine in the field (e.g. the annual water deficit) or represent divisions (e.g. altitude between 5 and 100 metres) that lead to classes which can neither be distinguished in the field nor on satellite data.

### **3.1.4 Defining a vegetation classification system for mapping vegetation from high resolution visible / infrared satellite data.**

The aim was to define a vegetation classification system that accommodates the conditions detailed in section 3.1.2.

It is proposed to base the classification system for mapping vegetation from high spatial resolution satellite data on several levels of geographical analysis. Factors of relevance to plant growth are used as differentiating criteria at all levels of analysis. Each level is linked to a particular type of data and method of analysis. Level (2) and (3) information is derived from the interpretation of high resolution space-borne data. Table 3.3 summarises the proposed vegetation classification system, while the following paragraphs define the proposed levels of geographical analysis in more detail.

#### Level 1: Eco-climatic regions

Eco-climatic regions are defined on climatic parameters and major features of relief at the continental scale of analysis. Examples are the Andes, the lowland Amazon, the Guyana Shield, or the Central Brazilian Shield. This level of analysis was not of relevance in this regionally limited study and has not been further elaborated.

#### Level 2: Geo-ecological formation

Geo-ecological formations refer to features of importance at the regional scale of analysis. The definition is based on parameters which are key determinants of plant growth and distribution, i.e. plant nutrient availability and the hydrological regime. These are determined by geological formation, regional geomorphology, and the hydrological regime (e.g. seasonal inundation of floodplains). These parameters can be mapped through the visual interpretation of high resolution satellite data, both from the visible / infrared and the radar spectrum.

Using these criteria, the Manáus region has been divided into three geo-ecological formations (chapter 2):

1. Terra firme: Areas that do not undergo seasonal inundation. This includes the floodplains of small rivers that may be flash-flooded at irregular intervals.
2. Floodplains that undergo regular seasonal inundation by sediment- and nutrient-rich whitewater rivers (sometimes called 'várzea').
3. Floodplains that undergo regular seasonal inundation by sediment- and nutrient-poor back water rivers (sometimes called 'igapo').

The three geo-ecological formations are fundamentally different in at least two environmental parameters that are important for plant growth and distribution: the occurrence of seasonal inundation and the availability of nutrients to plants. Because of the relative stability of environmental conditions in at least part of the Amazon region over possibly millions of years, plants have developed evolutionary adaptations to these environmental factors and the three geo-ecological formations are characterised by vegetation of largely different floristic composition.

The next level of analysis is characterised jointly by vegetation physiognomy and local environmental characteristics.

### Level 3: Vegetation formations

This represents the level of analysis that can be mapped from current high resolution spaceborne sensors such as Landsat TM or SPOT HRV. The definition of vegetation formations is based on vegetation physiognomy and local environmental characteristics.

#### (a) Vegetation physiognomy<sup>1</sup>

Vegetation formations are defined based on the physiognomy of the vegetation which has been found to be the parameter that most closely explains the spectral reflectance detected by the TM sensor in this study. This has also been found by Kalliola and Syrjänen in their study of vegetation in Finland using TM imagery (Kalliola and

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<sup>1</sup>'Physiognomy' as used in this study refers to the structure of the vegetation (i.e. dominance of trees, shrubs, herbaceous vegetation; morphology of the upper canopy)

Syrjänen 1991).

There are further reasons for defining vegetation formations primarily based on physiognomy: (a) Vegetation physiognomy can be recognised during overflights, the only feasible way of collecting ground truth information for large and inaccessible areas, such as the Manáus region. (b) Species diversity of many vegetation formations in the humid tropics is high and the floristic composition has been found to vary much more than the structure of the vegetation between sites.

In the definition of vegetation physiognomy particular importance must be attributed to those elements of the vegetation that are responsible for the spectral response detected by the satellite. For remote sensing in the visible and infrared spectrum (Landsat, SPOT, Indiasat) as well as for C-band radar (ERS-1), this is mostly the upper canopy. Air surveys carried out in support of satellite based mapping should collect as much information as possible on the upper canopy. The Landsat satellite as well as the SPOT satellites acquire imagery between approximately 9.00 - 10.00 am local sun time. It is important to carry out air surveys at the same time. The morphology of forest canopies can be quite distinct for certain forest formations. Even though the spatial resolution of TM or SPOT data is often not high enough to identify individual trees, image texture can nevertheless be an important criterion for the differentiation of forest formations in visual interpretation.

#### (b) Local environmental characteristics

Vegetation physiognomy does not fully explain the spectral response measured in the visible / infrared spectrum. It has been observed (section 6.2) that the spectral response of forest types may vary in function of the habitat. In the project region such variation appears to be related primarily to the hydrological conditions of a site, and secondly to changes from predominantly argillic to rather more sandy soils. Both parameters are closely related to local patterns of topography, hydrology, and soils.

#### Level 4: Plant associations

The diversity of species is particularly high in the humid tropics, even though pronounced differences in diversity exist between different vegetation types. It has been found that the structure of the vegetation varies much less than the floristic



composition over long distances. The proposed classification system takes this into account by basing the definition of vegetation categories on environmental determinants of plant growth and the physiognomy of the vegetation. As a result the same category may occur in different locations, with both sites having different floristic composition.

Kalliola et al. (1991) defined vegetation categories based on physiognomy and environmental characteristics for mapping the swamp vegetation of the Peruvian Amazon. They concluded however, that these categories should not be established for a wider use because the floristic composition may vary between sites.

The opposite point of view is taken here. It is argued that the definition of vegetation categories for mapping humid tropical vegetation should be based on physiognomy and environmental factors that can be interpreted from current satellite data. Floristic data should be used to characterise the occurrence of a vegetation category in a particular location. If vegetation categories are defined based on characteristics that can be interpreted from data such as Landsat TM and ERS-1 SAR that are available for almost the entire Amazon basin, this will provide a basis for the floristic comparison of vegetation over large distances.

High spatial resolution visible / infrared satellite data provide information for the definition of vegetation formations at levels (2) and (3) of the proposed system. The boundaries of geo-ecological formations can be visually interpreted from the data. Information for analysis at level (3) is encoded in the spectral pattern of features but also in their shape and location relative to other objects. This explains why visual analysis of TM, MSS, or SPOT data has repeatedly been found to give more accurate results than digital classifications based on the per pixel evaluation of spectral information (see, for example, King 1994; Rasch 1994; Ringrose et al. 1988; Rosenholm 1993; Tuomisto et al. 1994).

The physiognomy of the vegetation, in particular the morphometry of the upper canopy, is an important determinant for reflectance detected by visible and infrared spaceborne sensors. Recent experiments in Central American tropical vegetation have shown that multi-polarisation and multi-wavelength airborne radar provides a wealth of information on the physiognomy of vegetation formations (e.g. relative importance of vertical versus horizontal woody elements; green biomass versus

woody biomass; degree of canopy closure) (Pope et al. 1994). The large wavelengths (i.e. P-band and L-band) also provide information on the environmental conditions of a site (e.g. sub-canopy flooding) (Pope et al. 1994). The definition of vegetation formations based on physiognomy and environmental parameters appears to provide a conceptual framework suitable for space-based vegetation mapping not just from current sensors but also from future space-borne systems.

### **3.1.5 Vegetation formations of the Manáus region**

Table 3.4 shows the vegetation formations of the Manáus region that have been defined using the system outlined above. These formations will be described in detail in the following sections and linked to published information on floristic surveys carried out in the project region.

### **3.2. Vegetation in the floodplains of whitewater rivers**

The floodplains of the Amazon river in the Manáus region consist of a mosaic of different vegetation types. The main factors exercising influence on the spatial distribution of vegetation types are:

- (a) Sedimentation and erosion processes (influencing the age and the stability of a site).
- (b) The flood regime (duration of floods, extreme events, current velocity, etc.).
- (c) Edaphic factors.
- (d) Patterns of natural plant succession.
- (e) Anthropogenic influence on plant succession.

Those factors that have not been discussed in chapter two will be examined in order to facilitate understanding as to why particular vegetation formations occur in certain locations in the floodplain.



### **3.2.1. Factors determining the spatial distribution of vegetation formations in whitewater floodplains**

#### **3.2.1.1 Sedimentation and erosion processes**

Unlike some of its tributaries (e.g. Rio Purus), the Solimões and Amazon rivers do not have a meandering course. In the classification suggested by Morisawa (1985), these rivers would be classified as 'braided' (many shifting channels) to 'anastomosed' (many relatively stable channels). The rivers fork and come together again, embracing lenticular-shaped islands (i.e. Ilha do Careiro, Ilha Paciencia, Ilha Marchantaria; for locations in the Manaus region see Figure 3.1). These islands split the river into a master channel and one or more side ducts, called 'paranas' (Sternberg 1975).

Whereas the rate of morphological change in terra firme areas is comparatively low, whitewater floodplains undergo rapid change by erosion and sedimentation processes. Sediment deposition has frequently been ascribed to a decrease in current velocity. This may happen behind barriers (i.e. islands), at confluences, along the sides of channels, on the inside of river bends, and also on the floodplain. Floodplain deposits can be broadly divided into channel deposits and overbank deposits. Generally, coarser particles will be deposited in areas with higher current velocities (i.e. river channels), whereas very fine particles require a much stronger reduction in water currents to allow sediment deposition (e.g. backswamps). Therefore, channel deposits tend to exhibit a larger particle size than overbank deposits.

As the river overflows its banks, sedimentation takes place with particles becoming progressively finer away from the channel edge. The coarser material sediments rapidly at the channel margins, forming natural levees, locally known as 'restingas'. Depending on the amplitude of flooding, the crest of the levees may lie several metres higher than the seasonally flooded backswamps or lake basins. During high water levels, backswamps will be flooded through low sections in the levees along the main river channel. The resulting overflow channels constitute more or less intermittent streams, which assume a sinuous pattern and are flanked by their own deposits. Sternberg (1975) calls deposits formed by the main channel 'first order' features, whereas he refers to those ones formed by overflow channels as 'second order' features. The strips of higher ground formed by sediment deposition along

overflow channels partition off portions of the backswamps, forming backswamps seasonally occupied by lakes (Figure 3.2).

As pointed out above, islands frequently exhibit a lenticular shape. Vertically accreted overbank deposits, being higher riverwards, give a 'saucer-like' cross section to the islands. In the centre of such islands we typically encounter shallow lakes, expanding and contracting with the fluctuations of the main river course's water level to which the lakes tend to be connected by narrow igarapes<sup>2</sup> (e.g. Ilha do Careiro) (Sternberg 1975).

### **3.2.1.2 The flood regime**

One of the main ecological factors in the floodplain environment is the duration of seasonal flooding. Each place in the floodplain may be characterised according to its position on the flood level gradient, i.e. the mean flood duration. In the floodplains of the Manáus region, observations concerning the periodicity of flooding may be related to one another and also, converted to absolute height values based on the Manáus harbour hydrograph. Due to the very low gradient of the main rivers in the region, the Manáus hydrograph data are representative of the flooding conditions in comparatively large areas upstream and downstream of Manáus. Junk (1989a) reports that hydrographical data collected in the Janauaca area (60 km upstream of Manáus on the Rio Solimões) showed only a few centimetres of difference compared to the Manáus hydrograph. Figure 3.3 shows the relationship between the 'water gauge above sea level' and the 'days of inundation', calculated as average values for the period 1.1.1903-31.12.1982 from the Manáus hydrograph data.

As reported above, minimum and maximum flood levels in the Manáus region vary strongly between consecutive years. In a study on flood tolerance and tree distribution, Junk (1989a) therefore calculated (from the Manáus hydrograph data) average values over a period of 80 years for average, minimum and maximum number of dry and flood days per year (Figure 3.3). He defined flooding as the period when the river level is above the soil surface. However he noted, that this resulted in conservative estimates because flood stress starts when the water reaches the roots. He stresses that unusually long periods of wetness and dryness possibly have greater influence on tree distribution than the average duration of flooding. Furthermore,

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<sup>2</sup> The Brazilian term 'igarape' refers to narrow river channels.

'flood tolerance of adult trees may be greater than suggested by their position on the level gradient because seedling establishment may be more important for tree distribution than flood tolerance of adult trees' (Junk 1989a).

For the distribution of plant communities and species in the floodplain not only the duration of flooding, but also current velocity, the seasonal development of stagnant water conditions resulting in oxygen deficiency, and other factors must be expected to be of importance. The effect these factors exert on plant distribution is, however, still poorly understood.

### **3.2.1.3 Patterns of natural plant succession**

Field work in the whitewater floodplains of the Manáus region suggested that there are two pathways of succession from herbaceous vegetation to forest vegetation that depend on the hydrological conditions of a site.

#### (a) Succession in depressions (lake basins and swales):

The sedimentation rate in these areas is relatively low, with the sediments being of a predominantly argillic nature (overbank deposits, see above). Due to the low rate of sediment deposition the progression from low-lying areas to high-lying terrain may take many years. Typical sites include the margins of floodplain lakes, backswamp basins, and river channels that have been cut off from the main river course. Stagnant water conditions inducing low oxygen levels in the water and soil may occur. Succession appears to progress through the following stages:

- (1) Floating meadows: floating vegetation dominated by aquatic grasses.
- (2) Aninal: Herbaceous flood tolerant vegetation with islands of the giant Araceae Montrichardia arborescens (Photo 3.8).
- (3) Shrub swamps: vegetation dominated by shrubs with some low trees and herbaceous vegetation (Photos 3.6 and 3.7).
- (4) Open forest: intermediate forest succession with canopy closure below 80 percent (Photos 3.5 and 3.3).

- (5) Closed forest: includes the intermediate to late stage of forest succession (closed canopy lacking tall emergents and gaps) and the climax stage (closed canopy with tall emergents and gaps) (Photos 3.1 and 3.3).

The succession from (1) to (5) goes in parallel with a decrease of the duration of the inundated period and an increase of the total biomass of the vegetation.

(b) Succession on levees:

Such sites are encountered along the main river course or important side ducts. The current velocity during the inundated period can be high such that the sediments are dominated by the silt and sand fraction. Sedimentation rates tend to be high and, consequently, a site evolves relatively rapidly from conditions of long flooding to short flooding.

In many parts of the floodplain it can be observed that plant succession goes along with a decreased duration of mean annual flooding. Succession to late successional and climax forest is only possible in relatively stable parts of the floodplain. These tend to be either the levees formed by the main river course and paranas, or areas of higher ground formed by overbank deposition along overflow channels (Figure 3.2).

Worbes et al. (1992) describe the pattern of vegetation succession for sites undergoing intermediate to short flooding (175-200 days of flooding, equivalent to 23.0-25.0 m elevation) in the floodplains of the Amazon river 150 km upstream and downstream of Manáus. They used dendrochronological techniques in order to determine the minimum age of forest stands. By combining this information with forest surveys they were able to identify the following successional stages:

- (1) The initial stage of primary succession in whitewater floodplain habitats is dominated by tall grasses (e.g. Paspalum fasciculatum, Echinochloa polystachya) which colonise recently deposited sediments that fall dry for a few months during the low water period. With rising water levels, these grasses change from the terrestrial to the aquatic phase, forming the so-called 'floating meadows' (see Photo 3.12).

- (2) With continuing sediment deposition, the higher parts of the quickly growing point bars and lateral levees start to be colonised by trees, e.g. Salix humboldtiana and Alchornea castaneaefolia (primary stage of forest succession, not older than 20 years) (see Photo 3.11).
- (3) The pioneer stages are followed by an 'early secondary' stage which is species-poor and dominated by Cecropia species. Grasses are gradually eliminated (Photos 3.9, 3.10)(Junk 1984).
- (4) The 'intermediate secondary' stage is characterised by the Crataeva benthamii community (20-40 years old).
- (5) The 'late secondary' community is characterised by Pseudobombax munguba (not older than 70 years)(Photo 3.2).
- (6) Eventually, P. munguba reaches its maximum age (60-70 years) and is replaced by slower-growing species. The 'climax' community is characterised by Piranhea trifoliata and other emergent trees which may reach a greater age (200-400 years) (Photos 3.1, 3.3).

(Worbes et al. 1992)

Table 3.5 summarises the characteristics of successional stages as described by Worbes et al. (1992).

An important difference between succession in lake basins and swales and succession on levees arises from the fact that sediment deposition occurs at much reduced rates on the former sites. Vegetation in these areas tends to be exposed to long seasonal inundation for many years which is a factor of ecological stress to many plants. The vegetation communities in lake basins (shrub swamps, open forest) typically exhibit a low degree of canopy closure during many years of succession, while vegetation with a closed canopy appears to form much more rapidly on levees. This causes a different spectral response of the vegetation to the satellite sensor.

#### 3.2.1.4 Anthropogenic influences on plant succession

The floodplains of whitewater rivers have long been used agriculturally because of their high and sustained soil fertility (annual sediment deposition) in what is generally a nutrient-poor environment (most surrounding terra firme areas). The utilisation has not been constant but rather followed economical cycles. During the rubber boom in the late 19th and early 20th century, the original floodplain forest was cleared and replaced with plantations of rubber trees in parts of the floodplain in the vicinity of Manáus. After the sudden end of the boom, the plantations were largely abandoned and have reverted to late secondary or early climax vegetation since. During the second World War, a minor boom based on demand for rubber and other products, especially jute, occurred. Again, floodplain forest was cleared for plantations and agricultural production. With the end of this 'mini-boom' after the end of World War II, many such areas were abandoned and have reverted to secondary forest.

Having laid the basis for an understanding of the spatial pattern of vegetation formations in the whitewater floodplain, we shall now proceed to defining the individual formations.

#### 3.2.2. Vegetation formations of whitewater river floodplains

Herbaceous vegetation marks the earliest stages of succession in the floodplains. This may represent natural succession on low-lying terrain, but also includes high-lying areas influenced by human intervention, i.e. deforestation and burning. Three vegetation formations dominated by herbaceous elements can be distinguished in the Manáus region:

Floating meadows: Low-lying areas undergoing prolonged flooding that are covered by floating aquatic grasses during the high water season. No woody elements are present.

Aningal: Low-lying areas dominated by aquatic herbaceous vegetation with some woody elements (shrubs, low trees) and islands of the giant Araceae Montrichardia arborescens.



Várzea pasture: High-lying areas undergoing short flooding. Succession to forest is halted by human interference.

### 3.2.2.1. Floating meadows ('Paspalo - Echinochloetum')

**Photos:** 3.11, 3.12

Floating aquatic vegetation covers extensive areas in the floodplain of the Amazon during the inundated period. Much knowledge on the ecology of floating meadows on the middle Amazon has been gathered during the past 25 years (Junk 1986; Junk 1983a; Junk and Howard-Williams 1984). In the following paragraphs the main habitats will be described. Then, the grass species that form most of the 'floating meadows' will be introduced, stressing aspects of their life cycle of relevance to remote sensing projects.

#### (a) Habitat characteristics

Two factors govern the establishment of aquatic and semiaquatic vegetation in the várzea: (1) the amplitude of water level fluctuations, and (2) the degree of exposure of the habitat to strong water currents. Based primarily on these factors, Junk (1970) divided the whitewater habitats suitable for the development of floating meadows into three types (see also Figures 3.4 and 3.5): (1) bank and sedimentation zones in the main river course, (2) várzea lakes with high fluctuations of water level, and (3) várzea lakes with small fluctuations of water level ('small' and 'high' in comparison to the fluctuations of water level in the main river course). In the following, these habitats will be described with their typical species.

#### Bank and sedimentation regions in the Rio Solimões and Rio Amazonas

At places protected from currents, rapid sediment deposition may occur (Irion et al. 1984). When sedimentation reaches the point that sediment banks fall dry at low water periods, plant colonisation starts, mainly by the grasses

Echinochloa polystachya

Paspalum repens

Paspalum fasciculatum



Hymenachne amplexicaulis

Salix humboldtiana will settle as the first tree in the highest places (Photo 3.11) (Junk 1970). With rising water levels, the grasses grow up and form the so-called 'floating meadows'. These semiaquatic plants support further sediment deposition by reducing the water current and by the lodging of suspended material on their roots and stems. A typical example of this habitat is the large sedimentation zone east of the Ilha da Marchantaria, 30 km upstream of Manaus in the Rio Solimões (Photos 3.11, 3.12).

During the dry period, sedimentation zones and shore lines are frequently used for agriculture including jute plantations (Corchorus capsularis). During the inundated period, the grasses of the floating meadows may be harvested and used as cattle fodder.

**Várzea lakes with high fluctuations in water level**

These lakes represent the habitat with the highest species diversity. At high water levels, all lakes of this type have large populations of Paspalum repens and Echinochloa polystachya. Together with these grasses, further herbaceous plants may occur:

Leersia hexandra  
Hymenachne amplexicaulis  
Panicum chloroticum  
Oryza perennis  
Scirpus cubensis  
Eichhornia crassipes  
Reussia rotundifolia  
Phyllanthus fluitans  
Jussiaea natans  
Pistia stratiotes  
Ceratopteris sp.  
Salvinia auriculata  
Azolla sp.  
Marsilia sp.

(Junk 1970).

A typical representative is Lago Manacapuru, 90 km west of Manaus on the Rio Solimões.

### **Várzea lakes with small fluctuations in water level**

According to Junk (1970), this habitat is characterised by the development of large, often relatively old populations of Leersia hexandra and floating species of the family Cyperaceae. Further herbaceous plants found in these conditions include:

Paspalum repens

Victoria amazonica

Azolla sp.

Eichhornia crassipes

Compared to types (1) and (2), this habitat occupies relatively small areas in the Manaus region.

#### **(b) Important species**

Because of their ecological and economic importance, and for the considerable size of areas covered by floating grasses at high water levels, the most important species of the floating meadows will be briefly introduced. A more detailed account can be found in Junk (1970) and de Albuquerque (1981).

#### **Paspalum repens Berg (Gramineae)**

'Pirimembeca'

'Canarana rasteira'

P. repens, together with Echinochloa polystachya, is the species which contributes most to the development of floating meadows in the middle Amazon. With rising water, about December, an explosion-like development of populations begins. During the 5-6 months of rising water levels, a dense mat is formed which is completely detached from the substrate. Towards the middle of June, the flowering period begins. Soon after blossoming, the populations partially grow old with plant parts above the water surface dying and collapsing. When the areas fall dry at low water

levels, P. repens develops a terrestrial form which is morphologically very different from the aquatic state.

### **Echinochloa polystachya (H.B.K.) Hitchcock (Gramineae)**

E. polystachya and P. repens are the most important species forming the floating meadows of the middle Amazon, representing together about 80-90 % of floating grass in the Amazon and most of the várzea-lakes in the surroundings of Manaus (Junk 1970).

With rising water levels, the populations of E. polystachya rapidly increase and the plants grow up vertically. However, in contrast to P. repens, E. polystachya keeps attached to the substrate. The main flowering time lasts from April to July. Afterwards the plants typically turn yellowish-green (see Photo 3.12). When the habitat falls dry, the old stems either begin to rot or start rooting. New plants develop and grow up to big clusters of about 2 m height. E. polystachya together with P. fasciculatum form a main part of the dry-period-vegetation of the várzea lake bottoms and the river banks (Junk 1970).

### **Paspalum fasciculatum Willd. (Gramineae)**

'Muri', 'Capim Mori'

According to Junk (1970), P. fasciculatum is one of the most frequent grasses of the banks of rivers and the lakes of the várzea. In contrast to P. repens and E. polystachya, P. fasciculatum does not grow accompanying rising water levels, but becomes entirely flooded. It is not a floating grass but remains always firmly rooted in the substrate. During the dry period, mixed populations of P. fasciculatum and E. polystachya are frequently found. Then, with rising water level, a separation takes place, as E. polystachya grows up with the water whereas P. fasciculatum becomes gradually flooded (Junk 1970).

In case of a coexistence of all three species, P. fasciculatum, E. polystachya, and P. repens form three zones in the bank regions of rivers and lakes: P. fasciculatum rises above water level only near the bank. The population, however, may continue at the bottom up to a water depth of 6 to 10 metres. E. polystachya, populating almost the

same area, grows up with the water, forming the second zone at the water surface, the stems rooting in the substrate among the immersed P. fasciculatum population. At even deeper inundation levels, the P. repens population forms the third zone, being mostly free of the bottom (Junk 1970).

#### **3.2.2.2. Aningal**

##### **Photo: 3.8**

'fourrees marecageux ouvertes' (ORSTOM and INPA 1988)

'areas permanentemente inundadas' (dos Santos et al. 1983)

This vegetation formation is characterised by essentially graminoid vegetation and 'islands' of the giant Araceae Montrichardia arborescens which grows sometimes in clusters on thick layers of floating grasses, especially along the margins of várzea lakes and in depressions (ORSTOM and INPA 1988). Some trees and shrubs may be present. Frequent grasses of the herbaceous layer in the aningal area north of Lago do Arroz (Ilha do Careiro) are Paspalum repens and Oryza perennis (Boechat Lopes et al. 1983). The cover of the non-herbaceous vegetation is always below 50 %, and on the western part of the Ilha do Careiro it is typically between 10 % and 20 % as verified by overflights in August 1991 (Photo 3.8). The soils are in hydromorphic conditions throughout most of the year. On the Ilha do Careiro, this vegetation formation is intensively utilised. At high water levels, grass is being harvested to feed the cattle. At low water levels, the area is frequently burnt in order to facilitate the regrowth of fresh grass (ORSTOM and INPA 1988).

#### **3.2.2.3. Várzea pasture**

##### **Photo: 3.13**

Várzea pasture results from the clearing of mid-level and high-level floodplain forest. Due to the seasonal inundation and siltation, these areas are characterised by their high soil fertility. At low water levels, they are frequently used as cattle pasture (dos Santos et al. 1983). Typical aquatic and semiaquatic grasses on low-lying terrain are:

Echinochloa polystachya  
Paspalum repens  
Paspalum fasciculatum  
Hymenachne amplexicaulis  
Panicum zizanoides

(dos Santos et al. 1983)

Typical grass species of terrain with a short flooding period are:

Cynodon dactylon (pers. comm. Junk)  
Brachiaria mutica (improved pasture, frequent)  
Panicum maximum (improved pasture)

Some trees or shrubs may be present. Also, there may occur some commercially used palms:

Mauritia flexuosa  
Euterpe oleracea  
Iriarteia exorrhiza  
Oenocarpus pataua  
Oenocarpus distichus

(dos Santos et al. 1983)

#### **3.2.2.4. Shrub vegetation: early succession**

##### **(a) Shrub vegetation on levees**

**Photos:** 3.9, 3.10, 3.11

The youngest formations (Photo 3.11) that are found on recently deposited sediments are typically colonised by:

Salix humboldtiana  
Alchornea castaneaefolia

These are called 'pioneer community' by Worbes et al. (1992). The following stage of forest succession (Photos 3.9, 3.10) in the floodplain of whitewater rivers is dominated by Cecropia latiloba and Cecropia membranacea (ORSTOM and INPA 1988, Worbes et al. 1992). A dense canopy is formed while herbaceous elements are eliminated. Further tree species include:

Jacaranda copaia

Cassia obtusifolia

Ricinus communis

Vismia spp.

Indigofera spp.

Solanum spp.

Phenakospermum guyanense

Trema micrantha

(ORSTOM and INPA 1988)

On higher-lying areas that have recently been deforested the understory species Bonafusia tetrastarhya may develop dense 2-3 m high stands (Worbes et al. 1992).

#### **(b) Shrub vegetation in depressions**

**Photos:** 3.6, 3.7

Shrub swamps occur in extensive areas on the southern shore of the Rio Solimões which represent shallow depressions ('backswamp basins', 'floodbasins') behind the levees of the main river course (Figure 3.2). Flooding is prolonged. The soils are in a hydromorphic state throughout much of the year. During the overflight of extensive shrub swamp areas in August 1991 it was observed that shrub swamps exhibit a coverage of 30-70 % of shrubs and low trees (Photos 3.6 and 3.7). On 8-8-91, all shrub swamps that could be verified from the air were inundated (27.44 m a.s.l.). Due to the inundation, these areas could not be visited on the ground during the fieldwork period. No references to this vegetation type could be found in the literature. The number of woody species appears to be low, but no exact data are available.

### 3.2.2.5. Open forest: intermediate succession in depressions

**Photos:** 3.3, 3.4, 3.5,

'chavascal' (local name)

'palm swamps'

'fourrees marecageux' (ORSTOM and INPA 1988)

The forest canopy does not exhibit a clear stratification. There are neither tall emergents nor a pronounced gap structure (Photos 3.4, 3.5). Trees rarely grow taller than 20 metres. The canopy is not entirely closed (canopy closure typically 50-80%). In August 1991, the upper canopy was characterised by a large number of (semi-) deciduous trees on Ilha do Careiro (Photo 3.5). This confirms that the area undergoes intermediate to long flooding. Lianas and epiphytes are rare or entirely absent. Unlike the late successional and climax forest, arborescent palms are frequent in the upper canopy. ORSTOM and INPA (1988) report this vegetation formation occurring in areas characterised by permanently hydromorphic soils over the western half of Ilha do Careiro. According to ORSTOM and INPA (1988) typical tree species of this formation on the Ilha do Careiro are:

Pseudobombax munguba

Bactris sp.

Triplaris surinamensis

Vitex cymosa

Piptadenia peregrina

Cecropia latiloba

Cecropia membranacea

Astrocaryum sp.

### 3.2.2.6. Closed forest: late succession and climax stage

**Photos:** 3.1, 3.2, 3.3

'seasonal várzea' (Prance 1979)

'swamp forest (várzea) without canarana' (Prance 1989)



Seasonal várzea forest occupies intermediate to high positions on the topographic profile of whitewater floodplains. Average flooding lasts between 140 (25 m level) and 230 (22 m level) days per year (Junk 1989a). Below the 23 m mark, soils increasingly remain water-saturated between consecutive floods and there is a change into more open vegetation formations. Seasonal várzea forest supports a high biomass with many large trees and lianas. Buttress roots and pneumatophores are common. The herbaceous zone of the forest may be rich in individuals of Heliconia and Costus (Prance 1989; Prance 1979).

Variations in species composition depend on the duration of the flooded period and on the successional stage of the forest (Worbes et al. 1992). The highest species diversity is found in forest stands representing late successional climax vegetation, undergoing short periods of flooding (ORSTOM and INPA 1988, Worbes et al. 1992). Several authors list tree species typical of seasonal várzea forest on the middle Amazon (Hueck 1966; Junk 1984; Pires 1974; Prance 1989, 1979, 1978). According to these authors the following tree species may be regarded as 'typical' of the middle Amazon, an area much more extended than the Manáus region:

Astrocaryum jauari

Bothryospora corymbosa

Calycophyllum spruceanum

Carapa guianensis (\*)

Cassia grandis

Cecropia spp. (\*)

Ceiba pentandra (\*)

Couroupita subsessilis

Crataeva tapia (\*)

Eschweileira spp.

Euterpe oleracea

Gustavia augusta (\*)

Hevea brasiliensis (\*)

Hura crepitans (\*)

Macrolobium acaciifolium

Olmediophaena maxima

Piranhea trifoliata

Pithecellobium niopoides (\*)

Pseudobombax munguba

Sterculia elata

Vitex cymosa (\*)

(\*) also widespread outside the várzea (Junk 1984; Prance 1979; Ratter 1993 pers. comm.)

Only a limited number of forest surveys have been carried out in the whitewater floodplains in the vicinity of Manaus. The results are summarised in Tables 3.6 and 3.7. Table 3.6 displays only those tree species that have been explicitly mentioned as forming the upper canopy. Table 3.7 lists those tree species that have been found to be 'abundant', 'frequent', 'dominant', of a high IVI (Importance Value Index, Curtis and McIntosh 1951), or 'characteristic'. The following tree species have been mentioned in at least 3 surveys:

species	frequency of being mentioned	forming upper canopy
<u>Pseudobombax munguba</u>	7	x
<u>Craetava benthamii</u>	6	x
<u>Nectandra amazonum</u>	5	
<u>Piranhea trifoliata</u>	5	x
<u>Pterocarpus amazonum</u>	4	x
<u>Vitex cymosa</u>	4	x
<u>Casearia aculeata</u>	3	
<u>Crescentia amazonica</u>	3	
<u>Hura crepitans</u>	3	
<u>Laetia corymbulosa</u>	3	x
<u>Macrolobium acaciifolium</u>	3	x
<u>Pithecellobium inaequale</u>	3	
<u>Sorocea duckei</u>	3	
<u>Tabebuia barbata</u>	3	
<u>Triplaris surinamensis</u>	3	x

These species may be regarded as characteristic of late successional and climax forest of whitewater floodplains in the Manáus region (personal communication Prance 1993).

In várzea forest on the lower lying areas of the floodplain, the upper canopy is frequently characterised by (semi-) deciduous trees. Leaf fall is caused by oxygen stress in the root zone due to prolonged flooding (Photo 3.2). Deciduousness is typical of the forest formation that Junk (1989a) calls the 'mid-level tree community'. Typical deciduous species are:

Pseudobombax munguba

Triplaris surinamensis

Crataeva benthamii

Vitex cymosa

Crescentia amazonica (Junk 1989a)

With increasing duration of flooding the height of the upper canopy decreases, the biomass decreases, and the forest canopy gradually becomes more open. Within the closed forest formation, two sub-formations may be differentiated: the 'late successional stage' and the 'climax stage'. The late successional stage is characterised by a closed canopy that lacks tall emergents and large gaps. The canopy has a comparatively 'smooth' appearance during overflights. The climax forest is characterised by the presence of tall emergents and a pronounced gap structure. These features are even discernible on Landsat TM imagery (Figure 3.6). Gaps may also result from selective logging.

### **3.2.2.7. Agroforestry systems on restingas**

**Photos:** 3.4, 3.14, 3.15

In an undisturbed succession, restingas would be occupied by a tall floodplain forest, the duration of seasonal flooding being short or flooding occurring only in exceptional years. In the Manáus region, most restingas are utilised by smallholders and cattle farmers. Land use includes pasture, frequently with scattered fruit trees, vegetable gardens, and agroforestry systems (cacao, rubber). For details on land use in the whitewater floodplain near Manáus refer to ORSTOM and INPA (1988).

### **3.3. Vegetation in the floodplains of blackwater rivers**

#### **3.3.1. Factors determining the spatial distribution of vegetation formations in blackwater floodplains**

##### **3.3.1.1 Sedimentation and erosion processes**

As pointed out above, blackwater rivers typically carry a low sediment load and are fringed by much narrower floodplains than whitewater rivers. The variety of different habitats that is found in the floodplains of whitewater rivers, is much reduced along blackwater rivers.

The banks of the Rio Negro may represent sedimentation or erosion zones. Erosion on the lower Rio Negro results in river banks with clay-rich material, as the locally available parent material stems from argillic deposits of the Barreiras and Solimões formations (chapter 2). Sediments resulting from erosion on the Guyana shield are characterised by a high quartz content. Clay-rich soils tend to be marginally richer in nutrients and have a higher capacity to retain nutrients and water during the dry season than the soils of sandy river banks. The differences in soil conditions (argillic versus sandy soils) are reflected by the vegetation as Revilla (1981) found in an investigation of the vegetation at Praia Grande. Table 3.8 summarises his results.

##### **3.3.1.2 The flood regime**

The information given above for whitewater floodplains equally applies to blackwater floodplains and no further comments will be made.

##### **3.3.1.3 Patterns of natural plant succession**

As in whitewater floodplains, natural succession in blackwater river floodplains progresses from predominantly herbaceous vegetation on low-lying areas to closed forest on stable sites undergoing intermediate to short flooding. It appears that there are two lines of vegetation succession, depending on the hydrological conditions of the site.

(a) Succession from floodplain lakes

Following the early 'aningal' stage (characterised by Montrichardia arborescens), the next stage in forest development is characterised by Buchenavia suaveolens, Burdachia prismatocarpa, Laetia suaveolens, Rheedia floribunda, and Parkia discolor which are capable of surviving hydromorphic soil conditions. The third stage in succession shows a rather more dense physiognomy with plants of greater height such as Blastemanthus grandiflorus, Franchetella crassifolia, and Mollia speciosa. Finally, Aldina latifolia and other long-lived trees will establish themselves, marking the ultimate state in seasonal igapo forest succession (Revilla 1981, observations made at Praia Grande).

(b) Succession on river banks

Succession on river banks clearly proves the dependency of the floristic composition on the duration of flooding, as Keel and Prance (1979) demonstrated when studying a site located near the mouth of the Igarape Taruma Mirim on the Rio Negro 25 km west of Manaus. The site is characterised by white-sand podzol of high quartz content, high porosity, and low cation-retention capacity. Due to the tropical rains and the flooding, the soil is highly leached and must be considered an extremely oligotrophic environment. Keel and Prance (1979) surveyed 12 randomly chosen plots of 150 m<sup>2</sup> each and five transects. This proved sufficient to reach the plateau of the species-area curve. They describe the site as a low, open to closed one-story forest consisting of shrubs 2-5 m high as the main life-form. Most species are represented by few individuals. However, dominance existed with the leading dominant species being Myrciaria dubia and the subdominant species being Pithecellobium adiantifolium, Eugenia cachoeirensis, and Eugenia chrysobalanoides. They observed the following zonation of species according to flood duration:

metre a.s.l.	dominant species
22.45-23.25	<u>Myrciaria dubia</u>
23.25-24.35	<u>Myrciaria dubia</u> <u>Pithecellobium adiantifolium</u>

24.35-25.25	<u>Schistostemon macrophyllum</u> <u>Eugenia chrysobalanoides</u>
25.25-26.25	<u>Eugenia cachoeirensis</u>
26.25-27.65	<u>Pera distichophylla</u> <u>Eugenia cf. patrisii</u>

The transects Keel and Prance (1979) analysed, covered predominantly sandy areas exposed in the dry season. They noted the existence of permanently waterlogged areas with sparse vegetation stretching out from the shore into the water. The most frequent species in such areas were:

Eugenia inundata  
Sphinctanthus strullorus  
Securidaca longifolia

(Keel and Prance 1979)

#### **3.3.1.4 Anthropogenic influences on plant succession**

The soils of blackwater floodplains represent an extremely oligotrophic environment. Consequently, blackwater floodplains have traditionally been used little for agriculture. Only recently has deforestation for settlements on nearby terra firme areas begun to affect blackwater floodplains in the Manáus region.

#### **3.3.2. Vegetation formations of blackwater floodplains**

Only a limited number of studies on the floristic composition of the vegetation of blackwater floodplains in the Manáus region have been identified (dos Santos et al. 1983; Keel and Prance 1979; Revilla 1981; Worbes 1985, 1983). These studies confirm that the key environmental factors determining the distribution of vegetation in the blackwater floodplain are the duration of flooding and soil characteristics. Due to the general nutrient deficiency of both water and soils, slight variations in soil characteristics may exert a pronounced influence on the floristic composition and physiognomy of the vegetation. Trees and shrubs tend to be low and tortuous,

especially on sandy soils. Many species of trees and shrubs are endemic. However, some igapo species also grow in seasonal várzea forest (Prance 1979). Generally, the igapo vegetation is less diverse than the seasonal várzea vegetation of whitewater rivers. The forest usually has a lower biomass than seasonal várzea forest, which has been associated with the lack of nutrients (Prance 1989).

The blackwater floodplains in the immediate vicinity of Manaus are rather narrow compared to the whitewater floodplains of the Rio Solimões. Most vegetation formations occupy only small patches. Exceptions to this rule represent some Quaternary deposits of whitewater sediments which were formed when the confluence of the Rio Solimões and the Rio Negro was about 75 kilometres westward of its present location (personal communication Bruce Nelson, 1991). The Anavilhanas archipelago in the Rio Negro (about 100-200 kilometres northwest of Manaus) has been formed from sediments of the Rio Branco, is however not included in the project region.

#### **3.3.2.1. Grassland**

Seasonally floodable<sup>3</sup> savannah is rare in the blackwater floodplains of the Manaus region. One area which has been strongly degraded in recent years is situated near Cacao Pireira on the southern shore of the lower Rio Negro. Seasonally floodable savannah tends to occupy high-lying ground that undergoes short to very short flooding. Some scattered palms may be present. The vegetation is very dry, sparse, and of yellowish colour, with the soil being visible in August (dry season).

#### **3.3.2.2. Shrub vegetation of sand dunes**

(riverine but not subject to seasonal inundation)

Revilla (1981) has described this vegetation community as typical of the highest, non-flooded parts of sand dunes. The vegetation is sparse, discontinuous, species-poor, and does not exceed 10 m in height. Some areas remain open and resemble the campina vegetation of terra firme areas. The following list indicates the floristic composition at Praia Grande:

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<sup>3</sup> 'Floodable' means that the area is subject to seasonal inundation.



lower stratum:	<u>Ananas ananassoides</u>
	<u>Borreria capitata</u>
middle stratum: 3-5 m	<u>Xylopia aromatica</u>
	<u>Palicourea nitida</u>
5-10 m	<u>Pagamea coriacea</u>
	<u>Humiria balsamifera</u>
	<u>Byrsonima chrysophylla</u>

(Revilla 1981)

No areas of sand dunes are known to occur in the project region.

### 3.3.2.3. Aningal

This formation is found in places which undergo seasonal flooding for prolonged periods but are not exposed to strong water currents. The vegetation is predominantly herbaceous with dense patches consisting almost entirely of Montrichardia arborescens (3-5 m height). The subdominant species is Ferdinandusa rudgeoides.

No areas of aningal are known to occur in blackwater floodplains of the project region. However, they do occur near Praia Grande.

### 3.3.2.4. Shrubs and low open forest

'lower igapo' (Adis 1984)

The vegetation of river banks changes from low shrubs on the lowest-lying areas to low forest (5-10 metres high) on terrain undergoing long to intermediate flooding. In the August imagery most of the vegetation formation is still largely flooded. For information on the floristic composition see above.

#### **3.3.2.5. Closed forest**

**Photos:** 3.16, 3.17

'upper igapo' (Adis 1984)

'mata de igapo' (local name)

Seasonal igapo forest grows on argillic or sandy clay soils with a distinct humus layer. The forest is characterised by the almost entire absence of shrubs and herbs. Buttressed trees are common. The upper canopy is almost closed and is colonised by numerous epiphytes. With increasing elevation, the vegetation gradually turns into a forest with trees reaching 35 m in height. Inundation typically lasts 5-6 months with depths up to 5 m (Adis 1984).

Very few vegetation surveys of this formation have been published. Table 3.9 summarises information on characteristic tree species given by Adis (1984), Worbes (1985, 1983), and Revilla (1981). Only frequently occurring species and those trees forming the upper canopy have been included.

#### **3.3.2.6. Disturbed forest**

Some strongly degraded forest is found in the vicinity of Cacao Pireira. No information on the floristic composition of disturbed sites has been found.

### **3.4. Vegetation of terra firme areas**

#### **3.4.1. Factors determining the spatial distribution of vegetation formations in terra firme regions**

The distribution of vegetation formations in terra firme regions depends largely on soil properties and the hydrological conditions of a site. Plateaux characterised by well-drained clay-rich latosols tend to support the forest of the highest biomass and the highest diversity. The forest is tall (30-40 metres) with emergents and gaps indicating the climax stage of succession. Where the soils assume a more sandy nature, biomass and diversity are reduced. A similar tendency can be observed for sites with only moderate drainage, as are typically encountered on valley bottoms or

on the irregularly flooded plains of small streams. Changes in structure and floristic composition occur gradually, thereby making it difficult to define exact boundaries between vegetation formations. The following paragraphs will expand these rather general observations.

#### **3.4.1.1 Relationship between topography, soil, and vegetation in areas of predominantly argillic soils**

Chauvel et al. (1987) report on a project investigating the genesis of the soil mantle of the Barreiras sediments in the region of Manaus. They analysed soil-topography-vegetation relationships at the forestry experimental station of INPA<sup>4</sup>, about 60 km north of Manaus (for location see Figure 3.1). Using air photo interpretation, they showed that between plateaux and valley bottoms there are often intermediate surfaces which are slightly inclined towards the axis of the valley and which end in a short, sharp slope. These intermediate surfaces are longer and less inclined towards the downstream end of valleys, as can be seen in Figure 3.7.

The topographic profile closely corresponds to different soil types, with yellow clayey latosol ('latossolos amarelos alicos, textura argilosa') on the plateaux, eluviated soils ('podzolicos vermelho-amarelo latossolicos') on the upper and middle slopes, and podzols ('podzol alico') at the lower parts of the intermediate surfaces (for a detailed description of the profiles refer to Chauvel et al. 1987).

Chauvel et al. (1987) concluded that the observed sequences constitute a 'transformation system' in which the latosol is progressively replaced by podzol. Parallel to the changes in soil properties, a pronounced change in the vegetation was observed. Whereas the plateaux are covered by tall terra firme forest, the vegetation becomes progressively sparser downslope, and passes from dense forest to campinarana forest and then to open campina vegetation. Finally, only bushes and lichens survive on the white sands.

#### **3.4.1.2 Relationship between soil and vegetation in areas of white sand soils**

Amazon caatinga vegetation (see below) is limited to soils composed entirely of white sand. Where the sands grade into soils containing even a small percentage (< 5

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<sup>4</sup> INPA is the Brazilian national Amazon research institute, located in Manaus.

%) of clay within the reach of roots, caatinga gives way to other vegetation types. The low and tortuous growth of many caatinga shrubs and trees reflects the extreme edaphic stress of this habitat which is characterised by a severe lack of plant nutrients and periodic water deficiencies in the sandy soils (Anderson 1981). The soils have an exceptionally low cation exchange capacity. According to Anderson (1981), the oligotrophic nature of caatinga soils is largely due to their origins, which may include: (1) in situ weathering of sandstones, quartzites, or granites, (2) alluvial deposition of quartz sands originating from the Guyana and Brazilian Shields, and (3) podzolization due to a fluctuating water table which leaches organic matter and clay constituents ('sesquioxides') from the upper profile, leaving behind degraded sand (compare also Chauvel et al. 1987).

The exceptionally low cation retention capacity of white-sand soils causes specific adaptations of the vegetation for nutrient retention and nutrient cycling. Thick accumulations of slowly decomposing litter provide a substrate for the development of a dense root mat (10-30 cm) which hardly penetrates the mineral soil. These root mats may comprise over 60 % of the total biomass (Anderson 1981). Within the root mat, mycorrhizae are exceptionally abundant. Excessive drainage through the highly porous sandy soils may result in water stress during periods of reduced precipitation.

#### **3.4.2. Vegetation formations of terra firme regions**

Most of the floristic surveys of the Manáus region described in the literature have been carried out north of the Rio Negro. This may be due to the fact that Manáus and also most of the ecological reserves of research institutions based at Manáus (e.g. INPA) are situated north of Manáus. As a result, very little information on the floristic composition of forests south of the Rio Solimões is available in the literature. Given the dominance of two different geological formations north (Barreiras Formation) and south (Solimões Formation) of Manáus, it is possible that differences in the floristic composition exist, assuming a close parent geology - soil - plant association. For lack of data, however, this can not be substantiated at present.

### 3.4.2.1. Tall terra firme forest on plateaux

#### Photo: 3.18

This forest type is typically found on plateaux and gentle slopes of the Barreiras and Solimões formations. The soils are yellow clayey latosols (Brazilian soil classification: 'latossolos amarelos alícos, textura argilosa'). Where the soils assume a more sandy nature, biomass and diversity are reduced. Even though this forest type is frequently called 'evergreen', there is a considerable element of top-canopy semi-deciduous and deciduous trees. Guillaumet (1987) reports that of 47 tree species with known phenology, 29 were evergreen, 16 semi-deciduous (losing most but not all of their foliage periodically) and six fully deciduous.

Guillaumet (1987) regards palms as possibly the most characteristic feature of the terra firme forest north of Manaus. In a survey of the palm vegetation of terra firme at the tropical silviculture experimental station of INPA, Kahn and de Castro (1985) found that no palms reached the upper canopy on well drained soils (no palm species exceeded 15 m in height). However, the understory of the forest was dominated to a height of 5 m by the leaves of two acaulescent species:

Astrocaryum sociale

Attalea attaleoides

Terra firme forests north of Manaus are comparatively poor in climbers but are particularly rich in stranglers, epiphytes, and semi-parasites, both in terms of species and individuals. As is generally the case for the moist evergreen forest of the tropics, the forests of central Amazonia have a poorly developed herbaceous layer, which is mainly a consequence of low light intensity at the ground level (Guillaumet 1987). A typical element of well developed primary terra firme forest is its structural division into different canopy layers.

The diversity of tree species is particularly rich. Prance et al. (1976) found 235 tree species of dbh > 5 cm on one hectare. Jardim and Hosokawa (1986/87) found 324 tree species on 8 ha when surveying only trees of dbh > 20 cm. Even though they surveyed 8 ha, the species-area curve did not reach its asymptote, demonstrating the very high species diversity in the region. However, the 50 most abundant species

accounted for 66 % of all trees, and the 50 dominant species represented 68 % of the basal area. Table 3.10 summarises those tree species that were found to be abundant, dominant, or formed the upper canopy in the surveys reported by Guillaumet (1987), Jardim and Hosokawa (1986/87), Prance et al. (1976), and dos Santos et al. (1983). A further extensive survey undertaken by Higuchi et al. (1985) has not been included because, unfortunately, Higuchi et al. based their survey on local tree names which on a number of occasions included several botanical species under common Brazilian names.

While this comparison of the forest surveys confirms that most tree species found to be abundant or dominant on one site did not figure dominantly in other surveys, it appears that Eschweilera odora may be regarded as the character species of this forest type north of Manaus.

#### **3.4.2.2. Forest on alluvial soils of river floodplains**

'buritizal' (local name)

'mata-de-baixio' (Porto et al. 1976)

'swamp forest' (Guillaumet 1987)

'floodplain forest' (Prance 1979)

'aseasonal wetland forest' (Klinge et al. 1990)

This formation grows on the floodplains of small creeks which are flash-flooded by irregular rainfall at any time of the year rather than by regular seasonal flooding by large rivers. The soils are typically of a hydromorphic nature. Species composition strongly depends on the periodicity and the duration of flooding and, consequently, the hydromorphic condition of the soil. Where flooding tends to be of short duration, various species characteristic of terra firme forest on plateaux may also occur (Prance 1979). Tree height does not normally exceed 30 m, the 'upper canopy' being formed by palms and large trees of 12-25 m, sometimes 30 m. The basal area appears to be lower than in the forest of the plateaux (Guillaumet 1987). Buttresses and stilt roots are common. In this forest type, the trees do not form clearly discernible strata. The canopy is comparatively open so that much more light reaches the ground than in terra firme forest on plateaux, allowing a herbaceous layer and numerous epiphytes to develop (Takeuchi 1961a). Higher light levels in the lower strata also favour the growth of arborescent palms which do not reach the upper canopy in forest on well-



drained clayey soils of the plateaux (Kahn and de Castro 1985). The palm species increase in number per area as the width of the valley and the water content of the soil increase (Guillaumet 1987). At a survey of the palm vegetation at the Tropical Silviculture Experimental Station of INPA, Kahn and de Castro (1985) noted that arborescent palms were an important component of the forest canopy on poorly drained and waterlogged soils. They found with high frequency the following species with heights of 20-30 m:

Mauritia flexuosa

Mauritia aculeata

Jessenia bataua

Euterpe precatoria

(Kahn and de Castro 1985)

Porto et al. (1976) surveyed one hectare of 'mata-de-baixio' at the igarape Guarana (Estacao Experimental de Silvicultura do INPA). All trees with dbh > 5 cm were recorded on 20 % of the area, and trees with dbh > 30 cm were recorded on 50 % of the area. They concluded that the area surveyed was sufficiently large to reach the asymptote of the species-area curve. This indicates that the diversity of trees is significantly lower than for forest on well-drained plateaux. Within the area studied, species showed preferences for certain habitats, depending mainly on soil hydrological conditions. Whereas Mauritia flexuosa was found only in the wettest parts, Eschweileira odora was encountered almost exclusively in drier terrain. The canopy did not exhibit a clear stratification. Among 500 trees with DBH > 5 cm, 114 species were identified. Of these, four species accounted for almost 30 % of the total number of individuals:

Carapa guianensis

Vitex sprucei

Euterpe precatoria

Jessenia bataua

These, together with seven further species, constituted more than 50 % of the population:



Chromolucuma rubriflora

Eschweileira odora

Mabea caudata

Xylopia amazonica

Licania micrantha

Iryanthera macrophylla

Iryanthera elliptica

### **3.4.2.3. Hydromorphic campinarana forest**

No references to this forest type could be identified in the literature. It appears as distinct areas with low internal variance (indicating a smooth canopy with neither tall emergents nor large gaps) on Landsat TM imagery and is situated along the middle and lower courses of some rivers (e.g. Igarape Taruma Mirim; personal communication Ghilleen Prance, 1993). According to Bruce Nelson (personal communication 1991), it represents tall forest growing on waterlogged, highly organic soils consisting of sediments that have filled old riverbeds. During overflights, the presence of a tall forest with a smooth canopy could be confirmed (northwest of Igarape Taruma Mirim). However, no clear separation between this type of forest and tall terra firme forest on plateaux could be observed during overflights, even though the two types are spectrally distinct on TM imagery (near-IR: bands 4 and 5).

Figure 3.8 shows the Landsat TM RGB composite of an area of terra firme vegetation on sediments of the Barreiras formation, 20 kilometres west of Manaus. Tall forest on plateaux (Class 3.1) appears in green with a grainy texture. Hydromorphic campinarana forest (Class 3.3) appears in a bluish-green tone. The forest in depressions appears in a colour intermediate between the two previous classes. Forest on the alluvial soils of river floodplains (Class 3.2) appears distinctly in red.

#### 3.4.2.4. White-sand vegetation

'Amazonian caatinga'  
'campinarana'  
'campina'

White-sand vegetation occurs throughout the Amazon region. In the vicinity of Manaus it tends to occupy small (normally much smaller than 50-100 ha) and disjunct areas. However, in the upper Rio Negro and Rio Branco basins of north-western Amazonia, white-sand vegetation covers hundreds of thousands of square kilometres (Anderson 1981).

Within the Amazon region, different names are in use for this vegetation association. Guillaumet (1987) divides white-sand vegetation into (1) campina, and (2) campinarana. 'Campina' refers to open white-sand vegetation and areas with scattered clumps of shrubs and small trees, whereas 'campinarana' denotes a low, relatively light forest with thin-stemmed trees of 10-20 m height. Anderson (1981, 1978) suggests the term 'Amazon caatinga', including the entire continuum from open white sand areas to mostly closed forest on white-sand soils. He then subdivides 'Amazon caatinga' into four physiognomic types or 'structural phases':

##### (1) Caatinga savannah:

This phase is dominated by lichens and graminoids, which generally form a sparse cover over the bare sand. Occasional clusters of woody plants may be present, but they constitute a cover of less than 10 %.

##### (2) Caatinga scrub:

This phase is characterised by open areas of bare sand and herbaceous plants, intermixed with shrubs and small trees up to approximately 7 m tall. The latter may form distinctive clumps or be distributed singly, forming up to 90 % cover.

(3) Caatinga woodland:

This phase has a more or less continuous cover of shrubs and trees. The canopy is often patchy and variable in height, ranging from approximately 5 to 15 m, with occasional emergents to 20 m. Trees tend to be tortuous with a pronounced horizontal branching structure. The horizontal branches are covered with a heavy epiphyte load (personal communication G. Prance, 1994). Light penetration is high, permitting the presence of a dense understory of shrubs and small trees with thin trunks.

(4) Caatinga forest:

Here the canopy, which reaches heights of 20 m to almost 30 m, is generally uniform and continuous. Lower strata tend to form a patchy cover, which permits relatively high light penetration.

(Anderson 1981)

Types (1) and (2) may be regarded as 'campina', and types (3) and (4) as 'campinarana', in the sense of Guillaumet (1987).

All of the above types are more or less reduced in biomass and have relatively high light penetration. Features typical of tropical rain forest - such as drip-tips, tree buttresses, vines and big woody climbers - are relatively infrequent or absent. Epiphytic orchids, bromeliads, and bryophytes are often abundant and high in diversity (Anderson 1981).

The physiognomy of shrubs and trees shows many characteristics that suggest physiological stress. Shrubs and small trees typically have a 'dwarfed and rachitic' aspect, with reduced quantities of foliage, thin branches, and small crowns. The woody vegetation is sclerophyllous, with small, shiny leaves. Virtually all species are evergreen (Anderson 1981).

Caatinga vegetation is characterised by low diversity and a high degree of endemism. Due to the high incidence of endemic species, the floristic composition varies considerably from one region to another. However, a number of species exclusive to

caatinga have wide geographic ranges and may be taken as indicators of this vegetation over large areas of Amazonia (Anderson 1981). Examples include: Cephalostelon gracile, a herb common on humid sites in eastern Amazonia; Gaylussacia amazonica, a low shrub widespread throughout eastern and central Amazonia; Glycoxylon inophyllum and Pagamea duckei, shrubs or small trees often dominant on caatinga sites in central Amazonia (north of Manáus); Mauritia carana, a large palm characteristic of hydromorphic white-sands throughout the Rio Negro basin; Lissocarpa benthami, Hevea pauciflora var. coriacea, and Ladenbergia amazonensis, tree species typical of caatinga sites in western Amazonia (Ducke and Black 1953). A detailed floristic analysis of campina and campinarana vegetation north of Manáus is given in Anderson (1978).

As Anderson (1981) notes, plant communities in the caatinga have a comparatively reduced species richness, with a pronounced tendency towards dominance by one or a few species. White-sand vegetation in the vicinity of Manáus occurs in comparatively small patches.

#### **3.4.2.5. Secondary vegetation**

##### **(a) Secondary vegetation on argillic soils**

**Photos:** 3.19, 3.20

Since the declaration of the free trade zone of Manáus in 1967, much forest has been cleared in the Manáus region for pasture development, agriculture, charcoal production, timber extraction, brick burning and other purposes. Many of the originally cleared areas have been abandoned since, making 'secondary vegetation' one of the major land use types in the region. Little, however, has been published on the floristic composition and succession of secondary vegetation in the Manáus region, nor on the impact that different types of forest clearing and land utilisation have had on the floristic composition and temporal succession of secondary vegetation.

De Albuquerque (1980) reports a study on the floristic composition of young (18-20 months) secondary vegetation, located in the EMBRAPA research fields at km 31 of the Torquato-Tapajos road (3°8'S, 59°52'W). The soils were characterised as yellow

latosols (argillic texture, very deep, strongly leached, very acidic: pH 4.5). Trees of the original vegetation of this site included:

- Eschweileira odora
- Goupia glabra
- Holopyxidium jarana
- Pogonophora schomburgkiana
- Swartzia corrugata
- Peltogyne catingae
- Pithecellobium racemosum
- Caryocar villosum
- Pouteria guianensis
- Brosimum rubescens
- Aspidospermum oblongum

(de Albuquerque 1980)

During the 18-20 months available for regeneration, several of the colonising tree species reached a height of more than 6 m:

	rel. abundance
<u>Cecropia leucocoma</u>	6.79 %
<u>Cecropia purpurascens</u>	0.79 %
<u>Cecropia sciadophylla</u>	1.02 %
<u>Vismia guianensis</u>	5.46 %
<u>Vismia cayenensis</u>	2.26 %

These five species formed the 'upper canopy' 18 months after clearing. A large number of other species were found in areas still remaining open or in the lower strata (for details see de Albuquerque 1980).

Field work in the region between Cacao Pireira and Manacapuru showed that some cleared areas were covered by dense herbaceous vegetation, consisting largely of ferns. The regrowth of weeds and later of shrubs and trees involves a gradual change of a canopy dominated by herbaceous plants to a canopy formed by woody

vegetation.

According to Rita Mesquita (personal communication 1991), who has investigated the composition of secondary regrowth in the SUFRAMA ranching area north of Manaus, the floristic composition depends critically on clearing methods, especially burning practices, and utilisation history. Stands which had been cut in 1983, but were never burnt nor had pasture planted, typically showed a closed, very smooth, canopy of almost pure stands of Cecropia sciadophylla (August 1991, 8 years old). Areas that had been subjected to single or even repeated burning and had pasture planted, showed various species of Vismia and Bellucia (age about 4 years after end of utilisation as pasture). Cecropia was almost absent from such stands. These observations could be confirmed by Lucas and Honzak during a field campaign north of Manaus in 1993 (personal communication Richard Lucas, 1994).

#### **(b) Secondary vegetation on white-sand soils**

Many areas of white-sand vegetation north of Manaus have been destroyed by development over the past decades. Because an exceptionally high percentage of the nutrients is stored in the above ground biomass, i.e. the dense root mat, burning causes particularly high nutrient loss, the nutrient retention capacity of white-sand soils being very low (Anderson 1981). Anderson (1978) lists the following species as typical of secondary vegetation on white-sand soils:

Byrsonima chrysophylla

Cecropia concolor

Pteridium aquilinum

Solanum grandiflorum

Vismia spp.

Certain elements typical of the original vegetation are missing entirely, such as lichens, orchids, bromeliads, and bryophytes. The recolonization of former campina and campinarana sites by their original flora is difficult due to the island type distribution of the habitat and the extremely nutrient- impoverished state of the soils after burning. Prance and Schubart (1978) radio-carbon-dated charcoal and ceramic shards found at various caatinga sites in Central Amazonia. They found that the vegetation at those sites had been burnt 800-1100 years ago and concluded that open

white-sand vegetation in the central Amazon in some circumstances results from anthropogenic burning, with recolonization effectively being prevented by the environmental conditions of the habitat caused by the burning.

#### **3.4.2.6. Grassland**

##### **(a) Natural savannah**

Natural savannah occurs on a small number of sites in the region of Manáus. An example of natural savannah is the 'Savanna de Amelia' upstream of Manáus on the southern shore of the Rio Negro (outside the project region). Another, relatively degraded, area of natural savannah is situated near Cacao Pireira (personal communication Bruce Nelson 1991; personal communication Ghilleen Prance 1994). No reference to the floristic composition could be identified in the literature.

##### **(b) Pasture**

**Photos:** 3.19, 3.20

Pasture is covering an ever-increasing area of terra firme in the Manáus region. Especially north of Manáus in the SUFRAMA ranching area, between Manáus and Manacapuru, along the Manáus-Itacoatiara road, and along the Manáus - Porto Velho highway this land use is seen with much frequency. As soils are generally poor, stocking rates tend to be low. Weed invasion occurs within a few years after the initial clearing and burning. Farmers then reburn pastures in order to control weed invasion and the establishment of secondary forest. This practice causes the impoverishment of soils in nutrients, seeds, and also vegetative cover, ultimately leading to severe soil erosion, especially on slopes. The comparison of Landsat data from 1977, 1988, 1991, and ERS-1 SAR data of 1992/93 shows that most of the clearing in the Manáus region occurred between 1977 and 1988 (Corves, unpublished results).



### **3.5. Summary of results and conclusions**

#### **(1) The vegetation classification system**

The analysis presented in chapters 2 and 3 classifies the vegetation of the Manáus region, using geo-ecological, physiognomic, and local environmental information. The vegetation formations derived from these parameters are characterised by their floristic composition. The Manáus region shows environmental conditions and vegetation formations that are typical of the lowland Amazon environment. It is hoped that the vegetation classification system proposed in this study for use in satellite-based vegetation mapping is applicable in a wider region. An indication that this is the case is that the vegetation formations defined for whitewater floodplains are largely equivalent to the ones used by Kalliola et al. (1991) for mapping the swamp vegetation of the Peruvian Amazon from Landsat TM and MSS data.

#### **(2) Vegetation formations**

The vegetation formations and their key ecological and structural characteristics are shown in Table 3.11. Table 3.12 lists those species that can be regarded as characteristic of vegetation formations in the Manáus region for those formations where such species could be identified.

#### **(3) Floristic data**

The study has shown that considerable gaps still exist in our knowledge of the vegetation around Manáus, which is one of the better surveyed areas of the Amazon. While some vegetation formations, in particular well developed forest with harvestable timber on terra firme and on the higher levels of the whitewater floodplains, have been described repeatedly, other formations have received little attention to date. This is particularly true for vegetation on sites that remain in swampy conditions throughout much of the year.

The use of published surveys was the only feasible approach of obtaining floristic information, given the large variety of vegetation formations, the size of the project region, and the time and resources available for this study.

Certain problems were, however, related to this approach. Many surveys do not give the exact location of the survey site in map coordinates; neither is information provided on the exact sample size and sampling methodology in all publications. For use with remote sensing studies it would be useful to have more specific information on the floristic composition of the upper canopy layer.

#### (4) Dominance

It has been frequently stated that in humid tropical vegetation the diversity of woody species is so high that dominance of individual species does not exist. The floristic data assessed for the Manáus region allow a different interpretation. Most surveys have looked at well developed forest on terra firme or on the higher levels of the floodplains. These are the vegetation formations with the highest diversity and, consequently, low dominance of individual species. Many other vegetation types do exist, and the diversity of trees and shrubs in these formations appears to be much lower than in well developed forest. The following environmental factors, that affect a substantial proportion of areas around Manáus, appear to cause lower diversity and enhance dominance in the vegetation:

- \* seasonal deficiency of water in the soil
- \* seasonal excess of water in the soil
- \* prolonged periods of flooding
- \* soil nutrient deficiency, low cation exchange capacity
- \* areas affected by human intervention

If the analysis of floristic data is restricted to the upper canopy, this being largely responsible for the reflectance detected by visible/infrared (and C-band radar) sensors, the number of tree species under consideration is significantly reduced. The (admittedly scarce) data available suggest that even in the floristically most diverse formations the number of tree species forming the upper canopy is comparably low if compared with total tree diversity. Unfortunately, many of the published floristic surveys do not provide information as to which species form the different canopy levels. Concentrating on the trees that form the upper canopy layer might prove an efficient way of

characterising and subdividing forest formations that have been defined using physiognomic and environmental information.

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#### **4. Assessment and correction of radiometric distortions in system-corrected Landsat TM data**

Chapters 2 and 3 have described and analysed relationships between environment and vegetation in the Manáus region. A classification system for mapping the vegetation formations of the Manáus region from current high spatial resolution satellite data has been suggested. Based on this system, the vegetation formations of the Manáus region have been defined and described in detail.

The Landsat TM data of 8 August 1991 were the key dataset for mapping the vegetation of the Manáus region. It has been pointed out in chapter 1 that the accuracy of digital land cover classifications depends to a large extent on the radiometric quality of the data. Residual radiometric distortions, should they exist to any significant extent, need to be corrected before the classification of the data.

This chapter describes the assessment and correction of radiometric distortions encountered in the 8 August 1991 TM data.

Section 4.1 provides information on field work carried out in the Manáus region and the satellite datasets used in chapters 4-6.

Section 4.2 reports the results of a rapid visual assessment of radiometric distortions in the 8 August 91 TM data. Pronounced view angle dependent radiometric distortions (VADRD) and detector-related banding and striping were identified as the major types of distortions. Such residual distortions, if left uncorrected, seriously degrade the accuracy of land cover maps produced by use of digital classification techniques (chapter 6). However, standard image processing software, such as ERDAS, does not provide tools to remove the distortions encountered. Therefore, software had to be developed that can accomplish a reduction of these distortions (VADRD).

Section 4.3 describes the quantitative assessment and correction of view angle dependent radiometric distortions.

Section 4.4 describes the quantitative assessment and correction of level shift banding (lsb) and 16 line striping (16 ls).

## **4.1 Data and field work**

### **4.1.1 Data**

#### **4.1.1.1 Landsat Thematic Mapper (TM)**

The Landsat TM data were acquired at 'system-correction' level from the Brazilian Space Agency INPE<sup>1</sup>. System-corrected data have been geometrically corrected in the along scan direction for the effects of detector placement and delays, mirror scan profile, forward-reverse scan alignment, and line length variation (according to leader file specifications). The data have not been corrected for view angle dependent geometric distortions, Earth curvature effects, or skew. This correction level was the only product type that could be obtained from the Brazilian Space Agency INPE in December 1991. Table 4.1 shows which satellite data have been available for this study.

#### **4.1.1.2 Landsat Multispectral Scanner (MSS)**

Landsat-3 Multispectral Scanner data (path: 248, row: 62, date: 31-7-77) were acquired at system correction level (no correction of view angle dependent geometric distortions, Earth curvature effects, or skew).

#### **4.1.1.3 ERS-1 SAR**

ERS-1 SAR data were obtained at PRI ('precision image') pre-processing level. The precision image is a 3-look (speckle reduced), ground range, system-corrected image. The product is calibrated and corrected for the SAR antenna pattern and range-spreading loss. Radar backscatter ( $\sigma^0$ ) can be derived from the product, but no correction is applied for terrain-induced radiometric effects. The image is not geocoded, and terrain distortion (layover) has not been removed. The nominal spatial resolution is less than 33 metres in ground range, and less than 30 metres in azimuth (ESA, 1993).

---

<sup>1</sup> INPE is the Brazilian national space research institution.

#### **4.1.1.4 Reference maps**

The largest scale topographic maps available for large parts of the Brazilian Amazon are of 1:100,000 scale. The maps have been produced by the Brazilian Military Mapping Agency (DSG: Diretoria de Servico Geografico) based primarily on air photo surveys flown in the 1970s and 1980s. The map accuracy is specified to be 100 metres even though the printing accuracy has been found to be more limited for some of the map sheets: on map sheet MI-517 'Igarape Coana' the 'elementos de vegetacao' (vegetation) are printed more than 2 mm (200 m in the field) out of position in north-south direction. Comparison with the TM data showed that individual map sheets vary considerably in terms of their generalisation up to the point that no ground control points for georeferencing satellite data could be identified on some sheets.

#### **4.1.2 Field work**

Field work was carried out from July to September 1991. This period coincided with the dry season and the period of high water levels in the Manaus region. The dry season was selected because verification of the availability of Landsat data from previous years had shown that cloud free data were likely to be acquired only in July or August and it was planned to acquire air photography concurrent with a Landsat overpass. This was considered of high importance because the water levels of the Rio Negro and the Rio Solimões can fall with a rate of up to 30 cm per day in August, thereby possibly leading to drastic changes of the flooding conditions in the flood plains over the course of a few days.

The dates of Landsat overpass were obtained in advance and a plane was hired for the two days with the highest likelihood of cloud free imagery to be acquired. Overflights were carried out between 8.30 am and 10.30 am in order to coincide with the sun elevation at image acquisition. This enabled a qualitative assessment of how the canopy gap structure affects the distribution of canopy components in light and shadow for the different vegetation types.

The overflights were carried out with a small 'Carioca' plane. The door was removed such that photography could be acquired without being degraded by windows. The course of the flights was arranged according to the reliability maps described in chapter 5 in order to visit areas marked with the lowest reliability on the preliminary



1988 land cover maps with preference. The flight time had to be limited to 2 hours on each day because of the high cost of hiring a plane (US\$ 230 per hour in August 1991). This allowed the plane to venture about 100 km from the airport.

35 mm photography and S-VHS video material were acquired during the overflights. The latter proved most valuable for reconstructing the path of the plane over areas lacking easily identifiable land marks such as rivers or roads. In order to acquire photographs of the vegetation it proved useful to have the sun in the back (avoid atmospheric haze and reflections). Most vegetation types (except closed forest) allowed sub-canopy flooding to be detected by reflections of the sun on the water surface shining through the vegetation, preferably when viewing towards the sun.

The main objective of the field work was a reconnaissance level survey of vegetation and land use. The field survey consisted of qualitative observations on vegetation structure, estimates of the height of the upper canopy, and observations on hydrologic conditions of the site. The information on vegetation and site conditions was integrated with a review of published floristic surveys from the Manáus region. This enabled the comprehensive classification of the major vegetation formations of the Manáus region described in chapter 3.

## **4.2 Visual assessment of radiometric distortions in system-corrected Landsat TM data**

The Landsat TM data of 8 August 1991 formed the basis for mapping the vegetation through a spectrally based digital classification approach. Residual radiometric distortions present in the data after system correction has been performed by the receiving station cause a reduction of the spectral separability of land cover types (section 6.2). This in turn, constitutes one of the major sources of thematic error in digital classifications. Therefore, the reduction of residual radiometric distortions is of great importance in order to achieve a high thematic reliability.

### **4.2.1 Relative calibration versus absolute calibration of satellite data**

The type of radiometric calibration that is required in a mapping project depends on the nature of the information to be extracted from the remotely sensed data. Radiometric calibration may be broadly divided into two categories depending on the intended use of the data:

#### **(a) Relative calibration**

Intended use: Relative comparison of spectral data in one image. No quantitative comparison with other images. No quantitative measurement of physical parameters on the Earth's surface. This is commonly the situation in satellite-based land cover mapping.

Level of calibration required: The data need to be made internally consistent ('relative calibration'). This means that the digital count values in the image should depend only on the land cover type on the ground. Any other factor besides land cover that changes the radiance recorded in the satellite image is regarded as a radiometric distortion. This includes the following factors:

- \* Distortions arising from atmospheric effects.
- \* Distortions arising from the sensor.
- \* Distortions arising from sun-sensor geometry.
- \* Distortions arising from the terrain.
- \* Distortions arising from the target BRDF.

(b) Absolute calibration

Intended use: Quantitative comparison of radiance values with those of other images or quantitative measurement of physical parameters on the Earth surface.

Level of calibration required: The data (a) need to be made internally consistent and (b) need to be calibrated to physical radiance values ('absolute calibration').

The current study dealt with the classification of mono-temporal Landsat TM data into land cover types. Therefore, relative calibration but not absolute calibration of the data was required.

#### **4.2.2 Visual assessment of the 8 August 1991 TM data**

In order to make an initial assessment of the types of radiometric distortions that were dominant in the data, a visual inspection was carried out. This included both the assessment of the entire bands displayed individually on the monitor, as well as the evaluation of suitably contrast-stretched extracts of homogeneous ground cover, such as areas of water or forest.

Two definitions will be used throughout the following discussion of instrument-related radiometric distortions: 'Striping' refers to regular variations in average line brightness which are repeated at a frequency of 16 lines, the number of detectors in one scan of the TM sensor. 'Banding' refers to variations in brightness that affect entire scans, i.e. multiples of 16 lines. Banding in TM data normally takes two forms: forward-reverse scan banding (repeat frequency of 2 scans or 32 lines) and level shift banding which affects random multiples of 16 lines.

Figure 4.1 shows bands 1-5 and 7 for the entire image. The visual assessment suggested that the following types of radiometric distortions were most prominent in the 8-8-91 Landsat TM image:

- (a) View angle dependent radiometric distortions (VADRD) were found to exist in bands 1, 2, 3 and, to a lesser extent, also in bands 5 and 7. The brightness

of the image increases in scan direction from the eastern side to the western side of the image.

- (b) Scan correlated shifts in brightness (level shift banding) were found to be pronounced in bands 2 and 3.

Level shift banding is due to an effect which raises or lowers the signal of all pixels in a scan or a set of scans. The changes are aperiodic and occur at random intervals. The signal level is shifting during the mirror turn-around time. Murphy et al. note that "the magnitude of the shift from line to line depends on the particular detector, but if a shift is present for one detector, then a shift is present for all detectors for all bands" (Murphy et al. 1985). Level shift banding affects Landsat-4 and Landsat-5 data in different ways (Kieffer et al. 1985). Metzler and Malila concluded that "the magnitude of these shifts and the large number of scenes in which they occur places a high value on the correction of the effect for some applications" (Metzler and Malila 1985).

- (c) 16 line striping was found to be pronounced in band 1, but also existed to lesser degrees in the other bands.

16 line striping results from the fact that the individual detector-amplifier systems of the TM sensor show slightly different gains and offsets which also change throughout the lifetime of the satellite. The periodicity of 16 results from the fact that each scan of the TM sensor comprises 16 scan lines which are sampled by 16 independent detectors.

- (d) Variations in target reflectance due to topographic relief:

Several extracts of terra firme vegetation were examined in detail. Figure 4.2 shows an extract of band 4 (upper left: 3112/1342, lower right: 3562/1819). It can be observed that, even though absolute variations in altitude are limited in the region (30-120 m at most, normally 10-30 m difference between valley bottoms and hill tops), hills appear brighter on their eastern side and darker on the western side. This is typical of many terra firme regions in the central Amazon. It demonstrates that small scale topographic variations including

steep slopes are significant in lowland regions. The correction of relief-induced radiometric distortions depends largely on the availability of high resolution digital terrain data which are not available for the Manáus region. Therefore, no attempt has been made in this project to correct for such distortions.

(e) Atmospheric haze:

Atmospheric haze is frequently encountered in the humid tropics. Its effect on remotely sensed images in the visible spectrum is to reduce the contrast, particularly in the lower DN range. In the Manáus imagery, this affects dark targets such as water and dense forest. The impact of haze on data quality decreases from the blue to the red wavelength spectrum.

The minimum digital count value of dark targets, such as the water of the Rio Negro, allows us to draw some conclusion on the atmospheric condition at image acquisition time. The following table indicates the offset values for the digital count histograms of bands 1-5 and 7 of the 8 August 1991 Landsat TM image. The offset was defined as the lowest digital count with more than 0.5 % of the total number of pixels in the image:

band	offset
-----	
1	70
2	28
3	26
4	20
5	6
7	1

According to these band offset values, and to field observations of visibility (visibility estimated 20-25 km) taken at the day and hour of the satellite overpass, the atmosphere at image acquisition can be considered clear to moderately hazy (Chavez, 1988).

Nevertheless, even this moderate haze level affected strongly the spectral

contrast between forest types in bands 1 and 2. The contrast in band 1 was so low that almost no spectral differences between forest types did exist. Band 2 exhibited only a marginally better contrast than band 1.

#### **4.2.3 Conclusions**

Visual assessment of individual bands of the entire image and extracts at full resolution provides an easy way of detecting the main types of radiometric distortions in Landsat TM data. In the system-corrected data of the Manáus region acquired from INPE, view angle dependent radiometric distortions, scan-correlated shifts, and 16 line striping were particularly prominent. Other types of radiometric distortions (e.g. forward reverse scan banding, coherent noise, bin-radiance dependence, within line droop, bright target effects) have been reported in the literature (Fusco et al. 1986; Kieffer et al. 1985; Malaret et al. 1985; Metzler and Malila 1985; Murphy et al. 1985; Wrigley et al. 1985) but were not found to be severe in the data used for this study, as judged by visual inspection.

It was consequently decided to concentrate on (a) the quantitative assessment and correction of view angle dependent radiometric distortions (section 4.3), and (b) the quantitative assessment and correction of level shift banding and 16 line striping (section 4.4).

### **4.3 Assessment and Correction of View Angle Dependent Radiometric Distortions in Landsat TM Data for Tropical Forest Mapping**

Section 4.2 has shown that view angle dependent radiometric distortions (VADR) are one of the major residual radiometric distortions present in the Landsat Thematic Mapper data used for this study. These distortions needed to be removed before any detailed land cover classification could be attempted. Sections 4.3.1 and 4.3.2 analyse the causes of VADR in remotely sensed data. Section 4.3.3 assesses the magnitude of the distortions present in the TM data of 8 August 1991. A correction algorithm is described and the quality of the correction is assessed in section 4.3.4.

#### **4.3.1. Background**

View angle dependent radiometric distortion (VADR) is primarily dependent on sun-sensor geometry, atmospheric effects, and the bi-directional reflectance distribution function (BRDF) of the target.

##### **(a) Sun-sensor geometry:**

The processes of irradiation, reflection, and detection of radiation occur in 3-dimensional space. Remote sensing, therefore, has to consider possible variations in radiation detected by space measurements depending on the 3-D relationships between the sun, the target, and the detector. Figure 4.3 shows the sun-sensor geometry for the Landsat Thematic Mapper, projected onto the plane of the Earth surface. The parameters commonly used to describe sun-sensor geometry are sun elevation, sun azimuth, and scan azimuth.

##### **(b) Atmospheric effects:**

The amount of radiation that is detected by the satellite sensor depends, among other things, on the interaction of the radiation with the Earth's atmosphere. This interaction is generally described in terms of two processes: absorption and scattering. Atmospheric absorption depends primarily on oxygen, carbon dioxide, ozone, and water vapour. It is a selective process that affects only certain wavelengths. The sensors commonly used in Earth observation are designed to operate in the transmission windows between the atmospheric absorption regions (see, for example, Scorer 1990). Scattering is normally



discussed in terms of Rayleigh scattering and Mie scattering. Rayleigh scattering is caused by very small particles and molecules, with radii far less than the wavelength of the electromagnetic radiation of interest. The effect of this type of scattering is inversely proportional to the fourth power of the wavelength (short wavelengths are more seriously affected than longer wavelengths). Mie scattering is caused by particles, such as those associated with smoke, haze, and dust, with radii close to and slightly greater than the wavelength of interest. The intensity of Mie scattering varies inversely with wavelength. However, the exponent ranges from -0.7 to -2 rather than the -4 of Rayleigh scattering (see, for example, Mather 1987). Very clear atmospheres are dominated by Rayleigh scattering, moderately hazy atmospheres by a combination of Rayleigh and Mie scattering, while radiation passing through very hazy atmospheres is mostly influenced by Mie scattering. The parameters commonly used to describe atmospheric effects are view angle, wavelength, bandwidth (and sensitivity curve of the sensor), and atmospheric aerosol content (haze).

(c) Bi-directional reflectance distribution function (BRDF) of the target.

The radiance that the satellite sensor detects depends on (among other features) the reflectance properties of the target. In the visible and near infrared part of the spectrum almost all terrestrial targets are diffuse reflectors. 'Diffuse' means that the incident radiation will be scattered in all directions. The opposite is true for surface reflection from water which is a specular reflector, reflecting the incident radiation without scattering (angle of incidence being equal to angle of reflectance). The 3-dimensional reflectance characteristics of a target are described by its bi-directional reflectance distribution function (BRDF). A target which scatters light with equal density in all directions is called Lambertian. Most Earth surfaces (e.g. vegetation, water) do not exhibit Lambertian characteristics, that is, they do not reflect incident radiation equally in all directions. The distribution of radiation reflected from a target as measured by the satellite sensor, therefore, depends on the geometry of illumination and the geometry of measurement. A consequence of non-Lambertian reflectance characteristics is that the measurement of radiation reflected from the target and measured by the satellite depends on the view angle ('angular anisotropy of the reflective properties').

The dependence of the detected radiance on the BRDF of the target has been ignored in many studies. As Mather (1987) states '... a considerable body of work in remote sensing either explicitly or implicitly makes the assumption that Lambert's law applies...'.

It is often assumed that non-Lambertian properties only cause significant radiometric distortions when sensing at large view angles, as is the case for airborne scanner data or imagery of the AVHRR sensor. For example Duggin et al. (1985) state '...random variations might be expected to predominate over systematic variations for the smaller scan angle ( $\pm 7.7^\circ$ ) of the Thematic Mapper...' (see also Kleman 1987). While large viewing angles certainly aggravate the problem, viewing angles as occur in Landsat TM imagery ( $\pm 7.7^\circ$ ) may require correction in humid tropical vegetation mapping, depending on the BRDF of the target being sensed and atmospheric effects.

#### **4.3.2. Conclusions from past studies for mapping (forest) vegetation targets from system-corrected Landsat TM data**

In empirical studies it is difficult to isolate the effects of the various causes of VADRD. Therefore, several authors have made recourse to simulation approaches (Holben and Fraser 1984; Kirchner et al. 1981; Royer et al. 1985). Several studies have chosen to take an empirical approach. Such studies were mostly limited to either airborne scanner data (Barnsley 1984; Royer et al. 1985) or helicopter-based field measurements (Kleman 1987). Only a few studies have evaluated view angle dependent radiometric distortions in Landsat Thematic Mapper data (for example, Duggin et al. 1985). Assessing these studies with respect to view angle dependent radiometric distortions that may be encountered in system-corrected Landsat Thematic Mapper images of humid tropical vegetation, the following conclusions can be drawn:

##### **(a) Viewing angle:**

The strength of off-nadir effects increases with viewing angle (Duggin et al. 1985; Royer et al. 1985). Significant off-nadir distortions may be expected for TM viewing angles under unfavourable combinations of atmospheric conditions and target BRDF.

(b) Wavelength:

Off-nadir distortions decrease with increasing wavelength from blue to near-IR due to a decrease of atmospheric scattering (Kirchner et al. 1981; Royer et al. 1985). While for short wavelengths the atmospheric effect is the dominant cause of off-nadir distortions, for near-IR to mid-IR the BRDF of the target appears to be the dominant cause of VADRD. At near-IR, distortions have been found to be at a minimum (Kleman 1987), while increasing towards the near-to-mid IR wavelengths (1.6  $\mu\text{m}$ ). It should be noted, however, that it is difficult to generalise response patterns as these may vary with the target surface (see, for example, Barnsley 1984).

(c) Bandwidth:

The bandwidth of the detector is an important factor to consider when comparing results from empirical studies. Wide bandwidths (e.g. AVHRR) integrate reflection patterns over a range of wavelengths and the results may not be comparable to results obtained by sensors with narrower bandwidths (e.g. airborne scanners).

(d) Atmospheric aerosol content:

Off-nadir effects in the visible wavelengths sharply increase with increases in atmospheric aerosol content (Holben and Fraser 1984; Kirchner et al. 1981; Royer et al. 1985). The magnitude of the effect increases with decreasing wavelength from red to blue.

(e) Sun elevation angle:

The magnitude of increase in the apparent radiance for the sensor viewing away from the sun depends on the sun elevation angle. Decreasing solar elevation angles increase the magnitude of distortions at high view angles but decrease the variations seen within a view angle range of 0-35° (Kirchner et al. 1981).

- (f) Viewing direction relative to the illumination direction (sun azimuth relative to scan azimuth):

Off-nadir apparent radiance reflected from vegetated surfaces generally increases for the sensor viewing away from the sun (Holben and Fraser 1984; Kleman 1987; Royer et al. 1985), and has been reported to decrease for the sensor viewing towards the sun for vegetated surfaces (Kleman 1987; Royer et al. 1985).

- (g) Target bi-directional reflectance distribution function:

The BRDF of individual targets is difficult to predict. Most studies to date have focused on agricultural targets (cereals, grassland, soya, corn, orchards), few on northern boreal forests (pine, spruce). No studies are known to the author that have investigated off-nadir distortions for tropical vegetation, in particular broad-leaved tropical evergreen forest. Past studies have shown that the magnitude of off-nadir distortions is clearly a function of canopy geometry. It appears that 'smooth' canopies (comparatively less areas in shadow at nadir viewing) exhibit less pronounced variations with view angle than 'rough' canopies (comparatively more areas in shadow at nadir-viewing) (Kirchner et al. 1981; Kleman 1987).

Visible/IR satellite data from humid tropical forest regions frequently suffer from light to moderate haze, even if free from clouds. It is likely that off-nadir radiometric distortions are encountered in large numbers of Landsat TM scenes of humid tropical regions under such unfavourable atmospheric conditions and for canopies with a strong deviation from Lambertian properties. The frequency with which Landsat TM images of the humid tropics are affected by these distortions is demonstrated by a mosaic of Landsat TM band 3 scenes covering the entire Brazilian Amazon (Figure 4.4). Many scenes show an increase in the apparent radiance towards the western margin. This highlights the importance of developing software for correcting view angle dependent radiometric distortions prior to digital image classifications

### **4.3.3. Assessment of VADR in system-corrected Landsat TM data**

#### **4.3.3.1. Methods**

Assessment and correction software was implemented in the C language on a DEC VAX/VMS mainframe computer. The programs interface with images retained in ERDAS V. 7.5 format. ERDAS V 7.5 software was used for image display and subsequent image processing. Statistical analysis and production of graphs was performed in Microsoft EXCEL on an IBM compatible PC.

The following approach was chosen in order to perform a quantitative assessment of view angle dependent radiometric distortions.

It has been pointed out above that the magnitude of VADR depends on the BRDF of the vegetation target. In order to measure quantitatively the magnitude of VADR, a reference land cover type had to be selected. In the Manaus region, forest is the dominant land cover in terms of areal extent. It was therefore decided to base the evaluation of VADR on forest as the reference land cover (no differentiation was made between different forest types). In order to include only 'forest' pixels into the measurement of VADR, 'forest' pixels in the entire TM scene needed to be labelled. This was achieved as follows.

##### (a) Definition of the reference target 'forest':

TM bands 4 and 5 have the highest potential to discriminate vegetation classes in the Manaus region (chapter 6). Furthermore, visual analysis suggested that these bands were less affected by VADR than bands 1-3. It was therefore decided to base the spectral definition of the reference class 'forest' on bands 4 and 5. Sample pixels of forest were selected based on minimum and maximum greylevel values in bands 4 and 5 (parallelepiped rule).

Suitable box limits for the parallelepiped classification were derived by interactively defining 20 training areas of the reference class. In order to capture maximum spectral variations due to VADR, the training areas were located primarily around the margin of the image with a few additional areas representing the body of the image. The spectral statistics were calculated and box limits for the reference class

were derived as follows:

lower bound: (lowest mean value of the 20 areas) minus (one standard deviation of that sample), rounded to the nearest integer

higher bound: (highest mean value of the 20 areas) plus (one standard deviation of that sample), rounded to the nearest integer

The following box limits of the reference class were derived for bands 4 and 5:

band 4: (60,74)

band 5: (45,59)

Using the above spectral limits for 'forest', a box classification of the entire image was carried out in order to evaluate which vegetation types were included into the reference target. 63 % of the image was classified as 'forest' and 37 % as 'background'. 'Forest' pixels were well distributed over all parts of the image. A visual comparison of the forest mask with air photography taken at the date of TM image acquisition confirmed that the box limits included only forest pixels.

#### (b) Assessment software and sample datasets:

Software was encoded in the C language for the quantitative assessment of VADRD. The programme divided the image into rectangular blocks. Each pixel in the image was evaluated as to whether it belonged to the reference land cover, using the spectral condition and box limits described above. If a pixel belonged to the reference class it contributed to the calculation of the mean digital count of the reference class for the image block into which the pixel falls. For each block the following parameters were calculated and saved to a file:

- \* mean digital count
- \* number of pixels included in the calculation of the 'mean digital count'
- \* centre position of the block in image rows and columns

Two sample datasets were created by use of the assessment programme:

(a) Dataset 1:

This dataset was created in order to obtain a graphical representation of average digital counts of the reference class over the entire image. The 3-dimensional representation (Figures 4.5a-4.10a) allowed (a) the visual identification of view angle dependent trends in the data, and (b) the identification of spatial correlations between large scale variations in land cover and average digital counts.

The dataset consists of a regularly spaced grid covering the entire image:

Upper left:	33/2
Lower right:	6153/5921
Blocksize:	200*200 pixels

Graphical representation: Figures 4.5a-4.10a (the colours have been assigned at arbitrary intervals for visualisation purposes only).

(b) Dataset 2:

This dataset was created in order to allow the statistical analysis of view angle dependent trends in apparent radiance in scan direction. This extract represents only upland (terra firme) areas and excludes the extensive floodplains of the Rio Solimões (southern part of the image).

The northern 2000 scan lines of the image have been divided into blocks of 50 pixels in across track direction (X) and 2000 pixels in along track direction (Y).

Upper left:	33/2
Lower right:	6153/2001
Blocksize:	x: 50, y: 2000

Graphical representation: Figures 4.5c-4.10c



In order to facilitate the comparison of view angle dependent trends in the different wavebands, the data shown in Figures 4.5c-4.10c have been normalised to a zero-distortion at nadir by subtracting appropriate offsets.

(c) Modelling VADR as a function of image X (across track, scan position):

The shape of the curves shown in Figures 4.5c-4.10c suggested that a second order polynomial function was appropriate to model the relationship between the scan position of a pixel in X and the magnitude of VADR. Dataset 2 (see above) was used to derive the polynomial regression functions for bands 1, 2, 3, 5, and 7. A least squares fitting procedure was used to calculate the coefficients of the polynomial functions. Figures 4.5c-4.10c show the polynomial functions ('2nd order fit') and the data points used to derive them ('raw data').

#### **4.3.3.2. Results**

(1) Bands 1, 2, and 3:

Figures 4.5a-4.7a reflect two major influences on the apparent radiance of forest pixels: (a) a view angle dependent increase of apparent radiance in scan direction from the east to the west, and (b) large scale variations in forest type. An area of high apparent radiance can be observed that coincides with the floodplain of the Rio Solimões. A further area of increased apparent radiance can be observed south-west of the Rio Negro (compare Figures 4.5a-4.7a with the 8-8-91 image (Figure 4.12)). The northern 2000 lines of the image represent the area that is least affected by large scale changes in land cover (upper left: 33/2, lower right: 6153/2001, dataset 2). With reference to the nadir values, bands 1, 2, and 3 exhibit a pronounced increase of the apparent radiance towards the western margin of the scene (sensor viewing away from the sun), and a decrease towards the eastern margin (sensor viewing towards the sun) (Figures 4.5c-4.7c). The magnitude of the distortion decreases from the blue band (band 1) to the red band (band 3).

(2) Band 4:

The very regular and gradual increase of the apparent radiance for the sensor

viewing away from the sun that was observed in bands 1-3 is not encountered in band 4 (Figure 4.8). Rather it can be seen that the forest areas towards the south-west of the Rio Negro exhibit an apparent radiance that is significantly higher than the apparent radiance of forest areas towards the north-east of the Rio Negro. The change is abrupt and appears to reflect a change in vegetation rather than to depend on the view angle of the sensor.

(3) Bands 5 and 7:

The effect of different vegetation towards the north-east and the south-west of the Rio Negro on the apparent radiance that was detected in band 4 can, to a much lesser extent, also be observed in bands 5 (Figure 4.9a) and 7 (Figure 4.10a). It is, overlaid, however, by a viewing angle dependent increase of the apparent radiance for the sensor viewing away from the sun and a decrease for the sensor viewing towards the sun.

- (4) Table 4.2 shows the magnitude of VADRDR according to the 2nd order regression functions. The total across scan distortion is largest in band 1 (more than 8 DN). VADRDR is of the magnitude of 3-4 DN for bands 2, 3, and 5. This is approximately the same magnitude as spectral differences between forest types in the respective bands. Therefore, the distortions need to be corrected if digital classifications based on spectral differences are to be carried out for image extracts spanning large parts of the scan. The magnitude of VADRDR for band 7 is approximately 1 DN. This low absolute value still represents a significant distortion if the relatively low dynamic range of band 7 for green vegetation targets is considered.

#### **4.3.3.3. Conclusions**

- (1) Large scale variations in land cover affect the detectability of VADRDR. While variations in upland land cover were not sufficiently large as to impede the detection and quantification of VADRDR, the spectral difference between floodplain and upland forest was so strong as to render the measurement of VADRDR impossible. Floodplain areas therefore needed to be excluded from the analysis.

- (2) The increase in the apparent radiance with view angle that is detected appears to have two main components: atmospheric effects and target BRDF. The results obtained from simulation studies (section 4.3.2) suggest that the effect of the atmosphere is dominant in bands 1-3, causing an increase in apparent radiance for the sensor viewing away from the sun and a decrease for the sensor viewing towards the sun (with reference to nadir). The VADR that is observed in bands 5 and 7 appears to be more irregular and probably depends predominantly on the target BRDF. The results suggest that band 4 is not influenced by VADR. Therefore, band 4 was not subjected to any correction of VADR (see below).
- (3) The effect of BRDF for the forest reference class is tentatively explained as follows. The Landsat satellite acquires imagery at 9.30-9.45 am local sun time. At this time of the day, even at low latitudes, a certain part of the forest canopy is in shadow. The amount of shadow depends on the 3-dimensional structure of the forest canopy consisting of emergent trees and gaps. A nadir-pointing sensor views a certain proportion of shadowed components. If the sensor looks away from the sun, its field of view includes fewer shadowed components and more of the illuminated components of the canopy. Consequently, the detected apparent reflectance of the canopy increases. If the sensor looks towards the sun, the ratio of canopy in shadow to illuminated canopy increases and the detected apparent reflectance decreases.
- (4) The magnitude of the view angle dependent distortions renders detailed land cover classifications of entire TM scenes impossible if left uncorrected. In particular, bands 3 and 5, which together with band 4 are most important for mapping humid tropical vegetation (see chapter 6), need to be corrected. At the haze conditions that were encountered on 8-8-91, bands 1 and 2 provide little information on vegetation types.

#### 4.3.4. Correction of VADR in system-corrected Landsat TM data

##### 4.3.4.1. Background

In principle, two approaches are available for the correction of view angle dependent radiometric distortions: error modelling and empirical image-based correction. Error modelling requires the consideration of the atmospheric component and the BRDF of the target(s). Atmospheric models are widely available, even though input parameters frequently have to be estimated due to the unavailability of ground observations concurrent with the image acquisition. However, the BRDF of tropical land cover has been little investigated and suitable models are scarce. At the current state of knowledge empirical approaches to VADR correction are more promising. In order to correct the increase of the apparent radiance in scan direction in bands 1, 2, 3, 5, and 7 the following approach was chosen.

##### Correction algorithms:

Several approaches have been suggested to correct view angle dependent radiometric distortions (Royer et al. 1985). The two simplest ones are the subtraction method and the division method.

##### Subtraction method

This correction procedure consists of subtracting the estimated curve from the measured radiances. The corrected radiance at pixel position  $x$  is calculated from the equation:

$$Y_{\text{corrected}}(x) = Y_{\text{measured}}(x) - [Y_{\text{estimated}}(x) - Y_{\text{target}}(x)]$$

$Y_{\text{corrected}}(x)$ : corrected radiance

$Y_{\text{measured}}(x)$ : measured radiance

$Y_{\text{estimated}}(x)$ : radiance estimated by the polynomial function

$Y_{\text{target}}(x)$ : estimated radiance at nadir

(see Figure 4.11)

#### Division method:

The measured radiances are divided by the estimated radiances. The corrected radiance at pixel position  $x$  is calculated from the equation:

$$Y_{\text{corrected}}(x) = \frac{Y_{\text{measured}}(x)}{Y_{\text{estimated}}(x)} * Y_{\text{target}}(x)$$

$Y_{\text{corrected}}(x)$ : corrected radiance

$Y_{\text{measured}}(x)$ : measured radiance

$Y_{\text{estimated}}(x)$ : radiance estimated by the polynomial function

$Y_{\text{target}}(x)$ : estimated radiance at nadir

Both methods have been found effective in correcting VADRD in airborne scanner data, with Royer et al. (1985) reporting better results for the division method. However, the division method compresses the magnitude of deviations from the estimated curve. Such deviations may represent residual radiometric error or differences in land cover. The degree of compression depends on the relation of  $Y_{\text{target}}(x)$  to  $Y_{\text{estimated}}(x)$  and, therefore, is view angle dependent. In order to conserve spectral differences between land cover types, the subtraction method was selected for implementation.

#### **4.3.4.2. Methods**

##### **(a) Correction software**

For the correction of VADRD the radiance value at nadir estimated by the regression function was taken as the target value ( $Y_{\text{target}}(x)$ ). The program used the ERDAS 7.5 .LAN format for data input and also for data output. ERDAS 7.5 handles only integer (8 bit or 16 bit) images. The correction algorithm involves the use of floating point variables. Therefore, for output the data had to be rounded to the nearest integer. The correction of VADRD was followed by a linear contrast stretch to improve the image contrast. The scaling factors were chosen for optimal contrast of vegetated surfaces; water was scaled to '0' and high reflectance urban areas (e.g. Manáus) to '255'. The correction was applied to bands 1, 2, 3, 5, and 7 while band 4

was only subjected to a linear contrast enhancement. All corrections were applied to the full TM scenes.

**(b) Assessment software**

For the quantitative assessment of the success of the radiometric adjustment, an assessment programme similar to the one described in section 4.3.3.1. was implemented. In order to ensure that block means of forest pixels were calculated from the same sample of pixels in the original data and the corrected data, the following approach was chosen. Instead of applying the spectral condition for selecting sample pixels to the adjusted image, the pixels that were evaluated in the adjusted image were selected by applying the spectral condition to the corresponding pixels in the original data.

The assessment programme was run for the same two sets of parameters as described above:

- (a) Dataset 3: Regularly spaced grid covering the entire image:

Upper left:	33/2
Lower right:	6153/5921
Blocksize:	200*200

Graphical representation: Figures 4.5b-4.10b (the colours have been assigned at arbitrary intervals for visualisation purposes only).

- (b) Dataset 4: The northern 2000 scan lines of the image have been divided into blocks of 50 pixels in across track direction (X) and 2000 pixels in along track direction (Y).

Upper left:	33/2
Lower right:	6153/2001
Blocksize:	x: 50, y: 2000

Graphical representation: Figures 4.5c-4.10c

#### 4.3.4.3. Results and discussion

- (1) By comparing the original data (Figures 4.5a-4.10a, 4.5c-4.10c) with the adjusted data (Figures 4.5b-4.10b, 4.5c-4.10c) it is clear that the view angle dependent radiometric distortion has been effectively removed in bands 1, 2, 3, 5, and 7. This result was also confirmed by visual comparison of the uncorrected and corrected images. Figure 4.12 shows for band 3 (a) the system-corrected data and (b) the data after correction of view angle dependent radiometric distortions.
- (2) A regression analysis was carried out for bands 1, 2, 3, 5, and 7 in order to determine the coefficient of determination ( $r^2$ ) between the scan position of a block of forest pixels and its average digital count before and after the correction of VADRD. Table 4.3 shows the results. The  $r^2$  values confirm that the correction algorithm has effectively removed the view angle dependent radiometric distortion.
- (3) Limitations of output to integer images

As outlined above, the current implementation of the correction algorithm was limited by the fact that the output data finally had to be converted to integer format in order to interface with the ERDAS 7.5 software. This entailed several limitations. Without the contrast stretch subsequent to the radiometric correction, the corrected image exhibited a pronounced east-west 'saw tooth' brightness pattern due to the real to integer rounding. This pattern was visible in bands with a low dynamic range (bands 1, 2, 3, and 7) while it was not visible in band 5 which had a larger dynamic range for vegetation. However, the presence of the pattern could be proven by quantitative assessment (as described above) in all corrected bands. The pattern became more pronounced the smaller the ratio of the magnitude of VADRD to the dynamic range of digital counts for vegetation. By performing a contrast stretch before the real to integer conversion took place, this ratio was expanded and the rounding effects were smaller in relative terms. Consequently, in suitably contrast stretched images, the 'saw-tooth' pattern was much reduced or not visible.

In the current application it was not intended to achieve an absolute calibration



of radiance values but only an internal correction. Therefore, the necessity of performing a contrast stretch did not introduce problems for the subsequent analysis of the data (image classification). If an absolute calibration were to be performed, it would be essential to be able to maintain the output image in floating point format.

Ideally, VADRD-correction and absolute calibration should be performed in one step. The implementation of the correction algorithm would allow for the integration of absolute calibration factors as can be derived from an atmospheric simulation model (e.g. 5s, MODTRAN).

(4) Dependence of the correction algorithm on the reference land cover

The evaluation of agricultural targets and boreal forests has demonstrated that view angle dependent distortions are dependent on the BRDF of the target. The quadratic regression curves modelling the relation between view angle and the magnitude of distortion for forest targets in this study potentially may not be representative when applied to other targets. The correction based on the regression curves may therefore incorrectly compensate VADRD for non-forest targets. Due to the dominance of forest (63 % of the full TM scene and about 80 % of the non-water areas) and the lack of a different vegetation type that is evenly distributed over the entire scene, such possible mis-corrections could not be assessed. For the same reason, however, mis-corrections, should they exist, will affect only a minor percentage of the scene.

#### **4.3.4.4. Conclusions**

It has been shown that view angle dependent radiometric distortions of significant magnitude may exist in Landsat TM imagery of tropical forest regions. The distortions arise from atmospheric conditions and probably to some extent from canopy geometry / illumination effects. The distortions affect bands 1, 2, 3, 5, and 7. A correction algorithm based on the subtraction method allowed for the effective internal calibration of the data to nadir values.

**4.4.           Assessment and Correction of Level Shift Banding and 16 Line Striping in System-Corrected Landsat Thematic Mapper Images**

The visual assessment of Landsat TM data of the project region reported in section 4.2 had shown that scan-correlated shifts in brightness (hereafter called 'level shift banding' (lsb)) and 16 line striping were the most prominent instrument-related radiometric distortions. These distortions still remained in the data after the correction of view angle dependent radiometric distortions reported in section 4.3. Section 4.4 describes the quantitative assessment and correction of striping and banding patterns in the Landsat TM image of 8 August 1991. Section 4.4.1 assesses level shift banding and 16 line striping in Landsat TM data. Section 4.4.2 reports details of an algorithm that has been implemented to reduce banding and striping and assesses the success of the corrections made.

**4.4.1.       Assessment of 16 line striping and level shift banding**

**4.4.1.1.    Data**

Quantitative measurements for the assessment of 16 line striping and level shift banding were taken from two test areas of the Landsat TM 8 August 1991 image:

(a) Area of water in the Rio Negro:

Upper left:	3300/3044
Lower right:	3516/3261
Number of columns:	217
Number of lines:	218

(b) Area of forest:

Upper left:	3112/1342
Lower right:	3562/1819
Number of columns:	451
Number of lines:	478

For each area, two correction levels were evaluated:

- (a) System-corrected data (as acquired from INPE).
- (b) VABRD-corrected data: system-corrected data that had undergone additional correction of view angle dependent radiometric distortion and had been subjected to linear contrast enhancement (see section 4.3).

This resulted in a total of four data sets:

	area 1: water	area 2: forest
-----		
System-corrected data	data set 1	data set 2
VABRD corrected data	data set 3	data set 4
-----		

Only bands 1, 2, 3, 4, 5, and 7 were considered because of the low spatial resolution of 120 m of band 6 that renders it unsuitable for this mapping application.

It should be noted that the formal numbering of the detectors is in reverse order from their relative position in the image, i.e., the last line of a scan (bottom line in the image) is detector 1 (see, for example, Kieffer et al. 1985).

#### 4.4.1.2. Methods

Software for measuring the magnitude of 16 line striping and level shift banding was encoded in the C-language. The program used rectangular extracts of ERDAS V. 7.5 image files and calculated the average DN (digital number) for each line of pixels. Line number and average DN were output to a text file for visualisation in EXCEL. Vertical gridlines in Figures 4.13-4.17 and 4.22-4.25 mark scans of 16 lines.

#### 4.4.1.3. Results

##### (a) System-corrected data

###### Data set 1: water

Figure 4.13 shows the results obtained from measuring average DN's of lines over an area of water in the system-corrected data. 16 line striping existed in all bands. Only in band 1 did the magnitude of the effect significantly exceed 1 DN. Level shift banding was pronounced in bands 2 and 3, with the magnitude of the effect being higher in band 3 (average magnitude of all detectors: 0.7) than in band 2 (average magnitude of all detectors: 0.6). Changes in the 16 line pattern, dependent on the level shift state, were noted in all bands. These results confirm the visual assessment of the data reported in section 4.2. Similar results have been reported by Kieffer et al. (1985) and Metzler and Malila (1985).

###### Data set 2: forest

Figure 4.14 shows the results obtained from measuring average DN's of lines from an area of forest in the system-corrected Landsat TM data. The detector patterns of 16 lines periodicity observed in data set 1 (water) could not be observed for the forest data of bands 2, 3, 4, 5, and 7, while the band 1 periodicity is almost identical for the forest and water datasets. Nevertheless, band 2 forest data exhibited a different characteristic 16 line repeat pattern. This observation suggested that the response of individual detectors and, consequently, 16 line patterns depend on target brightness (a similar observation is reported by Kieffer et al. 1985). The data measured from the forest sample suggested that level shift also affected band 4 in addition to bands 2 and 3. However, visual inspection of the image could not confirm such a shift.

Almost identical results were obtained from the assessment of system-corrected data and data corrected for VADR. Therefore, only the results from one dataset (forest) will be reported in the following paragraph.

**(b) VADR corrected data:**

Data set 4: forest

Figure 4.15 shows line averages measured from the forest data set for VADR corrected data. By comparing Figures 4.14 and 4.15 it can be seen that the correction of VADR and the contrast enhancement did not markedly alter the patterns of line averages even though the magnitude of the detector imbalances is obviously enlarged in line with the contrast stretch.

**4.4.1.4. Conclusions**

Significant residual 16 line striping and level shift banding have been found in the system-corrected Landsat TM data. The following conclusions were drawn with respect to the individual bands:

- Band 1: Band 1 was severely degraded by 16 line striping and by atmospheric haze.
- Band 2: Band 2 was degraded by atmospheric haze (less than band 1), severe level shift banding and 16 line striping.
- Band 3: Band 3 was degraded by atmospheric haze, severe level shift banding and 16 line striping.
- Band 4: 16 line striping in band 4 could be measured over homogeneous areas of water. It could not be visually detected for vegetation targets due to the high dynamic range of this band.
- Band 5: 16 line striping in band 5 could be measured over homogeneous areas of water. However, it was barely visible for vegetation targets due to the high dynamic range of this band.
- Band 7: 16 line striping and minor level shift banding measured over water and forest targets could also be visually detected due to the low to intermediate dynamic range of band 7 for vegetation.

The magnitude of the distortions must be seen in relation to the dynamic range of vegetation targets in the different bands. The amplitude of 1 DN for 16 line striping has much less impact on the spectral separability of land cover types in bands 4 and 5 because these bands have a much higher dynamic range for vegetation than bands 2, 3 and 7. Furthermore, the haze level encountered in the 8 August 91 data severely reduces the spectral contrast between vegetation targets. This problem affects particularly land cover types such as forests that occupy a low DN range in bands 1-3. The already low spectral separability is further degraded by the banding and striping problems encountered in bands 1-3.

Landsat TM data (of the Manáus region) essentially represent a 3-dimensional data space for green vegetation targets: (1) bands 1, 2, and 3 are highly correlated; (2) band 4; (3) bands 5 and 7 are highly correlated (see chapter 6). Therefore, high importance should be placed on correcting level shift banding and 16 line striping in band 3 which is less affected by atmospheric distortions than band 2. If neither band 3 nor band 2 could be corrected, only a 2-dimensional data set would remain for use in digital classifications. It was decided to correct not only band 3 but also band 2 in order to test the validity of the correction algorithm on a second data set.

#### **4.4.2. Correction of level shift banding and 16 line striping in bands 2 and 3.**

##### **4.4.2.1. Background**

Ample information has been published on the correction of striping of regular frequency in satellite data, such as 16 line striping in Landsat TM data or 6th line striping in Landsat MSS data. However, few studies make reference to the correction of level shift banding which occurs at random intervals, affects random numbers of scans and, therefore, is more difficult to quantify and to correct. The following paragraphs will discuss methods that have been suggested to remove regular-spaced scan related striping. The understanding of the problem and the methods used to correct it facilitates the understanding of the approach that has been taken for correcting level shift banding.

(a)            **Correction of regular-spaced scan-related striping in satellite data.**

Several methods are available for removing regular-spaced, scan-related striping from satellite imagery. While some methods are equally suited for the correction of system-corrected and geometrically corrected data, others may be applied only to system-corrected data in which the relationship between scan lines and image lines remains intact:

	correction of system-corrected data	correction of geometrically corrected data
-----		
Linear method	+	-
Histogram equalisation	+	-
Spatial domain convolution	+	+
Fourier space multiplication	+	+
-----		
'+' technique can be applied		
'-' technique cannot be applied		

**Linear method**

According to the linear model, the detector output is a multiplicative factor ('gain') times the input radiance, plus an additive constant ('offset'). This means the sensor transfer function is assumed to be linear. Correction look-up tables are constructed by using relative gain and offset factors for mean and standard deviation of each detector and matching them to mean and standard deviation of the entire scene (Büttner and Kapovits 1990).

**Histogram equalisation**

A shortcoming of the linear method lies in the fact that it assumes linear transfer functions. Slightly different gain and offset values however, tend to be appropriate for different radiance ranges. The histogram matching algorithm equalises the cumulative gray level histogram of each detector to a target histogram, thereby allowing for non-linear transfer functions. In the original version, the target



histogram was calculated from the entire image (Horn and Woodham 1979).

Several studies compared the efficiency of the linear method and histogram equalisation for removing regular spaced striping from MSS data (6 line striping), Landsat TM data (16 line striping), and panchromatic SPOT data (2 line repeat frequency). These studies agreed that histogram equalisation generally gives results that are superior to linear model based approaches (Büttner and Kapovits 1990; Poros and Peterson 1985; Wegener 1990).

A key assumption of histogram equalisation is that all detector histograms are sampled from identical distributions of land cover. Only if this is the case, can differences in the cumulative gray level histograms be attributed to detector differences. In order to fulfil this condition, Wegener (1990) suggested that the detector histograms be calculated only from pixels belonging to 12\*12 pixel windows that represent areas of homogeneous land cover. This modified histogram equalisation algorithm succeeded in improving the results significantly over those obtained by the basic Horn-Woodham algorithm.

While the linear method and histogram equalisation depend on the relationship between detector scan lines and image lines being intact, real space convolution and Fourier space multiplication can be applied to system-corrected data as well as to geometrically corrected data.

### **Spatial domain convolution**

Several authors have suggested spatial domain convolution for the reduction of striping and banding in Landsat and SPOT data in recent years (e.g. Crippen 1989; Helder et al. 1992; Pan and Chang 1992; Srinivasan et al. 1988; Westin 1990). In contrast to histogram equalisation, filtering, being based on local statistics, does take into account that pixel values not only change between lines but also along lines (Helder et al. 1992). However, real space convolution also exhibits a number of disadvantages. Generally, not only striping or banding will be removed by digital filtering, but also image features of spatial frequency similar to the noise. The results of destriping by digital filtering in the spatial domain tend to improve with increasing filter size. However, large filter kernels also mean increasing computing cost.

## **Fourier space multiplication**

In principle, convolution in the spatial domain can be substituted by multiplication in Fourier space. In Fourier space, it is sometimes easier to identify and eliminate those frequencies that constitute noise. Because of the large size of satellite images (one full Landsat TM scene requires approximately 250 MB of disk space), computationally efficient algorithms are essential for destriping in Fourier space. Nevertheless, transforming an entire TM image into the frequency domain, performing corrections, and re-transforming the image back into the spatial domain is often not feasible on today's digital image processing systems due to the high computing cost involved (Helder et al. 1992).

## **Conclusions concerning the correction of 16 line striping**

Image striping consists of features that are constant along scan lines but also of features that vary with the along scan position. Generally, it is easier to correct for striping and banding when the data has not yet been geometrically corrected (i.e. image lines represent scan lines). In this case, linear model corrections or histogram equalisation as well as spatial domain convolution and Fourier space multiplication may be applied. Scan line based corrections cannot be applied to geometrically corrected imagery. Such data can be destriped by real space convolution or Fourier space multiplication.

Histogram equalisation has been found to give superior results than corrections based on the linear model. The success of destriping by histogram equalisation depends on the sample of pixels from which the detector histograms and the target histogram are derived. All detector histograms must be calculated from an identical composition of land cover. If entire TM scenes at system correction level are to be destriped, histogram equalisation appears to be preferable in terms of quality of correction and computing costs.

### **(b) Correction of level shift banding**

Procedures for the correction of level shift banding in Landsat TM data have been proposed by several authors (Kieffer et al. 1985; Metzler and Malila 1985; Murphy et al. 1985). Unfortunately, these methods tend to apply to TM raw data rather than to

TM data at system correction level, i.e. requiring information on calibration not supplied in system-corrected data (see, for example, Metzler and Malila 1985). Furthermore, none of the studies reported above actually describes the implementation and success of the suggested correction procedures. As reported in paragraph 4.4.1.3, the response of the 16 detectors and the magnitude of level shift banding depend on target brightness. Adding a constant detector-specific factor to all pixels in a scan line (as suggested, for example, by Metzler and Malila 1985), cannot be expected to provide a satisfactory correction. A further complication is given by the fact that the correction constants are floating point numbers between '-1' and '1'. As pointed out above, ERDAS 7.5 does not allow the utilisation of floating point images. It was therefore decided to base the correction algorithm for both 16 line striping and level shift banding on histogram equalisation. Two approaches were implemented and assessed as described below.

#### **4.4.2.2. Methods**

##### **(a) The correction algorithm**

The correction of level shift banding through histogram equalisation involved two stages:

1. Labelling of all lines of the image according to the level shift state of the respective scan as either 'high' or 'low'.
2. Construction of separate detector histograms for both level shift states; construction of the target histogram, the look up tables, and the adjustment of the image data.

##### **Stage 1: Labelling of all lines of the image according to the level shift state of the respective scan as either 'high' or 'low'.**

Close examination of the pattern of line averages calculated from 'water' extracts (Figures 4.16 (band 2) and 4.17 (band 3)) shows that not all detectors are affected to the same degree by level shift. As a result, the sensitivity of a detector relative to the other 15 detectors in a scan changes between level shift states. Band 2 may be taken as an example: In level shift state 'low', detector 5 consistently gives a lower response

than detector 4, while in level shift state 'high' this relative difference has been reversed, i.e. detector 5 consistently gives a higher response than detector 4 (see Figure 4.16). This change in the relative response patterns can be used to identify the level shift state of each scan. All lines of the image are then labelled according to the level shift state of their respective scan.

The algorithm works as follows. For each scan of 16 lines the difference of detectors 5 and 4 (band 2) is calculated:

$$\text{Difference} = (\text{LINE-MEAN}_{\text{detector\_5}}) - (\text{LINE-MEAN}_{\text{detector\_4}})$$

The histogram of this difference for all 370 scans in the TM image is shown in Figure 4.18. The histogram is bimodal with both maxima well separated. A threshold difference level (e.g. '-0.1') can be selected that allows for the labelling of each scan as being either in level shift state 'low' or 'high'. Figure 4.19 shows the distribution of scans in both level shift states over the entire image.

**Stage 2: Construction of separate detector histograms for both level shift states; construction of the target histogram, the look up tables, and the adjustment of the image data.**

The correction algorithm based on histogram equalisation involved the following stages:

- \* Calculation of the detector histograms for both level shift states (resulting in 32 detector histograms)
- \* Calculation of a target histogram.
- \* Derivation of the lookup tables (resulting in 32 lookup tables).
- \* Adjustment of the image data.

As explained above, the critical step in histogram equalisation is the derivation of the detector histograms. Only if all detectors sample identical distributions of land cover types, can differences in the cumulative gray level histograms be attributed to

detector imbalances. Two approaches to sampling the detector histograms were implemented and their validity assessed:

Approach 1:               No consideration of land cover was taken in sampling detector histograms.

Approach 2:               Land cover was considered when detector histograms were sampled.

**Approach 1:               No consideration of land cover was taken in sampling detector histograms.**

A program was encoded in the C-language that collected detector graylevel histograms (from the whole image) for 16 detectors in each level shift state (total of 32 detectors). The target histogram was calculated from detectors in level shift state 'high' and the image was adjusted by histogram matching as implemented through lookup tables.

This procedure worked well for removing level shift banding from image extracts of homogeneous land cover (i.e. only water or only forest). However, it did not give satisfactory results for image extracts that exhibited a different percentage contribution of land cover types to the histograms of individual detectors in the two level shift states. This result could not be improved by using the entire TM scene in order to take the largest possible sample of pixels for each histogram.

It was likely therefore, that the aperiodic occurrence of scans in the two level shift states when combined with the spatially uneven distribution of land cover types over the scene led to detector histograms that rather reflected the uneven contribution of land cover types than detector imbalances.

In order to verify this hypothesis, a land cover map of the full TM scene based on 11 spectral classes was created. The number of 11 classes was chosen because this represented approximately the number of classes that were distinct in a visual inspection of false colour composites (bands 4/5/3). Spectral signatures for the 11 classes were derived by k-means clustering. The classification used the minimum distance algorithm applied to TM bands 3, 4, and 5.

For each of the 16 detectors and the two level shift states the class membership histograms were sampled. These histograms indicate how many pixels from each spectral class have been sampled by each detector in the whole image (resulting in 32 class membership histograms). A summary of the results is presented in Figure 4.20.

This analysis proved that the 32 detector / level shift state histograms were not sampled from an identical composition of land cover classes. For example, pixels of spectral class '5' contributed as little as 21.82 % to the histogram of one detector (minimum contribution), but as much as 32.12 % to the histogram of another detector (maximum contribution) (Figure 4.20).

Figure 4.21 indicates the maximum/minimum ratio for the 11 classes. A high max/min ratio is of relatively minor importance in classes with a small pixel population (a small number of pixels belongs to this class in the entire image). However, it is significant in classes with a large population of pixels, for example classes 5 and 6.

It can be concluded that even though the total number of pixels in a full TM scene is approximately 37 million, detector / level shift state histograms cannot be expected to be sampled from an identical mix of land cover. The algorithm to sample detector histograms from the image must therefore, include a mechanism that considers the uneven spread of spectral classes / land cover types among level shift states and detectors.

**Approach 2: Land cover was considered when detector histograms were sampled.**

- \* A land cover map of the entire scene was created as described above.
- \* The correction lookup tables were created as follows:
  - Membership histograms for all detectors and the two level shift states from the land cover map (total of 32 histograms) were built.
  - The minimum number of pixels of any detector for each of the land cover types (see the actual numbers below) was established.

- The graylevel frequency histograms were sampled from the TM image: the histograms of all detectors were sampled from an identical composition of land cover classes by ignoring pixels of any particular land cover class from further sampling as soon as the detector concerned had reached the above established minimum class numbers.
- The cumulative detector histograms were calculated.
- The target histogram was created from detectors in level shift state 'high'.
- Lookup tables for all detectors were created.

\* The image data were adjusted.

The algorithm was applied to bands 2 and 3. The histograms were calculated from the entire image in order to take advantage of the large data volume (approximately 37 million pixels per band) to improve the quality of the statistics generated.

The numbers of pixels per detector and level shift histogram sampled from each class were as follows:

class	number of pixels
-----	
1	95,506
2	17,019
3	13,033
4	98,386
5	260,933
6	228,555
7	125,439
8	29,624
9	14,534
10	23,415
11	8,628



Two correction levels of input data were evaluated:

- (a) System-corrected data (as acquired from INPE).
- (b) VABRD corrected data: system-corrected data that had undergone additional correction of view angle dependent radiometric distortion and linear contrast enhancement (see section 4.3).

**(b) Assessment of the correction**

The quality of the corrections was assessed in three ways:

- (a) The entire image was displayed, contrast enhanced, and a visual assessment was performed.
- (b) An area of relatively homogeneous land cover (forest and water, upper left: 3069/2493, lower right: 4067/3491) was displayed, the contrast enhanced, and a visual assessment was performed.
- (c) Average DN's of lines for the same area of water as described in paragraph 4.4.1.1 (upper left: 3300/3044, lower right: 3516/3261) were calculated. The line averages were compared with the uncorrected data.

**4.4.2.3. Results**

**(a) System-corrected data**

The results obtained from 'forest' and 'water' targets were very similar. Therefore, figures will be presented only for the latter. Figure 4.22 shows band 2 line averages before and after correction and Figure 4.23 shows the results for band 3. The comparison with the uncorrected data shows that level shift banding, although not completely removed, has been largely reduced in both bands. The magnitude of 16 line striping has been somewhat reduced in band 2, but appears to be unchanged in band 3.

## **(b) VABRD corrected data**

The results for band 2 are shown in Figures 4.24, 4.26, and 4.27, while the results for band 3 are shown in Figures 4.25, 4.28, and 4.29. The photos and diagrams demonstrate that a considerable improvement of image quality can be achieved by the correction algorithm. In both bands 2 and 3 level shift banding has been largely removed. 16 line striping has been significantly reduced in both bands. However, some residual error remains after correction. This is probably because the magnitude of level shift banding is not entirely independent of scan angle.

### **4.4.2.4. Conclusions**

- (1) An algorithm was implemented for the correction of level shift banding and 16 line striping in bands 2 and 3 of Landsat TM data.
- (2) The algorithm removed to a large extent banding and striping from bands 2 and 3.
- (3) The correction algorithm worked well on both system-corrected data and those data that had undergone additional correction for view angle dependent radiometric distortions and contrast enhancement. The correction was superior on the latter data, in particular with respect to reducing 16 line striping.
- (4) The algorithm involved the creation of one large intermediary file (the classified image) and required a considerable amount of CPU-time.
- (5) A final word of caution must be given with respect to the classified reference image. When the number of classes was reduced from 11 to 4, the correction did not give satisfactory results. Obviously a minimum number of classes must be used in order to represent adequately the spectral variation in the image. On the other hand, the number of classes should be kept to a minimum in order to allow as many pixels as possible for each detector and class. A starting value of about 10 classes seems to be reasonable, however some experimentation may be required if results are not satisfactory.

# Chapter 5

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## **5. Geodetic and thematic accuracy of satellite-derived land cover maps**

Chapter 4 has discussed the correction of residual radiometric distortions in TM data as a means of improving the thematic accuracy in digital land cover classifications. Chapter 5 continues the discussion of map accuracy issues.

Section 5.1 looks at the issues involved in accurately coregistering and georeferencing spatial datasets for mapping the land cover of humid tropical regions. A simple approach to achieve a high geodetic accuracy by modelling the spatial distribution of registration error is described.

Section 5.2 discusses the shortcomings of traditional sample-based techniques for assessing the thematic accuracy of land cover maps. A new approach to derive reliability maps that indicate the spatial distribution of map reliability is introduced<sup>1</sup>.

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<sup>1</sup>An earlier version of section 5.2 has been published in: Corves, C. and Place, C.J. (1994): Mapping the reliability of satellite-derived landcover maps - an example from the Central Brazilian Amazon Basin. *International Journal of Remote Sensing*, Vol. 15, No. 6, pp. 1283-1294.

## **5.1. A systematic approach to ensuring a high geodetic accuracy in satellite-based land cover mapping in the humid tropics**

In an ideal remote sensing world there would be no need to waste one's time with coregistration and georeferencing of spatial data. All datasets would be available in the desired map projection at low cost. The geodetic accuracy specified by the data vendor would be correct.

For the remote sensing analyst who embarks on a land cover mapping project in the humid tropics using current satellite data and current image processing software, life is not that easy.

### **5.1.1. What are the problems?**

A series of problems are commonly encountered in georeferencing and coregistration of spatial datasets (i.e. satellite images) for mapping land cover in the humid tropics:

#### (a) Problems related to the spatial datasets:

Spatial datasets may have to be acquired at low levels of geometric correction. Products of low correction level tend to be much cheaper than georeferenced data. Sometimes also the receiving station does not provide the data at higher levels of geometric correction. The types of geometric distortions inherent to the data may not be known to the user.

#### (b) Problems related to the reference maps:

Maps of humid tropical forest regions are often available only at intermediate map scales (1:100,000 - 1:250,000). Individual map sheets may vary very strongly with respect to the level of generalisation.

#### (c) Problems related to ground control point selection:

In areas of humid tropical forests there is frequently a lack of location-invariant features that are suitable as ground control points. As a consequence, many ground control points (GCPs) of poor quality will be initially selected that need to be

detected and eliminated before mapping polynomials are derived.

(d) Problems related to the georeferencing software:

The software that is available for georeferencing (such as ERDAS) may be of poor quality, i.e. provides little help for identifying and eliminating poor quality control points and selecting the order of mapping polynomial required.

The issues to be dealt with by the image analyst are:

- \* to detect and eliminate ground control points of low geodetic accuracy before calculating the mapping polynomials
- \* to identify the lowest order of polynomial function that will achieve the specified georeferencing accuracy

Section 5.1.2 describes a simple but reliable approach to achieve these objectives.

Section 5.1.3 presents results from two case studies that illustrate the approach: (a) georeferencing system-corrected Landsat-5 TM data to topographic base maps in the UTM projection, and (b) registering Landsat-3 MSS data to system-corrected Landsat-5 TM data.

### **5.1.2. Methods**

#### **5.1.2.1 Coordinate transformation algorithms**

An efficient method for coordinate transformation involves the use of polynomials of the form:

$$\text{UTM} = c_0 + c_1x + c_2y + c_3x^2 + c_4xy + c_5y^2 + c_6x^3 + c_7x^2y + c_8xy^2 + c_9y^3 + \dots$$

(Welch et al., 1985, p. 1252)

where x,y are the known image coordinates in pixel and scanline values of GCPs, and UTM refers to the map coordinates. Once the coefficients have been determined by the method of least squares, these equations may be used to solve for easting and

northing coordinates in the UTM system (or any other projection). Although higher order polynomials may achieve an improved fit to the data points, significant and unpredictable error may be introduced in the gaps between the points and in regions of the image beyond the range of the GCPs. Welch et al. (1985) have shown that 4th and higher order polynomials significantly increase registration error measured on independent check points when registering system-corrected Landsat TM data to UTM maps. The selection of GCPs on reference map and image is a very time-consuming task and the number of points required rises with the order of the polynomial. For these reasons it is desirable to employ the lowest order polynomial that achieves the accuracy required.

#### **5.1.2.2 Determining the accuracy of control points**

The accuracy of ground control points is commonly expressed in terms of Root Mean Square (RMS) error. RMS error is determined as follows.

- (1) Two coordinate pairs exist for each ground control point (GCP): (a) the target coordinates (pixels of the image that is to be registered to a reference map or master image), and (b) the reference coordinates (reference map or master image). The coefficient matrix of the coordinate transformation polynomials is derived from the control points by use of a least squares fitting procedure.
- (2) Estimates of the reference coordinates are derived by use of the inverse of the transformation matrix.
- (3) The x-residual ( $XR_i$ ) and y-residual ( $YR_i$ ) of a  $GCP_i$  are calculated as:

$$XR_i = (\text{x-coordinate}_{\text{measured}}) - (\text{x-coordinate}_{\text{estimated}})$$

$$YR_i = (\text{y-coordinate}_{\text{measured}}) - (\text{y-coordinate}_{\text{estimated}})$$

- (4) The RMS error of individual points ( $RMS_i$ ) is calculated as:

$$RMS_i = \sqrt{(XR_i)^2 + (YR_i)^2}$$



- (5) The total RMS error (T) is the average RMS error of all points. It is calculated as:

$R_x$  = average x-residual of all GCPs

$R_y$  = average y-residual of all GCPs

T = average RMS error of all GCPs

n = the number of GCPs

i = a particular GCP

$$R_x = \sqrt{\left( n^{-1} * \sum_{i=1}^n (XR_i^2) \right)}$$

$$R_y = \sqrt{\left( n^{-1} * \sum_{i=1}^n (YR_i^2) \right)}$$

$$T = \sqrt{(R_x^2 + R_y^2)}$$

(ERDAS, 1991a)

While information on GCP error is summarised in the 'RMS error', it is important to note that the information on the vector properties of the error is lost: a residual can be positive or negative in both x and y. This information is extremely useful for determining which order of polynomial is required.

### 5.1.2.3 The analysis procedure

The analysis procedure described below represents a simple and reliable approach to (a) identifying the order of polynomial required in a particular mapping project, (b) eliminating unreliable control points, and (c) verifying that no trend between the magnitude of georeferencing error and the coordinates of points remains in the georeferenced data.

### (1) Determine which order of polynomial is required

- \* Select GCPs from image and reference map.
- \* Calculate the total RMS-error for successively deleting the point with the highest RMS error for a 1st order polynomial (ERDAS). Plot the total RMS-error versus the number of remaining ground control points (EXCEL). Identify through visual examination of the plot the number of points that contribute most to total RMS error (cut-off value).
- \* Derive a 1st order polynomial for the points below the cut-off value.
- \* Calculate x- and y-residual for each point and plot these against the x- and y-coordinates of the points. The shape of the resulting curves indicates the order of the mapping polynomial that is required.

### (2) Eliminate points of questionable reliability ('bad' points)

- \* Calculate the total RMS-error for successively deleting the point with the highest RMS error for the order of polynomial determined above (ERDAS). Plot the total RMS-error versus the number of remaining ground control points (EXCEL). Identify through visual examination of the plot the number of points that contribute most to total RMS error (cut-off value).
- \* Eliminate the control points above the cut-off value.

### (3) Model the accuracy of the georeferenced map

- \* Calculate the mapping polynomial of the order identified above from the remaining set of control points.
- \* Calculate the x- and y-residuals of all points and plot these against the x- and y-coordinate of the points. The resulting graph should now exhibit a random spread of the points around the zero-residual line. If the spread of the residuals suggests a non-linear relationship between residuals and coordinates of GCPs, the order of the polynomial mapping function must be increased.

- \* Calculate the polynomial regression function through residual and coordinate (e.g. x-residual versus x-coordinate) in order to highlight remaining trends for the dependence of georeferencing error on point position. The existence of any significant trend indicates that 'bad' points still exist among the ground control points.

The application of this technique will now be demonstrated with two examples.

### **5.1.3. Case studies**

#### **5.1.3.1. Image-to-map: Georeferencing system-corrected Landsat TM data to 1:100,000 scale topographic maps in the UTM projection**

90 GCPs were selected on the TM image and the 1:100,000 scale maps. The spread of the points with reference to the images is shown in Figure 5.1. Figure 5.2a shows a plot of total RMS error versus the number of ground control points for successive deletions of the point with the highest total residual for a 1st order polynomial. After visual examination of Figure 5.2a, the cut-off value was identified as '74'.

The coefficients for a first order polynomial were calculated using 74 points. X- and y-residuals for all 90 points were calculated. Figure 5.3 shows a plot of the residuals against the x- and y-coordinates of the points. X-residuals plotted against the x-coordinate of the points exhibit a pronounced 2nd order relationship (Figure 5.3a). Y-residuals exhibit a weak 2nd order relationship when plotted against the y-coordinate of the point (Figure 5.3b). It was concluded that a 2nd order polynomial was required to georeference the image.

Figure 5.2b shows a plot of total RMS error versus the number of GCPs for successively deleting the point with the highest total residual for a 2nd order polynomial. Through visual examination of Figure 5.2b, the cut-off value was identified as '81'. The coefficients for a 2nd order polynomial were calculated using 81 points. Figure 5.4 shows plots of x- and y-residuals against the x- and y-coordinates of the points. The 2nd order relationship between the residuals and the coordinates of the points has been removed. The regression analysis shows that the x- and y-residuals of a point in the georeferenced TM data are now independent of the point coordinates.

### **5.1.3.2. Image-to-image: Registering Landsat MSS data to system-corrected Landsat TM data.**

The second example refers to registering Landsat-3 MSS data to system-corrected TM data, as would be required for an analysis of land cover change. 76 GCPs were initially selected from the two data sets. The spread of the points is indicated in Figure 5.1. Figure 5.5a shows a plot of total RMS error versus the number of ground control points for successive deletions of the point with the highest total residual for a 1st order polynomial. The cut-off value was identified as '73' and, therefore, the coefficients for a 1st order polynomial were calculated using 73 points. X- and y-residuals for all 76 points were calculated and plotted against the x- and y-coordinates of the points. Figure 5.6a shows that a pronounced 3rd order relationship exists between the x-residual and the x-coordinate of a point, while a 2nd order relationship appears to exist between the y-residual and the y-coordinate of a point (Figure 5.6b). Consequently, a third order polynomial is required to register the MSS data to the TM data. Figure 5.5b shows a plot of total RMS error versus the number of GCPs for successively deleting the point with the highest residual (total RMS error) for a third order polynomial. The cut-off value was identified as '72'. Consequently, the coefficients for a 3rd order polynomial were calculated using 72 points. X- and y-residuals were calculated. Figure 5.7a shows a plot of x- and y-residuals versus the x- and y-coordinates of the points. The 3rd order relationship between x-residual and x-coordinate of a point as well as the 2nd order relationship between y-residual and y-coordinate of a point have been removed. The regression analysis between coordinates and residuals confirms that no trend remains.

The effect that not detecting and deleting all 'bad' control points may have on the geodetic accuracy of the registered data if polynomials of 3rd order are used, is demonstrated by the following example. The coefficients for the third order polynomial were calculated from the best 73 points (total RMS-error: 70.46 metres) instead of from the 72 best points (total RMS-error: 63.30 metres). Figure 5.8 shows a plot of x-residual versus the x-coordinate of the points. It can be observed that even though the pronounced third order relationship has been removed, x-residuals remain dependent on the x-coordinate of the points. The misregistration of the MSS data over a distance in scan direction of 150 kilometres amounts to 80 metres or almost three Landsat TM pixels. The example demonstrates that relying on 'total RMS error' may lead to 'bad' points not being identified and eliminated, which may cause

substantial misregistration. The problem can be avoided by spreadsheet modelling of the relationships between error magnitude/direction and point coordinates.

#### **5.1.4. Summary of results and conclusions**

- (1) Spreadsheet modelling represents a simple and reliable approach to (a) identifying the order of polynomial required in a particular mapping project, (b) eliminating unreliable control points, and (c) verifying that no trend between the magnitude of georeferencing error and the coordinates of points remains in the georeferenced data.
- (2) For Landsat MSS and TM sensors the method can be simplified: Due to the nature of the sensors (scanning devices), the highest geometric distortions tend to occur in the across track direction (due to view angle and Earth curvature effects). It is, therefore, sufficient to plot only the x-residual against the x-coordinate of the control points in order to identify the correct order of polynomial.
- (3) Conclusions concerning the order of the polynomial are made solely with respect to the area covered by the ground control points. A first order polynomial may be sufficient to achieve a specified accuracy for registering a small image extract, while a 2nd or 3rd order polynomial may be required for achieving the same accuracy when registering an entire scene.
- (4) Particularly for 2nd and 3rd order polynomials, single 'bad' points remaining in a large set of GCPs may introduce significant distortions. Hence, while attempting to maintain the maximum number of points, it is preferable to eliminate one point too many than one too few.
- (5) Total RMS error is sometimes misunderstood as being a measure of the geodetic accuracy of the georeferenced map. The formulas used to calculate total RMS error involve squaring the residuals. Whereas the residuals indicate the direction of distortion (plus or minus in x and y), the total RMS error does not. An increase in the number of control points tends to result in an increase in total RMS error. However, if error in control point location is assumed to be distributed at random with respect to its direction, increasing the number of

points can be expected to lead to an average zero distortion (provided that erroneous points are properly eliminated). Even though a large number of points may in fact decrease georeferencing error, total RMS error would indicate the opposite. If control point sampling does not allow the exact definition of image points and/or reference map coordinates, a larger sample of control points should be selected in order to make use of the statistical averaging of the positional error of each individual point.

- (6) Selecting ground control points is a very time consuming task. Selecting 100-120 points for rectifying an entire TM or MSS scene may take 3-5 days of operator work. The rectification itself demands significant amounts of processing time. If satellite data that are georeferenced to the required map projection are available from the data distributor, these should be preferred instead of system-corrected data.

## **5.2      Assessing the thematic reliability of digital land cover classifications: numerical accuracy assessment versus reliability mapping.**

### **5.2.1.      Introduction**

With the increasing use of digital geographic information the assessment of error in remote sensing products and geographic information systems has become an urgent research issue (Lunetta et al, 1991). The research reported in this section had two objectives:

- (a) To develop a methodology for assessing the reliability of digitally classified land cover maps in situations that do not allow sample-based accuracy assessment.
- (b) To develop a methodology that facilitates the location of possibly unreliable regions in digitally classified land cover maps.

### **5.2.2.      Assessing Accuracy and Reliability of Land cover Maps**

The accuracy and reliability of a classification depend on two factors, which jointly are frequently called 'misclassification'. 'Misclassification' needs to be separated into two aspects: (1) misclassification due to low class separability, and (2) mislabelling by the image analyst.

Misclassification is due to spectral overlap of two or more user-defined map units. As a consequence, if the classification of the image is based on spectral image information only, the computer does not have any means of differentiating such overlapping classes. Misclassification can be quantified with the classical sample-based methods of accuracy assessment: the error matrix, accuracy and confidence estimates based on the binomial distribution, and the Kappa coefficient.

Mislabelling occurs in situations where there is an incomplete knowledge of the land cover types present in the project region. This may result in missing a number of land cover types when classification categories are defined. Pixels belonging to any of the missing classes will either be wrongly classified into any of the existing ones or remain unclassified. Incomplete knowledge of the land cover and mislabelling pose a



serious problem to mapping inaccessible areas. The problem is aggravated if mapping is performed by people who are not familiar with the area being mapped. Mislabelling is more difficult to detect than misclassification, as it requires extensive verification of the land cover map in the field. If the area being mapped is large and inaccessible, a means of selecting areas for field verification is needed. This can be achieved by 'reliability maps' as described below.

In the following discussion, the two expressions 'accuracy' and 'reliability' will be used. Accuracy refers to the comparison between contextual information (ground truth, air photographs, maps) and the classified image, resulting in measures such as the 'error-matrix', 'overall classification accuracy' (OCA), or the Kappa-coefficient. Reliability is a measure which is proposed here, based on the spectral distance (from class mean) values for each pixel in a probability file, which is created during the classification. Pixel vectors which have a large distance to the mean vector of the class they have been assigned to, are likely to be the most unreliable ones in a classified image.

Strategies to assess the accuracy and reliability of classified images can broadly be divided into two groups: (1) Methods which are based on drawing a representative sample of pixels from the classified image and comparing it with contextual information and (2) techniques which - based on so-called 'probability files' - allow the user to identify pixels / regions within the image which have a high or a low probability of being correctly classified.

Traditionally, the focus of accuracy assessment has been put on the use of error matrices and various matrix coefficients which attempt to summarise the information contained in such matrices. However, the use of probability files opens up new perspectives for the assessment of classified images. The following paragraph will briefly review sampling schemes and commonly used sampling-based methods of accuracy assessment. Then, a technique to derive reliability maps for classified images will be described.

### **5.2.2.1. Sample-Based Methods of Accuracy Assessment**

#### **(a) Sampling and sample verification**

In order to assess map accuracy, one must determine sample size, sampling strategy and the statistical tests to be used for evaluating the samples (Dicks and Lo, 1989). The choice of a sampling scheme determines the statistical techniques that are to be applied in evaluating the sample (Green et al., 1993; Stehman, 1992). The sampling scheme needs to satisfy the following criteria (Ginevan, 1979):

1. The probability of accepting a map of low accuracy (consumer's risk) should be low;
2. The probability of rejecting a map of high accuracy (producer's risk) should be low;
3. A minimum number of ground truth samples should be required.

Ginevan (1979) and Rosenfield et al. (1982) discuss methods of estimating the minimum sample size required. Generally, the larger the sample size, the greater the confidence one can have in assessments based on that sample. Simple random sampling can be biased towards classes with a high population of pixels. Stratified random sampling is used when it is necessary to make sure that small, but important, areas are to be represented in the sample (Congalton, 1988). Stratified systematic unaligned sampling and systematic sampling must be used with caution. Periodicity in error can result in poor estimates of population parameters (Congalton, 1988; Stehman, 1992).

Both random and systematic sampling schemes may pose serious problems in terms of verifying the land cover of sample pixels in regions which are not easily accessible for field visits. Two strategies are commonly employed in order to reduce the cost of sample verification: (a) a sample of reduced size, or (b) field verification is replaced with interpreting the land cover of sample pixels from air photography. Both strategies can lead to sample-based accuracy assessment of little reliability.

An example for case (a) can be found in a study on mapping tropical vegetation from Landsat TM data in south-west India reported by Saxena et al. (1992). Saxena et al. carried out a digital land cover classification using 10 classes. The percentage of total project area occupied by individual classes ranged from 0.01 to 21.70 percent. 129 pixels were randomly selected for accuracy assessment. The extremely uneven distribution of the pixel population between classes suggests that random sampling may not have been ideal in this case. Furthermore, the total number of sample pixels was so low that no class had more than 21 sample pixels, and several classes had only between 3 and 7 sample pixels. Nevertheless, Saxena et al. proceeded to calculate percentage accuracies from as little as 3 pixels (e.g. '71.43' percent accuracy calculated from 5 pixels).

Unfortunately, this uncritical approach is not untypical of other studies published in internationally renowned remote sensing journals. Another, even more misleading, approach to numerical accuracy assessment is to calculate map accuracy indices from the pixels used to train the classification algorithm (see, for example, Saxena et al., 1992). Accuracy assessments of these characteristics tend to be heavily biased towards inflated accuracy values. The question must be asked whether this was, in fact, the very intention of the whole exercise. Only one conclusion is possible: if a properly designed accuracy assessment can not be performed for resource limitations, it is much more honest and useful for map users to state this clearly and rather to perform a qualitative, written description of possible accuracy problems.

Even if an adequate sampling scheme has been chosen and the sample size is sufficiently large, the verification of the sample by interpreting the land cover of sample pixels from air photography may be highly dependent on operator judgement. Congalton and Green (1993) undertook a detailed assessment of the possible error arising from the use of colour aerial photography (1:12,000 or larger scales) for accuracy assessment instead of ground visits. Their study revealed significant problems: (a) the land cover of test sites may have changed between the acquisition of aerial photography and the acquisition of the satellite data; (b) assuming ground reference data to be truth, 8 out of 40 photo sites that were visited on the ground were incorrectly photo-interpreted; (c) of 27 sites that were photo-interpreted by two different interpreters, 11 or 41 percent were given a different class by each interpreter. Such problems with the verification of test pixels draw into severe doubt the entire concept of accuracy assessment based on samples of pixels, when mapping

the land cover of large, inaccessible areas.

The conditions to perform sample-based accuracy assessment in the Manáus region were particularly adverse. Aerial photography has not been acquired since the 1970s. The lack of roads and the inaccessibility of the terrain made the verification of a statistically valid sample of pixels on the ground for a project region of approximately 4000 square kilometres unfeasible.

## **(b) Sample Evaluation**

The results of verifying a sample of pixels are commonly presented in the form of an error matrix. The reference data are represented by the columns of the matrix and the classified data are represented by the rows. The major diagonal represents the agreement between the two. The Overall Classification Accuracy is calculated by dividing the sum of the entries that form the major diagonal (i.e. number of correct classifications) by the total number of samples taken. The Producer Accuracy is the probability for a reference sample to be correctly classified. The User Accuracy is the probability that a sample from the classified image actually represents that category on the ground. A numerical example is given in Story and Congalton (1986).

The error matrix can be statistically evaluated. The most common statistical test is based on the binomial distribution (Aronoff 1985, 1982a, and 1982b; Ginevan 1979; Rosenfield and Melley 1980; Thomas and Allcock 1984). Binomial probabilities may be calculated for the classification as a whole or for individual classes.

Various coefficients based on discrete multivariate theory have been proposed to summarise the information of error matrices. Most commonly used in the field of accuracy assessment is the Kappa coefficient (Bishop et al. (1975); Rosenfield and Fitzpatrick-Lins (1986)). Congalton et al. (1983) proposed the use of Kappa as a measure of overall agreement between the classification (i.e. agreement between classification and reference data as indicated by the major diagonal) and the chance agreement which is indicated by the product of the row and column marginals of the error matrix. However, Foody has pointed out that Kappa may overestimate the degree of chance agreement (Foody, 1992). The correct formulation of the Kappa coefficient is given by Hudson and Ramm (1987). Kappa indicates how well the classification agrees with the reference data. The coefficient can also be calculated

for individual categories of a matrix. The large sample asymptotic distribution of Kappa is normal (Congalton and Mead, 1983). This allows the calculation of a test statistic Z which compares the difference between two Kappa coefficients and is itself normally distributed. Using this statistic, the analyst can test whether two matrices (representing two classifications) are different at a specified level of significance or not (Congalton et al., 1983).

### **(c) Sample Based Methods - The Limitations**

The traditional sample-based methods of accuracy assessment allow the detection of misclassification in the strict sense which is due to spectral overlap of user defined classes. The validity of sample-based accuracy assessment depends on a variety of factors:

- \* A sampling scheme appropriate to the conditions of the study area has been selected.
- \* The number of sample pixels for each class satisfies the requirements of the statistical methods to be applied.
- \* The land cover type of all sample points can be established without error. In particular, operator judgement is not a critical factor in this respect.

In practice, these factors frequently can not be complied with due to limitations in time and other resources. However, any numerical accuracy assessment, even if performed in a statistically valid way, falls short in two very important aspects:

- \* It will fail to detect classes that are missing in the classification system.
- \* It fails to give any indication as to where in the classified image unreliably classified pixels are located.

#### **5.2.2.2. Probability File Based Methods of 'Reliability Assessment'**

During a Mahalanobis or Bayesian decision rule classification, for each pixel the distance to the mean vectors of all classes is calculated. Pixels are assigned to the

class with the minimum distance. Normally, the classification results in two output files. Firstly, the classified image, and secondly, the so-called probability file. The following paragraphs introduce a technique to derive a 'reliability map' - based on the information available in the probability file - in order to indicate the location of those regions of the classified image which are likely to have been unreliably classified.

**(a) Probability Files**

As a result of any image classification based on Mahalanobis Distance or Bayesian decision rules, there will be regions within the classified image which have a high reliability (high likelihood of being accurately classified) and others which have been less reliably classified. Generally, it may be assumed that those pixels which exhibit the largest spectral distance to the mean vector of the class they have been assigned to during the classification are the least reliable ones. This information about spectral distances is available in some image processing packages (e.g. ERDAS) in so-called 'probability files'. The actual values in the probability file depend on the classification method used. If the classification was based on Mahalanobis distance or Bayesian decision rule, then each data file value in the probability file is the Mahalanobis distance between the measurement vector of the pixel and the mean vector of the class to which it has been assigned. The Mahalanobis distance is defined as:

$$D = (X - M_c)^T (Cov_c^{-1}) (X - M_c)$$

where

- D = Mahalanobis distance
- c = a particular class
- X = the measurement vector of the candidate pixel
- M<sub>c</sub> = the mean vector of the signature of class c
- Cov<sub>c</sub> = the covariance matrix of the pixels in the signature
- Cov<sub>c</sub><sup>-1</sup> = inverse of Cov<sub>c</sub>
- T = transposition function

(ERDAS, 1991b)

In all these measurements, the probability of membership of the allocated class decreases with an increase in the distance measurement.

## (b) Thresholding a Classified Image

Using the probability file, the analyst can threshold the classified image. Thresholding involves weeding out those pixels whose 'probability' file value is above a certain user-defined threshold, indicating that such pixels are spectrally distant from the class they have been assigned to. Such pixels are considered to be the most likely ones to be classified incorrectly. Thresholding can be a means of improving the accuracy of image classifications (Foody, 1990).

For image classifications based on either the Mahalanobis or Bayesian algorithms, chi-square statistics may be used to derive threshold values, if the following requirements are - at least approximately - fulfilled. Firstly, the signatures used in the classification must approach normal distribution in every band (as required for a maximum likelihood algorithm), and secondly, the input bands should approach independence (as after principal components analysis). Then, the histogram of all those pixels which have been assigned to any one class will approximate a chi-square distribution. The fulfilment of the above requirements may be demonstrated graphically by displaying the histogram of the corresponding pixels in the probability file for each class.

The chi-square distribution is mathematically defined as

$$\chi^2(N) = \frac{\sum_{i=1}^N (Y_i - \mu)^2}{\sigma^2}$$

where

N = number of independent observations taken at random from a normal population with



$\mu$  = population mean, and  
 $\sigma^2$  = population variance

(Hays and Winkler, 1970)

For the histogram of the probability file, the x-axis represents the distance values, and the y-axis the frequency of any specific instance of distance values. The area under the curve represents the number of points that exhibit a distance value between zero and a user-specified upper distance limit. This allows the selection of a threshold value T for the distance, such that a certain percentage of all the pixels within any one class have a distance value between zero and T. In practice the analyst may wish to threshold for any one class the 5 percent most unreliably classified pixels, or in other words, retain only the 95 percent most reliably classified pixels (doing this is called 'selecting a 95 % confidence limit'). The corresponding threshold value can be found in tables of the chi-square distribution. The chi-square values are a function of (1) the confidence level, and (2) the number of degrees of freedom, which is represented by the number of input bands to the classification.

### (c) **Reliability Maps**

The probability file stores the reliability information for each pixel of the image. If the file is mapped to a range of 0...255 and displayed on the VDU, its visual appearance is rather 'speckled' (Figure 5.9). This poses the problem of how to derive a reliability map from this information which represents a small number of homogeneous regions of reliability in order to produce results which are easily interpreted. The following paragraphs show how probability files can be used to create reliability maps that represent the major regions of unreliably classified pixels only.

#### **5.2.3. Approach**

The land cover mapping process was structured into three phases. In the first phase, based on the 15-08-88 image and limited ground truth, a preliminary land cover map and the accompanying reliability map were produced. In the second phase, field checking of both maps was carried out at Manáus. This included extensive work on the ground as well as the acquisition of overflight photography as an intermediate

level of resolution in the image interpretation process. In the third stage, based on the 08-08-91 image and the much improved knowledge of the project region's land cover types, a definitive land cover map was produced.

#### **5.2.3.1. Phase 1: Land cover Mapping from 15-8-88 Landsat TM data**

Based on limited ground truth a supervised maximum-likelihood classification was performed based on the 15-8-88 TM image. For this classification, a reliability map was produced as described below. Training sites for the following land cover classes were known at this stage:

1. Sediment poor water ('whitewater').
2. Sediment rich water ('blackwater').
3. Forest on terra firme.
4. Forest of the flood plains.
5. Terrestrial grassland.
6. Floating aquatic grasses.
7. Urban areas.

#### **(a) Production of the Reliability Map**

The probability file was smoothed with a low pass filters (all cells with equal weighting). An 11\*11 kernel size proved to be the most useful one in terms of removing the speckle while keeping the major features of the probability file (Figure 5.10). By comparing it with the original probability file (Figure 5.9), it can be seen that even though the smoothing is strong, the smoothed image still shows the same spatial pattern of bright (unreliably classified) and dark (reliably classified) regions as the original probability file.

Based on the 11\*11 smoothed probability file, numerical thresholding was performed at a confidence level of 90 percent. This resulted in a preliminary reliability map showing two classes: (1) pixels rejected at a 90 % confidence level, and (2) background. At this stage, the preliminary reliability map still showed a large number of small clusters of a few pixels only, which were regarded as non essential. In order to eliminate such clusters, the preliminary reliability map was filtered with a 11\*11 majority filter. The final reliability map (Figure 5.11) showed the following class

percentages:

Class	Description	Percentage
1	'unreliable'	12.5
2	background	87.5

Even though the confidence level was chosen at 90 percent, the actual level of rejection with 12.5 percent is slightly higher than the expected 10 percent. This is a result of the fact that the 2 conditions implicit in the maximum likelihood decision rule, (1) normal distribution of class signatures in all bands, and (2) band independence, were not completely fulfilled.

#### **(b) Overlaying the Reliability Map on the Land Cover Map**

It proved useful to obtain copies of the false colour composite and the land cover map with the corresponding reliability information overlaid onto it for use during field verification, especially for targeting areas during overflights in order to identify 'missing classes'. In order to obtain such maps, the following approach was chosen. Using a boundary detection filter, the bounding polygons of class 1 ('unreliable') of the reliability map were obtained. The resulting boundary map was overlaid onto the false colour composite and onto the land cover map. Figure 5.12 shows the 1988 land cover map with overlaid boundaries for 'unreliable areas'. Reliability maps, exhibiting different levels of spatial detail, can be created by varying the kernel size of the low pass filter used to smooth the probability file. A smaller kernel will result in a reliability map showing a higher degree of small scale detail.

#### **5.2.3.2. Phase 2: field verification**

One application of a reliability map as created above is the identification of unreliably classified regions as target areas for further field checks. The utility of the reliability map for this purpose was evaluated by fieldwork during August 1991. Due to the substantial size of the project region (4000 square kilometres) and its poor accessibility by road and river, the reliability maps were of crucial importance for selecting areas for ground verification as well as for the acquisition of air

photography. By verifying the land cover of a selection of those areas which were unreliably classified, several further land cover classes which had not been known in the previous classification could be identified. These classes included: (1) secondary forest on terra firme, (2) swamps in areas of whitewater influence with a mixture of herbaceous and bush vegetation, and (3) several stages of forest succession in whitewater flood plains.

Figure 5.13a shows an extract of the 1988 land cover map with overlaid 10 percent reliability contours. This area was verified both by overflight and on the ground. Whereas in the 1988 classification the areas outlined by the reliability contours were classified mostly into a mixture of the classes 4 (floodplain forest), 5 (terrestrial grassland), and 6 (floating aquatic grasses), field verification proved that it was covered largely by none of these classes but by upland secondary forest, a class not included in the 1988 classification. Figure 5.13b shows the same area classified from the 1991 image after including the class 'Secondary Forest on Terra Firme'. It can be seen that the reliability contours define reasonably well areas of upland secondary forest.

During field verification and overflights, it proved extremely useful to have 2 different 'reliability maps' which were created by selecting 2 different confidence levels (3 percent and 10 percent) at the thresholding stage. This enabled a structured and time-efficient approach to field verification, starting with the inspection of the most unreliable areas and progressing from there into regions of higher degrees of reliability. At the actual field stage, reliability contours overlaid on false colour composites (TM bands 4, 5, and 3) proved more useful than overlays with the classified land cover map, because orientation in the field and from the plane was easier based on the false colour composites.

#### **5.2.3.3. Phase 3: land cover mapping from 8-8-91 Landsat TM data**

Based on the improved ground truth and a more recent Landsat TM image (08-08-91), a new land cover map was produced which is described in chapter 6.

#### **5.2.4. Conclusions**

Reliability maps as described in this section represent a step towards a spatial

description of the reliability of satellite derived land cover maps. Whereas misclassification due to spectral overlap of classes can be estimated based on traditional sampling based techniques, reliability maps help to reduce thematic map error due to mislabelling and aid in the identification of missing classes as well as improved training site selection in supervised classification. In situations which do not permit the exact assessment of thematic map accuracy, reliability maps increase the utility of the land cover map in the decision making process and decrease the risk of taking decisions based on erroneous maps.

# Chapter 6

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## **6. The use of ERS-1 SAR and Landsat Thematic data for studying vegetation in the Manáus region**

Chapters 4 and 5 have highlighted several measures that can be taken in order to improve the thematic and geodetic accuracy of satellite-derived land cover maps. This chapter examines which types of vegetation can be mapped from ERS-1 SAR and Landsat TM data.

Section 6.1 provides an assessment of the potential of ERS-1 SAR data for mapping vegetation and forest clearing.

Section 6.2 presents an analysis of the information content of the Landsat TM spectral bands for mapping the vegetation of the Manáus region. The separability of vegetation types in TM spectral space is evaluated.

Section 6.3 describes the mapping of the vegetation of the Manáus region by a hybrid technique, involving the visual interpretation of the floodplain / upland boundary from ERS-1 SAR data and the digital classification of Landsat TM data.



## **6.1 Assessment of ERS-1 SAR data for mapping vegetation and monitoring forest clearing in the Manáus region**

Section 6.1 assesses which information can be extracted from ERS-1 SAR PRI data for the study of vegetation in the Manáus region.

The study has concentrated on the following issues:

- \* Which vegetation types are distinct in terms of backscatter amplitude?
- \* To what extent do seasonal changes in backscatter exist?
- \* Can the forest / non-forest boundary be detected on ERS-1 SAR data?
- \* Which dates of imagery are most suitable to detect deforestation in the Manáus region?
- \* What are likely obstacles to mapping deforestation in the Manáus region through the digital classification of ERS-1 SAR data?
- \* Identification of a promising approach for monitoring deforestation

The following analyses were performed:

- \* Analysis of seasonal changes in backscatter amplitude.
- \* Classification of ERS-1 SAR data of a terra firme test site into forest / non-forest.
- \* Comparison of the ERS-1 forest map with a Landsat TM forest map.
- \* Segmentation of multi-temporal ERS-1 SAR.

### **6.1.1 Test site**

A test site (15 km<sup>2</sup>) for the detailed study of forest / non-forest separability on terra firme was selected near the village of Iranduba, about 40 kilometres south-west of Manáus between the Rio Negro and the Rio Solimões. The area is characterised by plateaux of the Tertiary sediments of the Barreiras Formation, dissected by steep and narrow valleys. A large number of small to medium-sized clearings has been

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<sup>1</sup> The image segmentation has kindly been carried out by Ron Caves and Sean Quegan at the School of Mathematics and Statistics, The University of Sheffield, PO Box 597, Sheffield S3 7RH, England.

established in this region in the late 1970s and during the 1980s. Clearings have been made primarily for cattle ranching and in order to provide fuelwood for the local brick-making industry. Some smaller clearings have been established for smallholder agriculture. Forest clearing in the region starts with the felling of trees in the early to mid dry season (May to August). The debris is left to dry and (often) is burnt towards the end of the dry season (August to October).

### **6.1.2 Data**

The study has used Landsat TM data of 8 August 1991 (path 231, row 62) and ERS-1 SAR PRI data of descending orbits (track: 196; frames: 3663, 3681) of 8 dates (15-5-92, 19-6-92, 24-7-92, 6-11-92, 11-12-92, 15-1-93, 30-4-93, 4-6-93). A reconnaissance survey of vegetation and land use has been carried out in July-September 1991 (see chapter 4 for details).

### **6.1.3 Analysis of backscatter seasonality**

#### **6.1.3.1 Methods**

The ERS-1 SAR PRI data were compressed from 16 bit to 8 bit by dividing by '3'. In order to allow for the exact comparison with the 8 August 1991 Landsat TM image, the ERS-1 images were registered to the TM data using cubic convolution resampling to the 30 metres by 30 metres grid size of TM data.

The resampling reduced the autocorrelation between adjacent pixels to 0.05 (in PRI data it is about 0.6). Also, the resampling appeared to preserve the first order statistics, i.e. the data fitted a 3-look speckle amplitude model, square root gamma probability density function with order parameter 3 (personal communication Ron Caves, 1995; for details on the statistical models of radar data refer to Caves, 1993).

Homogeneous sample areas of all vegetation types were delineated for the analysis of backscatter seasonality (the number of pixels was higher than 200 in all samples). The signature legends in Figures 6.1 and 6.2 refer to the vegetation formation codes used in Table 6.1.

### 6.1.3.2 Results

#### (a) Terra firme test site

No significant differences in backscatter level were observed for different forest types. Secondary forest could not be differentiated from primary forest (Figure 6.1.a).

One site that during field verification in August 1991 was covered by a dense stand of ferns (about 1.50 metres in height) with some scattered *Cecropia* trees (2-4 meters in height) could not be differentiated from forest sites only 9 months later (Figure 6.1.a: signature 3.5.a.2). Grassland exhibited a generally lower level of backscatter than woody vegetation.

However, an increase in backscatter from grassland was observed during the rainy season from December to May. The highest contrast in backscatter between woody vegetation and pasture existed in the dry season from June to October (Figures 6.1.a,b). Relief induced strong backscatter variations. Forest on steep slopes facing away from the sensor exhibited low backscatter levels similar to grassland.

Only a few relatively small areas of forest appear to have been cleared in the project region during the period covered by the available ERS-1 SAR data. Two such areas were examined to assess the detectability of clearings through time. Area '1' (forest clearing '1' on Figure 6.1.c) was covered by secondary forest in August 1991. The drop in backscatter suggests that the area has been cleared of its secondary forest between 15 May and 19 June 1992. Backscatter remained low until 4 June 1993, although an increase during the rainy season typical of grassland areas occurred. Area '2' (forest clearing '2' on Figure 6.1.c) was covered by primary forest in August 1991. Backscatter from this area decreased between June / July and 6 November 1992, indicating the clearing of the area. The backscatter level remained low until 15 January 1993. However, the 30 April and 4 June 1993 images exhibited a high level of backscatter comparable to woody vegetation targets. The reason for this increase may be starting regrowth of secondary forest. No definite conclusion could be drawn due to the lack of field verification concurrent with image acquisition. Nevertheless, the example demonstrates that new forest clearings may remain visible on ERS-1 SAR imagery for a time span of only a few months (less than a year).

## **(b) Floodplains of the Rio Solimões**

Vegetation predominantly formed by woody elements exhibited an approximately constant level of backscatter throughout the year. No significant differences were observed between vegetation types dominated by trees or by shrubs (Figure 6.2.a). The level of backscatter from woody vegetation appeared to be marginally higher in whitewater floodplains (Figure 6.2.a) than on terra firme (Figure 6.1.a). Backscatter from woody vegetation targets was not influenced significantly by sub-canopy flooding.

Herbaceous vegetation showed a wide spectrum of backscatter levels. Dense mats of floating aquatic grasses exhibited backscatter levels similar to woody vegetation during the high water season (Figures 6.2.a,b).

Backscatter from herbaceous vegetation underwent pronounced seasonal changes (Figure 6.2.b). It is likely that these differences depended on seasonal changes in flooding conditions and in the morphology of the dominant grasses. However, no definitive conclusions could be drawn because field verification did not coincide with the dates of image acquisition. ERS-1 SAR data of the low water season (November) appeared to be best suited for the separation of herbaceous and woody vegetation in the floodplains. The availability of two dates of imagery (July: late high water season; November: low water season) improved the visual discrimination of herbaceous from woody vegetation.

## **(c) Floodplains of the Rio Negro**

Backscatter from woody vegetation in blackwater floodplains was approximately constant throughout the year (Figure 6.2.c). The pronounced drop in backscatter level observed for the site with low open shrub vegetation on 4 June 93 may be related to the inundation of the site. The seasonal pattern of backscatter from grassland on high-lying ground (Figure 6.2.c) resembled closely sites of similar vegetation on terra firme (Figure 6.1.b).

#### **6.1.4 Production of a forest / non-forest map of the terra firme test site by pixel-based classification of ERS-1 SAR data**

##### **6.1.4.1 Methods**

The ERS-1 SAR PRI data were compressed to 8 bit and georeferenced to the Landsat TM data as described above. Speckle reduction included a first pass with the GMAP-filter<sup>2</sup> (5\*5 kernel) and a second pass median filter (5\*5 kernel). Classifications were performed based on the minimum Euclidean Distance algorithm after interactive training.

##### **6.1.4.2 Results**

Only two classes could be differentiated based on backscatter amplitude:

- (1) 'Vegetation without woody elements': Areas of grassland without tree trunks, trees, palms, shrubs. This class included many areas of forest on slopes facing away from the sensor (topographic shadow).
- (2) 'Vegetation with woody elements': Areas of forest, secondary forest, beginning regrowth of dense herbaceous vegetation and scattered trees.

The separability of these two classes was highest in dry season imagery. Class separability improved only marginally when more than one date of imagery was used. The classification (Figure 6.3.d) based on three acquisition dates (15-5-92; 6-11-92; 4-6-93) was practically identical to ones using four to eight dates of imagery.

#### **6.1.5 Comparison with the TM forest map**

The classification of the ERS-1 data (Figure 6.3.d) was compared to a classification of the TM data (Figure 6.3.c) and the unclassified RGB composites of TM (Figure 6.3.a) and ERS-1 SAR data (Figure 6.3.b). The TM data were classified into four classes (1: grassland; 2: primary forest; 3: secondary forest; 4: early secondary

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<sup>2</sup> The GMAP filter has been developed and provided by Edmond Nezry and Franco De Grandi at the Joint Research Centre of the Commission of the European Union, Institute for Remote Sensing Applications, 21027 Ispra (VA), Italy.

regrowth). Table 6.2 shows the assignment of classes in the TM map for areas classified 'grassland' on the ERS-1 map. Table 6.3 shows the assignment of classes in the TM map for areas classified 'woody vegetation' on the ERS-1 map.

If the TM map is taken as the reference dataset, error in the ERS-1 map derived principally from two sources.

- \* Areas of woody vegetation on slopes facing away from the sensor exhibited low levels of backscatter and were misclassified as 'grassland'. This type of error leads to the overestimation of the extent of cleared areas.
- \* Cleared areas with vegetation different from grass are misclassified into the 'woody vegetation' class. This affected areas covered by early secondary regrowth (dense herbaceous, shrubs, low trees) and areas used for agricultural production. This type of error leads to the underestimation of cleared areas.

### **6.1.6 Segmentation of multi-temporal ERS-1 SAR data<sup>3</sup>**

#### **6.1.6.1 Data and methods**

Four dates of ERS-1 SAR PRI images (15-5-92, 24-7-92, 6-11-92, 11-12-92) were compressed to 8 bits and georeferenced to the TM data as described above.

The segmentation algorithm is based on an iterative process of multi-dimensional edge detection and segment growing. Detected edges are used to limit segment growing. The resulting segmentation is then used to generate a more accurate edge map and in turn an improved segmentation. Iteration continues until there is no further improvement in segment homogeneity from one iteration to the next. The segmentation generated by the previous iteration is then output. Finally, a check is made that all segment boundaries represent significant structural features. Boundaries which fail this test are deleted and the segments they separate merged. This process is useful for determining whether a segment represents a feature present in all the input

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<sup>3</sup> The image segmentation has kindly been carried out by Ron Caves and Sean Quegan at the School of Mathematics and Statistics, The University of Sheffield, PO Box 597, Sheffield S3 7RH, England.

images, just some of them, or only one. Significance is defined in terms of a probability of false alarm based on the ratio of the mean intensities of segments and their sizes.

The original single-channel version of the algorithm is described in White (1991). The Sheffield implementation of the single-channel version of the algorithm and its application to ERS-1 images is discussed in Quegan et al. (1993). Some initial results on multi-dimensional segmentation are given in Caves and Quegan (1994).

The similarities and differences between the segmentation of the different images are most easily interpreted by looking at the mean value within segments or the segment boundaries. RGB composites of the mean images appear mainly grey indicating little change. Coloured regions indicate areas of change. For the assessment of the segmentation, the segment boundaries were overlaid onto the ERS-1 SAR data (Figure 6.4.a) and the Landsat TM data of 8-8-91 (Figure 6.4.b).

#### **6.1.6.2 Results**

- \* With only a few minor exceptions the segmentation algorithm created segments that represented accurately areas of distinct backscatter amplitude (Figure 6.4.a). The segmentation was relatively robust against small-scale terrain-induced distortions of backscatter amplitude, particularly if the regions concerned were of linear shape.
- \* The overlay of the segment boundaries derived from the 6-11-92 ERS-1 image onto the TM data of 8-8-91 confirmed that ERS-1 backscatter amplitude does not allow for the discrimination between primary forest, secondary forest, and early secondary regrowth (Figure 6.4.b).
- \* The false colour composite of segment mean images (red: 15-5-92, green/blue: 6-11-92) highlights terra firme areas that are likely to have been cleared between the acquisition dates in red. Areas where no change has occurred appear in different tones of grey (Figure 6.4.c). However, in the floodplain, 'red' indicates areas that are covered by floating aquatic grasses during the high water season (high backscatter amplitude). These areas are mostly covered by terrestrial grasses during the low water season (low backscatter). Therefore, an



automated change detection algorithm would need to separate between floodplains and terra firme regions. The location of the floodplain boundary can be visually interpreted from ERS-1 SAR images.

### **6.1.7 Texture**

Texture has been assessed based on PRI data (compressed to 8 bit). The visual examination of the data did not suggest the existence of texture differences between grassland and woody vegetation. The coefficient of variance did neither detect any texture differences between vegetation types. 'Texture' resulted mainly from relief and land/water transitions.

### **6.1.8 Conclusions**

#### **(a) Vegetation mapping**

On level terrain of terra firme, two classes existed in terms of backscatter amplitude: (a) vegetation with woody elements, and (b) vegetation without woody elements (i.e. grassland). Neither secondary forest nor early secondary regrowth could be differentiated from primary forest. Backscatter from woody vegetation targets in the floodplains was not (or, at most, only very marginally) influenced by sub-canopy flooding. Backscatter amplitude from predominantly herbaceous vegetation in the floodplains was strongly influenced by seasonal changes in flooding conditions and vegetation structure. These results correspond closely to results obtained by other researchers (see section 1.2.3).

#### **(b) Mapping the forest / non-forest boundary on terra firme**

Digital mapping of the forest / non-forest boundary of terra firme areas in the Manáus region would have to overcome the following obstacles:

- \* Relief-induced distortions: Relief-induced distortions in backscatter are pronounced in the Manáus region. In particular forest on slopes facing away from the satellite exhibit low backscatter values that are very similar to

grassland on level terrain.

- \* Highly variable backscatter from open water surfaces: Backscatter from open water surfaces varies strongly depending on wind conditions.
- \* Highly variable backscatter from herbaceous vegetation in the floodplains: Backscatter from herbaceous vegetation in the floodplains varies depending on seasonal flooding conditions. During the high water season, herbaceous vegetation in the floodplains exhibits backscatter levels similar to woody vegetation.

Even if these problems could be solved, it appears that the potential of mapping the true extent of cleared areas from ERS-1 SAR amplitude data would still be limited by the low capability to discriminate forest from areas of early secondary regrowth or secondary forest.

#### **(c) Detecting forest clearing**

Dry season imagery (June - early November) provided the highest contrast in backscatter level between woody vegetation and grassland. Deforested areas remained detectable for several months, however, for less than a year. October and September appeared to be the months most suitable for detecting newly cleared areas on single date imagery. The use of one image from the late rainy / early dry season (May-June: before forest clearing starts) and one image of the end of the dry season (late October / early November) allowed for the detection of forest clearing between image acquisition dates.

#### **(d) Potential use of ERS-1 SAR data**

ERS-1 SAR amplitude data appeared to be useful for the updating of existing vegetation maps for recent forest clearing in terra firme regions. This would probably require at least two images per year: (a) late rainy / early dry season, and (b) late dry season. This study suggests that a promising approach to the automated detection of forest clearing might involve the following elements: (1) multi-temporal segmentation of ERS-1 SAR data, and (2) segment classification by matching the temporal backscatter profiles of the resulting segments with reference profiles in

spectral libraries.

The following section will report an analysis of the information content of TM spectral bands for vegetation mapping and an analysis of the separability of vegetation types in Landsat TM's spectral space.

## **6.2. Analysis of Landsat TM spectral information for mapping the vegetation of the Manáus region.**

Section 6.2.1 briefly examines the information content of TM bands for mapping the vegetation of the Manáus region. Bands 4, 5, and 3 are identified as the bands with the highest potential to discriminate vegetation.

Section 6.2.2 assesses the separability of vegetation types in the spectral space defined by bands 3, 4, and 5.

Section 6.2.3 presents an evaluation of how the radiometric pre-processing reported in chapter 4 affects the spectral separability of vegetation types.

### **6.2.1 The information content of TM spectral bands for vegetation: principal components analysis**

Landsat TM bands were analysed in terms of their information content for vegetation mapping. The assessment was based on principal components analysis (PCA) of the TM data that had been corrected for view angle dependent radiometric distortions, level shift banding and 16 line striping. A vegetation map produced from combined visual analysis of ERS-1 SAR data and digital classification of Landsat TM data was prepared (see section 6.3). All pixels representing water, bare soil, urban areas, or very sparse grass vegetation were masked in the image data. The remaining pixels represented green vegetation targets ranging from herbaceous and grass vegetation to closed forest. Eigenvectors and eigenvalues for the principal components transformation were calculated from these green vegetation targets only.

#### **6.2.1.1 Principal components analysis of TM bands 1, 2, and 3.**

Three principal component bands were calculated from bands 1, 2, and 3. Most of the variance was explained by the first component:

component	variance (percent)
-----	
1	86.26
2	10.00
3	3.74

Visual inspection showed that only the first component band contained information on land cover, while components 2 and 3 contained only noise. The analysis showed that bands 1, 2, and 3 were highly correlated for green vegetation targets, with band 3 providing most of the information. In the current image this may have been reinforced by the low dynamic range of bands 1 and 2 due to atmospheric haze.

#### 6.2.1.2 Principal components analysis of TM bands 5 and 7

Two component bands were calculated from TM bands 5 and 7. Most of the variance was contained in the first component:

component	variance (percent)
-----	
1	93.17
2	6.83

Visual inspection showed that all information on land cover was in component band 1, while component band 2 contained only noise.

#### 6.2.1.3 Principal components analysis of bands 1-5 and 7

Six principal component bands were calculated from TM bands 1-5 and 7. Most of the variance was contained in the first three component bands:

component	variance (percent)
1	60.31
2	20.38
3	12.94
4	2.94
5	2.42
6	1.00

Visual inspection showed that all information on land cover was contained in components 1, 2, and 3, while components 4 to 6 contained only noise.

Based on the analysis presented in the preceding section it was decided to use only TM bands 3, 4, and 5 for all further analysis.

## 6.2.2 The separability of vegetation formations in TM spectral space

This section presents an assessment of the spectral separability of the vegetation formations defined in chapter 3 in the spectral space of bands 3, 4, and 5. Only the results for woody vegetation types (forest and shrub formations) will be presented here, because these represented the vegetation formations of most interest to this study.

### 6.2.2.1 Methods

Sample areas of each vegetation formation were delineated on the TM image based on field verification and air photography. Class signatures were extracted from the system-corrected TM data. A classification (Euclidean Distance algorithm of bands 3, 4, and 5) of the training polygons was performed in order to obtain an indication of the separability of the classes. Table 6.4 shows the results of the classification in the form of a confusion matrix.

### 6.2.2.2 Results

The data presented in Table 6.4, combined with the information given on the

structure of vegetation formations in chapter 3, allow two main conclusions:

- (1) Landsat TM data appear to reflect primarily vegetation structure.
- (2) Woody vegetation types of similar canopy structure on terra firme, in whitewater floodplains, and in blackwater floodplains cannot be separated based on TM bands 3, 4, and 5 spectral information.

An attempt was made to analyse in a qualitative sense the spectral response detected by the TM sensor for different land cover targets. This was done by relating the differences in the spectral response from a variety of locations and vegetation types to a visual interpretation of the air photographs which had been acquired at the day and hour of the TM overpass on 8 August 1991. The following factors appeared to be key determinants of spectral response:

- (1) Reflectance from green vegetation:

The reflectance is determined by the structure of the vegetation, primarily the upper canopy. Species composition is related to reflectance only in very species poor environments, for example, certain types of secondary forest, where the canopy is formed almost entirely by Cecropia species.

- (2) Reflectance from soil:

Soil contributes to reflectance in the Manáus region only in few environments. These include sparse and dry grassland, white sand campina vegetation, and areas in the floodplains where bare soil is exposed at falling water levels.

- (3) Reflectance from water:

Reflectance from water is an important factor in the floodplains. August imagery represents falling water levels. Puddles and shallow ponds, often of sub-pixel size, remain in many parts of the floodplains.

In August, reflectance from many vegetation types represents a mixture of several structural types of vegetation, water and soil. The contribution of these



factors to reflectance varies for many types of vegetation depending on the hydrologic conditions of a site. This causes a large spectral variability of some vegetation types in the floodplain.

(4) Shadow

Shadow may arise from clouds, topography, and (at sub-pixel level) from canopy geometry. Mixed reflectance from water and green vegetation appears to be spectrally similar to mixed reflectance from shadow and green vegetation.

Forest on steep slopes in topographic shadow on terra firme had a tendency to be misclassified as 'water' in digital classifications. Pixels that represented mixtures between green non-forest vegetation and water in the floodplains tended to be misclassified as climax forest. This is the vegetation type in the floodplains that has a pronounced gap structure with large parts of the canopy in shadow at the time of image acquisition.

(5) Metal roofs, concrete, asphalt

Pixels of urban areas of Manáus represent spectral mixtures of reflectance from corrugated iron, concrete, and green vegetation. These areas could not be differentiated spectrally from bare soils and eroded pasture with very sparse vegetation in terra firme regions.

This analysis suggests that spectral mixture modelling based on the factors

1. green vegetation
2. soil
3. water / shadow

might be a promising approach to improve the understanding of the spectral response of vegetation canopies in the Manáus region.

### **6.2.3 The impact of radiometric pre-processing on the spectral separability of land cover types**

The purpose of the radiometric pre-processing steps described in chapter 4 was to improve the spectral separability of the land cover types prior to image classification. This section evaluates the success of the corrections that have been performed.

#### **6.2.3.1 Methods**

Sample areas for all formations of woody vegetation were delineated on the TM image based on field verification and air photography. Class signatures were extracted from the TM data at three levels of pre-processing:

Level 1: The system-corrected data as they were acquired from INPE.

Level 2: Level 1 data with additional correction of view angle dependent radiometric distortions (vadr), level shift banding (lsb), and 16 line striping.

Level 3: Level 2 data with additional 2 pass median filtering using a 3\*3 pixel kernel.

The training polygons were classified using the Euclidean Distance algorithm (TM bands 3, 4, and 5).

#### **6.2.3.2 Results**

The comparison of Tables 6.4 and 6.5 suggests that a moderate improvement in class separability has been achieved at level 2. However, these results are likely to underestimate the true level of improvement because sample polygons spanned only a third of a scan (approximately 60 kilometres). Furthermore, the area covered by the sample polygons was located in the eastern third of the scan, the area least affected by VADR (see section 4.3). The evaluation could not be extended to the entire scan for the lack of ground data.

The results measured for level 3 data (Table 6.6) indicate a pronounced improvement

in class separability due to the 2 pass median filtering.

Figure 6.5 summarises the results.

#### **6.2.4 Conclusions**

The six Landsat TM spectral bands represent an essentially 3-dimensional feature space for green vegetation targets in the Manáus region. Most of the information is contained in band 4, closely followed by band 5, with band 3 coming as a far third.

Landsat TM data appear to reflect primarily vegetation structure. Woody vegetation types of similar canopy structure on terra firme, in whitewater floodplains, and in blackwater floodplains cannot be separated based on TM bands 3, 4, and 5 spectral information.

The spectral separability is largely improved by the pre-processing steps described in chapter 4 followed by 2 pass median filtering of the data. However, woody vegetation types of similar canopy structure on terra firme, in whitewater floodplains, and in blackwater floodplains can still not be fully separated.

The following section describes the strategy that has been taken in the light of these findings for mapping the vegetation around Manáus.

### **6.3. Combined visual interpretation of ERS-1 SAR and digital classification of Landsat Thematic Mapper data.**

The land cover mapping process was structured into three phases. In the first phase, based on the 15 August 1988 image and limited ground truth, a preliminary land cover map and its accompanying reliability map were produced (section 5.2). In the second phase, field verification of both maps was carried out at Manáus, as described above. At the third stage, based on the 8 August 1991 TM image and the much improved knowledge of the project region's land cover types, an improved land cover map was produced, as reported here.

#### **6.3.1. Pre-processing the system-corrected Landsat TM data of 8-8-91.**

Residual radiometric distortions in the system-corrected Landsat TM data were corrected as described in detail in chapter 4. The first step involved the correction of view angle dependent radiometric distortions (VADRD). The spectral statistics for the correction of VADRD were calculated from the northern 2000 lines of the scene. Bands 2, 3, 5, and 7 (entire scene) were corrected and subjected to a linear contrast stretch. Band 4 was only subjected to a linear contrast enhancement (section 4.3). After the correction of VADRD, level shift banding and 16 line striping in bands 2 and 3 have been reduced. The statistics for the correction have been calculated from the entire scene (section 4.4).

It is known that the accuracy of single pixel based land cover classifications from digital satellite data is reduced by the internal variation of land cover units. It has been shown that this effect increases with the spatial resolution of the digital data. At the same time the percentage of an image represented by mixed pixels (pixels representing several land cover types) is reduced with increasing spatial resolution. Several types of smoothing filters have been suggested to reduce the internal variability of land cover units. In the application of smoothing filters a compromise has to be struck between the degree of smoothing and the loss of boundary sharpness and high frequency detail. Increasing the kernel size of a smoothing filter improves the smoothing but also leads to an increase of 'mixed' pixels along boundaries between land cover types. Mixed pixels tend to be a source of misclassification. Simple averaging filters and median filters are commonly used in pre-classification

smoothing of visible / infrared data. While averaging filters lead to a marginally stronger reduction of noise than median filters of the same kernel size, median filters have the advantage of maintaining edges much better than averaging filters (Cushnie and Atkinson, 1985; Cushnie, 1987). More sophisticated filters that assess local neighbourhoods for the existence of homogeneous sub-regions before applying smoothing operations have been shown to produce a better trade-off between smoothing and edge preservation (Abramson and Schowengerdt, 1993; Meer et al., 1994), were however not available for this study.

Here, the image (bands 2, 3, 4, 5, and 7) was subjected to 2 passes of median filtering (using a 3\*3 pixel convolution kernel).

### **6.3.2. From vegetation types to map units.**

Section 6.2 has shown that the types of woody vegetation defined in chapter 3 could not be fully separated based on TM spectral information alone.

In order to avoid misclassification, the following approach was adopted: The boundaries of the three geo-ecological formations (terra firme, whitewater floodplains, blackwater floodplains) were visually interpreted from the satellite data. Each of the three subregions was then classified separately, thereby avoiding misclassification between structurally similar vegetation formations occurring in different geo-ecological formations. Table 6.1 shows which map units have been defined and how they relate to the vegetation formations described in chapter 3.

### **6.3.3. Visual interpretation of the floodplain / upland divide from ERS-1 SAR and Landsat TM data.**

Large parts of the floodplains are covered by dense shrub or forest vegetation such that flooding occurs underneath the vegetation canopy. Sub-canopy flooding, however, cannot be detected on visible / infrared wavelength and C-band radar data. The delineation of the floodplain / upland divide had to depend to a large extent on the interpretation of geomorphologic features and, to a lesser extent, on land cover. While the ERS-1 data provide information on geomorphology and dissection

patterns, the TM data highlight the types of land cover.

The floodplain / upland divide was visually interpreted from the first principal component band calculated from 5 dates of ERS-1 SAR data, which was found to provide a much better interpretability of terrain features than single date imagery. Geomorphologic features, such as the dissection pattern, were taken as the primary indicator for the floodplain / upland division.

The floodplain boundary was easily identified in regions where the floodplains cut through sediments of the strongly dissected Barreiras Formation (Figure 6.6). The identification of the floodplain boundary was less secure in regions where the floodplains cut through sediments of the much less dissected Solimões Formation.

#### **6.3.4. Image classification**

In order to prevent spectral confusion between map units of the floodplains and of terra firme areas, the entire study area was classified three times (see Figure 6.7 for a flow diagram of the classification process). Each time, only a subset of the spectral signatures was used:

Subset 1: Only spectral signatures representing map units of terra firme.

Subset 2: Only spectral signatures representing map units of whitewater floodplains.

Subset 3: Only spectral signatures representing map units of blackwater floodplains.

This resulted in three land cover maps, with map 1, map 2, and map 3 representing the land cover of terra firme, whitewater floodplains, and blackwater floodplains, respectively.

The classifications were carried out using the Euclidean Distance algorithm. When evaluating the Mahalanobis Distance algorithm, much inferior results were obtained.

Misclassification of pixels occurred particularly in floodplain areas. The poor results can probably be attributed to the fact that many signatures, particularly in the floodplains, represent mixtures of land cover types (water, green vegetation, soil) and deviate from the Gaussian distribution. The image classification was based on TM bands 3, 4, and 5. When including also bands 2 and/or 7, the classification result remained essentially the same, as judged by visual inspection. This was to be expected given the high correlation of bands 2 and 3, and bands 5 and 7 for green vegetation targets (see section 6.2).

#### **6.3.5. Post-classification sorting**

The three land cover maps were recombined into a common land cover map of the project region using the map of geo-ecological formations derived from visual interpretation of the ERS-1 SAR and TM data (class 1: whitewater floodplains; class 2: blackwater floodplains; class 3: terra firme; class 4: water). This map served as a pointer, indicating from which of the three land cover maps the class value for a pixel in the output map was to be obtained.

#### **6.3.6. Map accuracy.**

It has been argued in section 5.2 that a sample-based numerical accuracy assessment could not be performed for various reasons.

- (a) The project region is relatively large (4000 square kilometres). Most of the region is largely inaccessible by road or river and the finances available for this project did not allow the use of a helicopter to reach remote locations. The verification of a statistically valid sample of control points on the ground was, therefore, not feasible. In addition, the replacement of ground verification by the interpretation of air photographs does not provide a secure means of verifying the land cover of sample points (see section 5.2.2.1). Furthermore, the most recent air photographs available for the region dated from the early 1970s and were considered too out-of-date upon which to base an accuracy assessment.



- (b) Reliability maps, as introduced in section 5.2, could not be used for assessing the accuracy of the land cover map. Reliability maps are useful for indicating potential ‘missing classes’ in the classification scheme: i.e. they highlight areas in the imagery that may not adequately be represented by a spectral class during image classification. Therefore, reliability maps are useful to detect an ‘undersegmentation’ of spectral space (too few classes) but not an ‘oversegmentation’ of spectral space (too many classes). If too many classes have been selected for spectral classification, the spectral overlap between similar classes increases as does misclassification due to low spectral separability.

The reliability of the land cover map, therefore, could only be assessed in qualitative terms. The problem was approached by assessing what the most likely sources of error are, given the data and methodology used.

Error in the land cover map may result (a) from a wrong interpretation of the floodplain / upland boundary, and (b) from error in the spectral classification of Landsat TM data.

**(a) Error in the interpretation of the floodplain / upland boundary**

It has been pointed out that the boundary between seasonally inundated floodplains and terra firme areas is a well defined division in areas of the Barreiras formation, but is represented by a zone of transition in areas of the Solimões formation. Areas in this transition zone may undergo flooding in one year but will remain dry in other years. It is assumed that the floodplain boundary interpreted from geomorphologic features represents the maximum extent of flooding. Thematic error resulting from this interpretation would result in terra firme pixels being labelled as floodplain.

However, the structural type of vegetation would not be affected, i.e. a forest on terra firme may be equivocally labelled as floodplain forest but would not be misclassified as grassland. Furthermore, this type of error is more likely to occur in zones of contact between floodplains and Solimões formation than along the boundary between Barreiras formation and floodplains.

**(b) Error resulting from the spectral classification of Landsat TM data**

Training areas for the digital classification have been defined to represent vegetation formations that are distinct and homogeneous in terms of vegetation structure. The spectral separability between vegetation types has been optimized by the radiometric preprocessing described in chapter 4.

Misclassification is likely to occur in areas of mixed land cover and transition zones between cover types. A close comparison of such areas on the classified image with available air photography and field data showed:

- \* It is difficult and highly subjective to draw a line between classes in areas of transition zones even in a visual interpretation of the data.
- \* 'Misclassification' occurs between structurally similar classes. For example, areas that according to air photo interpretation should have been classified as 'intermediate forest succession' may have been digitally classified as 'early forest succession'. Misclassification from 'closed forest' to 'grassland' is highly unlikely to occur. This confirms the results obtained in the analysis of the spectral separability of vegetation formations presented in section 6.2.2.

This highlights a shortcoming of binary decision type (right / wrong) accuracy assessment: A pixel label 'early forest succession' may be wrong in the binary sense, even though it still conveys information: the pixels is likely to represent some type of forest succession rather than closed climax forest, grassland, water etc.

Binary type accuracy assessment is less adequate still for the assessment of land cover maps that have been produced from different information sources (spatial data layers in a geographic information system). Each input layer contributes in a specific way to possible error in the resulting output map. This is to say that a map can be correct in certain attributes of a pixel, but wrong in other ones. In this mapping project: (a) error in the structural description of vegetation formations, and (b) error in the floodplain / upland label occur largely independent from one another.

The comparison of the digital classification with the Landsat TM false colour

composite will highlight merits and problems of the digitally classified map in more detail.

### **6.3.7 Terra firme case study**

Most of the vegetation formations defined for terra firme areas (Table 6.1) are readily identified on the Landsat TM false colour composite ('TM FCC') (red: band 4; green: band 5; blue: band 3) (Figure 6.8.a). The comparison of the TM FCC with the vegetation map derived from digital classification of the TM data (Figure 6.9.a) demonstrates a good overall agreement (the legend and class colours for the classified TM data are shown in Figure 6.8.b).

Considering that the classified image has not been subjected to any post-classification filtering (such as majority analysis), it can be noted that the amount of small clusters and individual pixels is low. This demonstrates the quality of the pre-processing strategy applied before the classification. Figure 6.9.b shows the same area classified from the original system-corrected TM data (same training polygons, same classification parameters as Figure 6.9.a). The improvement in the classification result through pre-processing is obvious, underlining the importance of this step for achieving a high thematic accuracy in digital image classifications.

### **6.3.8 Floodplain case study**

The area of case study 2 includes the Ilha da Marchantaria in the lower Rio Solimões and the Ilha do Careiro at the confluence of Rio Solimões and Rio Negro. The western half of the Ilha do Careiro has been a relatively stable floodplain site for more than 1000 years, as dated from pottery discovered on the island (Worbes et al., 1992; ORSTOM and INPA, 1988). The south-western and north-western shores of the island are formed by high-lying levees that undergo flooding only for a few weeks or may remain entirely dry in some years. The south-western shore is occupied by small to medium scale cattle ranches with interspersed fruit and vegetable gardens. The north-western shore is occupied by smallholders producing fruits and vegetables for the Manaus markets in an intensive agroforestry system (see ORSTOM and INPA, 1988, for details).

The Ilha de Marchantaria is situated 15 kilometres south of Manaus in the lower Rio Solimões. The eastern half of the island is of recent origin, representing sediments that have been deposited and colonised by vegetation over the past 10 to 20 years (comparison with Landsat MSS data of 1977, unpublished results, Corves 1994).

The classified image (Figures 6.10.a and 6.11.a) matches well with the vegetation patterns visible in the false colour composite (Figures 6.10.b and 6.11.b). Comparison with air photo coverage and observations made during the field evaluation shows that the digitally classified land cover map represents accurately the structure of the vegetation. However, it was not possible to differentiate the agroforestry system on the north-western shore of Ilha do Careiro from areas covered by structurally similar stages of forest succession. While the spectrally based digital classification failed to recognise these different types of vegetation and land use, a visual interpretation of the data based on a good knowledge of local vegetation and land use could make the required differentiation by taking into account the location and shape of features.

The assessment of the accuracy of the digital classification is more dependent on subjective judgement in the floodplains than on terra firme. This is due to the larger variety of vegetation types in the floodplain, the comparatively smaller size of vegetation units in the floodplains than on terra firme, and, in particular, to the fact that a much larger percentage of the floodplains than of terra firme is covered by successional stages of vegetation that cannot be easily grouped into well defined classes. For the spectrally and spatially complex floodplain environment digital classification based exclusively on spectral characteristics is less reliable than for terra firme areas. The higher the degree of spectral and spatial complexity in the image, the less able is digital classification based on spectral features alone to extract meaningful information.

#### **6.3.9 Summary of results and conclusions**

- (1) The floodplain boundary was mapped through visual interpretation of geomorphologic features visible in ERS-1 SAR data and land cover information in Landsat TM data. Floodplain boundaries were clearly discernible in areas of contact between the floodplains and the strongly

dissected Barreiras sediments but were more difficult to identify in areas of contact between the floodplains and the less dissected sediments of the Solimões formation.

- (2) The floodplains of the sediment-poor Rio Negro are much narrower than those of the Rio Solimões. Field work and air photo acquisition in 1991 focused on the floodplains of the Solimões. It is possible that narrow stretches of floodplains along the blackwater rivers have not been recognised in the interpretation of ERS-1 and TM data.
- (3) The high water mark of the rivers varies considerably between years. The geomorphologic floodplain boundary does not represent the exact area of flooding of any particular year. The higher-lying areas of the floodplains will be flooded for many weeks in one year, but also may remain dry for several consecutive years. Classifying satellite imagery into 'floodplains' or 'terra firme' inevitably imposes clear boundaries where gradual transitions exist in many places.
- (4) Landsat TM data did not allow for the spectral differentiation of structurally similar vegetation types on floodplains and terra firme. This problem affected particularly woody vegetation.
- (5) Due to sedimentation and erosion, floodplains represent naturally unstable environments. The spatial mosaic of vegetation units is more complex in floodplains than on terra firme. Large parts of the floodplains are occupied by various stages of forest succession. Many pixels of TM data of floodplains represent mixtures between different structural types of vegetation, soil and water, while terra firme pixels tend to be much more homogeneous and are dominated by green vegetation reflectance. All these factors contribute to the fact that (a) floodplain vegetation is more difficult to categorise than terra firme vegetation, and (b) digital classification of Landsat TM data is more reliable in terra firme areas than in floodplains.
- (6) Visual interpretation allowed for the differentiation of a larger number of classes than digital classification. Digital classification provided highly accurate results for mapping basic structural classes of vegetation, such as (1)

closed forest; (2) forest succession, open forest and shrubs; (3) non-forest: grassland, bare soil. Secondary forest on terra firme has been found to be a spectrally distinct vegetation type and could be mapped digitally with high accuracy.

- (7) Even though the 2-pass median filtering creates a more homogeneous classification output than using the original data, the classified image still has a large number of small clusters of pixels. The map produced from pixel-wise digital classification is not suitable for vectorization. Majority filtering is commonly applied to remove scattered pixels and clusters of few pixels. It degrades, however, very significantly the spatial quality of a classified image, without entirely solving the problem of small clusters in vectorization. Visual interpretation avoids this problem altogether. If a land cover map is ultimately required in vector format, this may be a strong argument for preferring visual interpretation instead of digital classification.
- (8) A further significant advantage of visual interpretation is that pre-processing requirements (noise removal, atmospheric corrections, etc.) are much less stringent for visual interpretation than for digital classification. Also, visual interpretations can be performed with less expensive hardware and software and by technically less specialised staff.

# Chapter 7

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## **7. Summary of Main Results and Conclusions**

The work described in this thesis has looked at measures that can be taken to improve the accuracy of satellite-based land cover mapping. Chapters 3 to 6 provide conclusions on the technical aspects of the respective topics. This chapter summarises the main results and highlights aspects that may deserve further investigation.

### **7.1 Ecological objectives**

#### **7.1.1 To define a system of categorising vegetation for satellite-based land cover mapping**

The system for categorising the vegetation and defining map units presents an important means of achieving a high thematic accuracy in satellite-based mapping. Traditional vegetation classification systems have largely been based on botanical observations. Such systems fail to consider the characteristics of data and mapping techniques.

A vegetation classification system has been proposed that integrates the capabilities and limitations of mapping from current 'high resolution' satellite data (visible / infrared spectrum) into the definition of vegetation formations. The system defines vegetation formations based on local environmental characteristics and the structure of the vegetation. It has been found that, in the Manaus region, the vegetation formations defined by these characteristics agreed well with the characterisation of vegetation by their floristic composition. In the proposed system, the floristic composition of the vegetation characterises the occurrence of a vegetation formation in a particular location. However, floristic composition does not contribute to the definition of that vegetation formation. Thus, the system provides a basis for the mapping and floristic comparison of vegetation in distant locations.

It would be interesting to evaluate the applicability of the proposed vegetation classification system in other parts of the Amazon basin. This could lead to the adaptation and refinement of the system, or to its rejection. However, the important issue is that the characteristics of satellite data need to be taken into account in the design of future systems of classifying vegetation. Only satellite data will allow the mapping of vegetation in a consistent way over large regions.

### **7.1.2 To investigate the separability of vegetation formations in Landsat TM spectral space**

The spectral information content of Landsat TM data for mapping vegetation in the Manaus region has been assessed. It was found that band 4 contained most information, followed by band 5, and band 3. Bands 1, 2, and 3 were highly correlated for green vegetation targets, as were bands 5 and 7. Landsat TM data therefore presented an essentially 3-dimensional dataset for green vegetation targets. The analysis highlighted the importance of band 5, a wavelength that is not included in SPOT HRV data. Particularly in humid tropical regions with their often hazy atmosphere, Landsat TM data are likely to provide more spectral information for the discrimination of vegetation than SPOT HRV data.

Landsat TM data did not allow for the satisfactory discrimination of the vegetation formations defined in chapter 3 based on spectral information alone. The study highlighted two major problems of digital land cover mapping using current satellite data and image processing software:

- (a) Only a part of the information contained in an image is of a spectral nature. Current image processing software (such as ERDAS 7.5 or Imagine) does not provide any tools for using important types of non-spectral information (texture, shape, spatial context of objects) in the image classification process. This causes the frequently reported poor thematic accuracy of digital image classifications if compared with the visual interpretation of the data. Mapping

land cover by digital classification of satellite data cannot be considered an 'operational' technique for any but the simplest of classification schemes (e.g. forest / non-forest) at present. This underlines the need to develop software tools for extracting non-spectral information from images.

- (b) Current satellite sensors provide only a very crude representation of the visible and near to mid infrared spectrum. Operational use of satellite data for mapping and monitoring land cover at scales relevant to local and regional planning will not only require a significant improvement in the spatial resolution, but also in the spectral resolution of the data.

### **7.1.3 To map the vegetation of the Manáus region using digital satellite imagery.**

The spectral separability analysis had shown that Landsat TM data did not allow for the spectral separation of all vegetation types. However, the vegetation types of each of the three geo-ecological formations 'terra firme', 'whitewater floodplains', and 'blackwater floodplains' could be separated spectrally. Therefore, the boundary between these formations was visually interpreted from ERS-1 SAR and Landsat TM data. Each of the resulting image regions was subsequently classified with the corresponding subset of classes. The classification highlighted problems in several areas.

The imposition of rigidly defined categories on natural vegetation areas characterized by ecotones limits the accuracy of land cover maps created by digital classification of satellite data. To a large extent the location of boundaries is subject to highly subjective judgements made by the image analyst. This poses equally into question the concept of sample-based map accuracy assessment.

The thematic accuracy of categorical land cover maps is commonly evaluated by sample-based accuracy assessment. Over large and inaccessible areas with a

complicated mosaic of vegetation types as in the project region, the verification of statistically valid samples for accuracy assessment becomes too expensive or impossible. The assessment of thematic map accuracy and its meaning in such regions requires further research.

#### **7.1.4 To investigate the potential of ERS-1 SAR data for mapping and monitoring vegetation in the Manaus region**

In agreement with the results reported by other researchers (chapter 1), the utility of ERS-1 SAR data for general vegetation mapping has been found to be rather limited. However, ERS-1 SAR data appeared to be suitable for the updating of existing vegetation maps for further forest clearing. The data were also found useful for the visual interpretation of the floodplain boundary from geomorphological features.

The segmentation of the SAR images based on region growing and edge detection appeared to be a more promising tool for detecting forest clearings than the pixel-based classification of the data. The results obtained in this study underline the need for image processing to move from pixel-based approaches to region-oriented ones not only for the classification of SAR data but equally for the classification of visible / infrared wavelength satellite imagery.

### **7.2 Image data processing related objectives**

#### **7.2.1 To investigate the effects of and correct for residual radiometric distortions**

The presence of residual radiometric distortions in visible / infrared satellite data has long been a well known, but apparently sometimes underestimated problem. This study has shown that radiometric distortions of considerable magnitude may exist in Landsat TM data. View angle dependent radiometric distortions, level shift banding, and 16 line striping were identified as the main distortions present in the dataset used for this project. The lack of any software tools to correct Landsat TM radiometric

distortions in 'ERDAS 7.5' and 'Imagine' software necessitated the in-house implementation of suitable software tools. These tools enabled a considerable reduction of the distortions encountered. It was demonstrated that the corrections performed significantly improved the spectral separability of vegetation types in subsequent land cover classifications. It appears that the correction of such distortions needs to be given more attention in satellite-based mapping, particularly if the areas to be mapped are large (full scenes) and a high thematic resolution is required.

### **7.2.2 To improve techniques for the co-registration and georeferencing of spatial datasets from remote regions**

Mapping vegetation and monitoring forest clearing require the exact co-registration and georeferencing of spatial datasets. The poor quality of reference maps, the difficulty of identifying ground control points on satellite images (especially SAR images), and the sometimes little known geodetic characteristics of the satellite data complicate this task. The issues to be tackled in empirical coordinate transformation by polynomial functions are (a) the detection and elimination of inaccurate ground control points, and (b) the identification of the lowest order of polynomial function that will achieve a specified georeferencing accuracy. The 'total RMS error' is commonly used as an indicator of georeferencing accuracy. However, it neither provides a quantitative measure of georeferencing accuracy nor does it allow the reliable identification of inaccurate control points because its calculation involves the squaring of the error residuals. The information on the directional properties of registration error contained in control point residuals is lost in the calculation of the total RMS error. Also, no information is provided on the spatial distribution of georeferencing accuracy.

A strategy for the exact co-registration and georeferencing of spatial datasets based on modelling the spatial distribution of ground control point x- and y-residuals with respect to the datasets has been described. The strategy allows for the reliable

detection of inaccurate control points and the identification of the required order of polynomial function. It also allows for the quantification of registration accuracy.

Image processing software should allow not only the visualisation of the spatial distribution of error during the registration process, but also store this information together with the spatial data layers concerned. This would allow map users to make their own judgements concerning the utility of data layers for a specific use. It would also provide a basis for tracing the progression of geodetic accuracy in operations involving several layers of spatial data.

### **7.2.3 To map and investigate unreliably classified regions in satellite-derived land cover maps**

The value of spatial data to the user would be greatly enhanced if any spatial datasets were accompanied by a spatial representation of the reliability of the data. Current spatial data handling systems (image processing as well as geographic information systems) largely fail to account for this need. Neither the spatial representation of the reliability of data layers nor the progression of error and reliability through a data processing chain are handled in an integrated way.

Any manipulation of spatial data should provide two types of output: (a) the result of the operation, and (b) a spatial representation of the reliability of the result. Digital image classifications are known to provide land cover maps of often limited accuracy. A major shortcoming of traditional sample-based land cover map accuracy assessment is the failure to map the spatial distribution of land cover map reliability.

A technique to model the spatial distribution of the 'reliability' of satellite-derived land cover maps based on the spectral distance information derived during the classification process has been described. The utility of the resulting 'reliability map' for identifying incorrectly classified areas on land cover maps has been demonstrated by field verification.

Future work should investigate how spectral distance information can be transformed to a standardised estimate of reliability (e.g. on a scale of 0-1), thereby allowing for comparisons of mapping reliability between independently classified areas.



## 8. Bibliography

- Abramson, S.B. and Schowengerdt, R.A. (1993): Evaluation of edge-preserving smoothing filters for digital image mapping. *ISPRS Journal of Photogrammetry and Remote Sensing*, Vol. 48, No. 2, pp. 2-17.
- Achard, F. and Blasco, F. (1990): Analysis of vegetation seasonal evolution and mapping of forest cover in West Africa with the use of NOAA AVHRR HRPT data. *Photogrammetric Engineering and Remote Sensing*, Vol. 56, No. 10, pp. 1359-1365.
- Adis, J. (1984): 'Seasonal igapo'-forests of Central Amazonian blackwater rivers and their terrestrial arthropod fauna. In: Sioli, H. (ed.), *The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin*. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 245-268.
- Ahern, F.J., Campbell, F.H.A., Elizondo, C., Kux, H.J.H., Novo, E., Paradella, W., Raney, R.K., Salcedo, R., Shimabukuro, Y., and Sighroy, V. (1993): C-band SAR for resource management in tropical environments: Lessons from SAREX-92 investigations in Brazil, Costa Rica, Venezuela, and Guyana. In: *European Space Agency: South American Radar Experiment. Proceedings of the SAREX-92 Workshop at ESA Headquarters, Paris, 6-8 December 1993*. Pp: 235-246.
- Anderson, A.B. (1978): Aspectos florísticos e fitogeográficos de campinas e campinaranas na Amazonia Central. Tese apresentada ao curso de pós-graduação do Instituto Nacional de Pesquisas da Amazonia e Universidade do Amazonas para obtenção do grau de magister scientiae. Manaus.
- Anderson, A.B. (1981): White-sand vegetation of Brazilian Amazonia. *Biotropica*, Vol. 13, No. 3, pp. 199-210.
- Aronoff, S. (1982a): Classification accuracy: a user approach. *Photogrammetric Engineering and Remote Sensing*, Vol. 48, pp. 1299-1307.
- Aronoff, S. (1982b): The map accuracy report: a user's view. *Photogrammetric Engineering and Remote Sensing*, Vol. 48, pp. 1309-1312.
- Aronoff, S. (1985): The minimum accuracy value as an index of classification accuracy. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, pp. 99-111.

- Baker, J.R., Mitchell, P.L., Cordey, R.A., Groom, G.B., Settle, J.J., and Stileman, M.R. (1994): Relationships between physical characteristics and polarimetric radar backscatter for Corsican pine stands in Thetford Forest, UK. *International Journal of Remote Sensing*, Vol. 15, No. 14, pp. 2827-2849.
- Barnsley, M.J. (1984): Effects of off-nadir view angles on the detected spectral response of vegetation canopies. *International Journal of Remote Sensing*, Vol. 5, No. 4, pp. 715-728.
- Bayley, P.B. and Moreira, J.C. (1978): Interpretacoes preliminares dos recursos aquaticos da Amazonia central utilizando imagens do Landsat. I Simposio Brasileiro do Sensoriamento Remoto, 27 a 29 de Novembro de 1978, S.J. Campos, S.P., Brazil.
- Bigarella, J.J. and Ferreira, A.M.M. (1985): Amazonian geology and the Pleistocene and the Cenozoic environments and palaeoclimates. In: Prance, G.T. and Lovejoy, T.E. (eds.): *Key environments. Amazonia*. Pergamon Press, Oxford, New York, 1985, pp. 445.
- Bishop, Y., Fienberg, S., and Holland, P. (1975): *Discrete multivariate analysis. Theory and practice*. (Cambridge, Massachusetts: MIT Press).
- Boechat Lopes, U., de Menezes Santos, U., and de Nazare Goes Ribeiro, M. (1983): Limnologia quimica do Lago do Arroz (Ilha do Careiro), suas flutuacoes em funcao do meio hidrico do Rio Amazonas. *Acta Amazonica*, Vol. 13, No. 2, pp. 227-153.
- Büttner, G. and Kapovits, A. (1990): Characterization and removal of horizontal striping from SPOT panchromatic imagery. *International Journal of Remote Sensing*, Vol. 11, No.2, pp. 359-366.
- Caves, R.G. (1993): Automatic matching of features in synthetic aperture radar data to digital map data. PhD thesis, University of Sheffield, 228 pp.)
- Caves, R.G. and Quegan, S. (1994): Matching segmentation algorithms to ERS-1 SAR applications. In: *Proc. SAR Data Processing for Remote Sensing* (Rome, 1994), SPIE Vol. 2316, pp. 148-158, 1994.
- Chauvel, A., Lucas, Y. and Boulet, R. (1987): On the genesis of the soil mantle of the region of Manaus, Central Amazonia, Brazil. *Experientia*, Vol. 43, pp. 234-241.
- Chavez, P.S., Jr. (1988): An improved dark-object subtraction technique for atmospheric scattering correction of multispectral data. *Remote Sensing of Environment*, Vol. 24, pp. 459-479.

- Congalton, R.G. (1988): A comparison of sampling schemes used in generating error matrices for assessing the accuracy of maps generated from remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, Vol. 54, pp. 593-600.
- Congalton, R.G. and Green, K. (1993): A practical look at the sources of confusion in error matrix generation. *Photogrammetric Engineering and Remote Sensing*, Vol. 59, No. 5, pp. 641-644.
- Congalton, R.G. and Mead, R.A. (1983): A quantitative method to test for consistency and correctness in photointerpretation. *Photogrammetric Engineering and Remote Sensing*, Vol. 49, pp. 69-74.
- Congalton, R.G., Oderwald, R.G., and Mead, R.A. (1983): Assessing Landsat classification accuracy using discrete multivariate statistical techniques. *Photogrammetric Engineering and Remote Sensing*, Vol. 49, pp. 1671-1678.
- Crippen, R.E. (1989): A simple spatial filtering routine for the cosmetic removal of scan-line noise from Landsat TM-P tape imagery. *Photogrammetric Engineering and Remote Sensing*, Vol. 55, No. 3, pp. 327-331.
- Cross, A.M., Settle, J.J., Drake, N.A., and Paivinen, R.T. (1991): Subpixel measurement of tropical forest cover using AVHRR data. *International Journal of Remote Sensing*, Vol. 12, No. 5, pp. 1119-1129.
- Curtis, J.T. and McIntosh, R.T. (1951): An upland forest continuum in the prairie-forest border region of Wisconsin. *Ecology*, Vol. 32, pp. 476-496.
- Cushnie, J.L. (1987): The interactive effect of spatial resolution and degree of internal variability within land cover types on classification accuracies. *International Journal of Remote Sensing*, Vol. 8, No. 1, pp. 15-29.
- Cushnie, J.L. and Atkinson, P. (1985): Effect of spatial filtering on scene noise and boundary detail in Thematic Mapper imagery. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1483-1493.
- de Albuquerque, B.W.P. (1981): Plantas forrageiras da Amazonia. 1. Aquaticas flutuantes livres. *Acta Amazonica*, Vol. 11, No. 3, pp. 457-471.
- de Albuquerque, J.M. (1980): Identificacao de plantas invasoras de cultura da regio de Manaus. *Acta Amazonica*, Vol. 10, No. 1, pp. 47-95.
- Dicks, S.E. and Lo, T.H.C. (1989): Evaluation of thematic map accuracy in a landuse and cover mapping program. *Proceedings of the 1989 ASPRS/ACSM meeting*, Vol. 4 GIS/LIS, Baltimore, April 2-7, pp. 7-20.

- dos Santos, J.R., dos Santos, A.P., and de Aquino, L.C.S. (1983): Avaliacao da cobertura vegetal e uso da terra nas areas programas do PDRI-AM atraves da tecnica de sensoriamento remoto. INPE-2701-NTE/199, Sao Jose dos Campos, Brazil.
- Ducke, A. and Black, G.A. (1953): Phytogeographical notes on the Brazilian Amazon. *Ann. Acad. Bras. Sci.*, Vol. 25, pp. 1-46.
- Duggin, M.J., Sakhavat, H., and Lindsay, J. (1985): Systematic and random variations in Thematic Mapper digital radiance data. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1427-1434.
- ERDAS (1991a): Image processing module, Version 7.5, Atlanta, GA, USA.
- ERDAS (1991b): ERDAS Field Guide. Second Edition, Version 7.5. ERDAS Inc., Atlanta, USA, 394 pp.
- ESA (1993): ERS User Handbook. ESA SP-1148 Rev. 1. ESA Publications Division, ESTEC, Noordwijk, The Netherlands.
- Fittkau, E.J. (1974): Zur ökologischen Gliederung Amazoniens. I. Die erdgeschichtliche Entwicklung Amazoniens. *Amazoniana*, Vol. 5, No. 1, pp. 77-134.
- Foody, G.M. (1990): Directed ground survey for improved maximum likelihood classification of remotely sensed data. *International Journal of Remote Sensing*, Vol. 11, pp. 1935-1940.
- Foody, G.M. (1992): On the compensation for chance agreement in image classification accuracy assessment. *Photogrammetric Engineering and Remote Sensing*, Vol. 58, No. 10, pp. 1459-1460.
- Furley, P. A. (1986): Radar surveys for resource evaluation in Brazil: An illustration from Rondonia. In: Eden, M.J. and J.T. Parry (1986): *Remote sensing and tropical land management*. John Wiley and Sons, Chichester.
- Furley, P.A. (1990): The nature and sustainability of Brazilian Amazon Soils. In: Goodman, D. and Hall, A. (eds.): *The future of Amazonia. Destruction or sustainable development?* MacMillan. Basingstoke, Hampshire and London, 1990, pp. 309-359.
- Fusco, L., Frei, U., Trevese, D., Blonda, P.N., Pasquariello, G., and Milillo, G. (1986): Landsat TM image forward/reverse scan banding: characterization and correction. *International Journal of Remote Sensing*, Vol. 7, No. 4, pp. 557-575.

- Garcia, M.C. and Alvarez, R. (1994): TM digital processing of a tropical forest region in southeastern Mexico. *International Journal of Remote Sensing*, Vol. 15, No. 8, pp. 1611-1632.
- Ginevan, M.E. (1979): Testing land-use map accuracy: another look. *Photogrammetric Engineering and Remote Sensing*, Vol. 45, pp. 1371-1377.
- Green, E.J., Strawderman, W.E., and Airola, T.M. (1993): Assessing classification probabilities for thematic maps. *Photogrammetric Engineering and Remote Sensing*, Vol. 59, No. 5, pp. 635-639.
- Guillaumet, J.L. (1987): Some structural and floristic aspects of the forest. *Experientia*, Vol. 43, No. 7, pp. 241-251.
- Haralick, R.M. (1979): Statistical and structural approaches to texture. *Proceedings of the IEEE*, Vol. 67, No. 5, May 1979, pp. 786-804.
- Haralick, R.M., Shanmugam, K., and Dinstein, I. (1973): Textural features for image classification. *IEEE Transactions on Systems, Man, and Cybernetics*. November 1973, pp. 610-621.
- Hayes, L. (1985): The current use of TIROS-N series of meteorological satellites for land-cover studies. *International Journal of Remote Sensing*, Vol. 6, No. 1, pp. 35-45.
- Hays, W.L. and Winkler, R.L. (1970): *Statistics: probability, inference, and decision*. (New York: Holt, Rinehart and Winston, Inc.).
- Helder, D.L., Quirk, B.K., and Hood, J.J. (1992): A technique for the reduction of banding in Landsat Thematic Mapper images. *Photogrammetric Engineering and Remote Sensing*, Vol. 58, No. 10, pp. 1425-1431.
- Higuchi, N., Jardim, F.C.S., dos Santos, J., Barbosa, A.P., and Wood, T.W.W. (1985): Bacia 3 - Inventário florestal comercial. *Acta Amazonica*, Vol. 15, No. 3-4, pp. 327-369.
- Hoekman, D.H. (1990): Radar remote sensing data for applications in forestry. Ph.D. thesis, Wageningen Agricultural University, The Netherlands, 279 pp.
- Holben, B. and Fraser, R.S. (1984): Red and near-infrared response to off-nadir viewing. *International Journal of Remote Sensing*, Vol. 5, No. 1, pp. 145-160.
- Horn, B.K.P. and Woodham, R.J. (1979): Destriping Landsat MSS images by histogram modification. *Computer Graphics and Image Processing* Vol. 10, pp. 69-83.

- Hudson, W.D. and Ramm, C.W. (1987): Correct formulation of the Kappa coefficient of agreement. *Photogrammetric Engineering and Remote Sensing*, Vol. 53, pp. 421-422.
- Hueck, K. (1966): *Die Wälder Südamerikas. Ökologie, Zusammensetzung und wirtschaftliche Bedeutung*. Gustav Fischer Verlag, Stuttgart, FRG, 442 pp.
- Irion, G. (1989): Quaternary geological history of the Amazon lowlands. In: Holm-Nielsen, L.B., Nielsen, J.C., and Balslev, H. (eds.) (1989): *Tropical forests. Botanical dynamics, speciation and diversity*. Academic Press, London-San Diego-Boston-New York-Sydney-Tokyo-Toronto, pp. 23-34.
- Irion, G., Adis, J., Junk, W.J., and Wunderlich, F. (1984): *Sedimentaufbau einer Amazonas-Insel*. *Natur und Museum*, Vol. 114, No. 1, pp. 1-13.
- Jardim, F.C. da S. and Hosokawa, R.T. (1986/87): *Estrutura da floresta equatorial umida da Estacao Experimental de Silvicultura Tropical do INPA*. *Acta Amazonica*, Vol. 16/17, pp. 411-508.
- Jordan, C.F. (1985): Soils of the Amazon rainforest. In: Prance, G.T. and Lovejoy, T.E. (eds.): *Key Environments: Amazonia*. Pergamon Press, Oxford, New York, 1985, pp. 83-94.
- Junk, W.J. (1970): Investigations on the ecology and production-biology of the 'floating meadows' (*Paspalo-Echinochloetum*) on the middle Amazon. *Amazoniana*, Vol. 2, No. 4, pp. 449-495.
- Junk, W.J. (1983a): Ecology of swamps on the middle Amazon. In: Gore, A.J.P. (ed.): *Mires: swamp, bog, fen and moor*. B. Regional Studies. Elsevier Scientific Publishing Company, Amsterdam, 1983.
- Junk, W.J. (1984): Ecology of the varzea, floodplain of Amazonian whitewater rivers. In: Sioli, H. (ed.), *The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin*. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 215-243.
- Junk, W.J. (1986): Aquatic plants of the Amazon system. In: Davies, B.R. and Walker, K.F. (eds.): *The ecology of river systems*. Dr. W. Junk Publishers, Dordrecht, The Netherlands.
- Junk, W.J. (1989a): Flood tolerance and tree distribution in central Amazonian floodplains. In: Holm-Nielsen, L.B., Nielsen, J.C., and Balslev, H. (eds.) (1989): *Tropical forests. Botanical dynamics, speciation and diversity*. Academic Press, Harcourt Brace Jovanovich Publishers, London-San Diego-New York, pp. 47-64.



- Junk, W.J. and Furch, K. (1985): The physical and chemical properties of Amazonian waters and their relationship with the biota. In: Prance, G.T. and Lovejoy, T.E. (eds.): *Key Environments: Amazonia*. Pergamon Press, Oxford, New York, 1985, pp. 3-17.
- Junk, W.J. and Howard-Williams, C. (1984): Ecology of aquatic macrophytes in Amazonia. In: Sioli, H. (ed.), *The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin*. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 269-293.
- Justice, C.O., Townshend, J.R.G., Holben, B.N., and Tucker, C.J. (1985): Analysis of the phenology of global vegetation using meteorological satellite data. *International Journal of Remote Sensing*, Vol. 6, No. 8, pp. 1271-1318.
- Kahn, F. and de Castro, A. (1985): The palm community in a forest of central Amazonia, Brazil. *Biotropica*, Vol. 17, No. 3, pp. 210-216.
- Kalliola, R. and Syrjänen, K. (1991): To what extent are vegetation types visible in satellite imagery? *Ann. Bot. Fennici*, Vol. 28, pp. 45-57.
- Kalliola, R., Puhakka, M., Salo, J., Tuomisto, H., and Ruokolainen, K. (1991): The dynamics, distribution and classification of swamp vegetation in Peruvian Amazonia. *Annales Botanici Fennici*, Vol. 28, pp. 225-239.
- Keel, S.H.K. and Prance, G.T. (1979): Studies on the vegetation of a white-sand black-water igapo (Rio Negro, Brazil). *Acta Amazonica*, Vol. 9, No. 4, pp. 645-655.
- Kent, M. and Coker, P. (1992): *Vegetation description and analysis. A practical approach*. CRC Press, Boca Raton, Ann Arbor. Belhaven Press, London. 363 pp.
- Kieffer, H.H., Cook, D.A., Eliason, E.M., and Eliason, P.T. (1985): Intraband radiometric performance of the Landsat Thematic Mappers. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1331-1350.
- King, B. (1994): The value of ground resolution, spectral range and stereoscopy of satellite imagery for land system and land-use mapping of the humid tropics. *International Journal of Remote Sensing*, Vol. 15, No. 3, pp. 521-530.
- Kirchner, J.A., Schnetzler, C.C., and Smith, J.A. (1981): Simulated directional radiances of vegetation from satellite platforms. *International Journal of Remote Sensing*, Vol. 2, No. 3, pp. 253-264.



- Klammer, G. (1984): The relief of the extra-Andean Amazon basin. In: Sioli, H. (ed.), *The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin*. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 48-83.
- Kleman, J. (1987): Directional reflectance factor distributions for two forest canopies. *Remote Sensing of Environment*, Vol. 23, pp. 83-96.
- Klinge, H., Junk, W.J. and Revilla, C.J. (1990): Status and distribution of forested wetlands in tropical South America. *Forest Ecology and Management*. Vol. 33/34, pp. 81-101.
- Leckie, D.G. (1990): Synergism of synthetic aperture radar and visible / infrared data for forest type discrimination. *Photogrammetric Engineering and Remote Sensing*, Vol. 56, No. 9, pp. 1237-1246.
- Leysen, M.M., Conway, J.A., and Sieber, A.J. (1993): Evaluating multi-temporal ERS-1 SAR data for tropical forest mapping: Regional mapping and change detection applications. *Proceedings of the Second ERS-1 Symposium - Space at the Service of our Environment*, Hamburg, Germany, 11-14 October 1993, ESA SP-361 (January 1994), pp. 447-452.
- Lozano-Garcia, D.F. and Hoffer, R.M. (1993): Synergistic effects of combined Landsat TM and SIR-B data for forest resources assessment. *International Journal of Remote Sensing*, Vol. 14, No. 14, pp. 2677-2694.
- Lunetta, R.S., Congalton, R.G., Fenstermaker, L.K., Jensen, J.R., McGwire, K.C., and Tinney, L.R. (1991): Remote sensing and geographic information system data integration: error sources and research issues. *Photogrammetric Engineering and Remote Sensing*, Vol. 57, pp. 677-687.
- Malaret, E., Bartolucci, L.A., Lozano, D.F., Anuta, P.E., and McGillem, C.D. (1985): Landsat-4 and Landsat-5 Thematic Mapper data quality analysis. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1407-1416.
- Malingraeau, J.P., Tucker, C.J. and Laporte, N. (1989): AVHRR for monitoring global tropical deforestation. *International Journal of Remote Sensing*, Vol. 10, No. 4/5, pp. 855-867.
- Malingreau, J.P. (1986): Global vegetation dynamics : satellite observations over Asia. *International Journal of Remote Sensing*, Vol. 7, No. 9, pp. 1121-1146.
- Malingreau, J.P. and Tucker, C.J. (1990): Ranching in the Amazon. Large-scale changes observed by AVHRR. *International Journal of Remote Sensing*, Vol. 11, No. 2, pp. 187-189.

- Malingreau, J.P., Achard, F., D'Souza, G., Stibig, H.J., D'Souza, J., Estreguil, C., and Eva, H. (1993): AVHRR for global tropical forest monitoring: The lessons of the TREES project. Paper presented at the First TREES Conference: The Application of Remote Sensing to Tropical Forest Inventory and Monitoring, 20-21 October 1993, Belgirate, Italy.
- Mather, P.M. (1987): Computer processing of remotely sensed images. Wiley, Chichester.
- Matson, M. and Holben, B. (1987): Satellite detection of tropical burning in Brazil. *International Journal of Remote Sensing*, Vol. 8, No. 3, pp. 509-516.
- Meer, P., Park, R.-H., and Cho, K. (1994): Multiresolution adaptive image smoothing. *CVGIP: Graphical Models and Image Processing*, Vol. 56, No. 2, pp. 140-148.
- Metzler, M.D. and Malila, W.A. (1985): Characterization and comparison of Landsat-4 and Landsat-5 Thematic Mapper data. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1315-1330.
- Millington, A.C., Styles, P.J., and Critchley, R.W. (1992): Mapping forests and savannas in sub-Saharan Africa from advanced very high resolution radiometer (AVHRR) imagery. In: Furley, P.A., Proctor, J., and Ratter, J.A. (eds.): *Nature and dynamics of forest-savanna boundaries*. Chapman and Hall, London - Glasgow - New York - Tokyo - Melbourne - Madras, pp. 37-62.
- MME/DNPM (Ministerio da Minas e Energia, Departamento Nacional da Producao Mineral) (1978): Projeto Radambrasil. Vol. 18. Folha SA.20 Manaus. Levantamento de Recursos Naturais. Rio de Janeiro.
- Morisawa, M. (1985): Rivers. Forms and processes. *Geomorphology texts* 7. Longman Group Limited, London & New York, 222 pp.
- Murphy, J.M., Ahern, F.J., Duff, P.F., and Fitzgerald, A.J. (1985): Assessment of radiometric accuracy of Landsat-4 and Landsat-5 Thematic Mapper data products from Canadian production systems. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1359-1369.
- Nelson, R. and Holben, B.N. (1986): Identifying deforestation in Brazil using multiresolution satellite data. *International Journal of Remote Sensing*, Vol. 7, No. 3, pp. 429-448.
- Nelson, R., Horning, N. and Stone, T.A. (1987): Determining the rate of forest conversion in Mato Grosso, Brazil, using Landsat MSS and AVHRR data. *International Journal of Remote Sensing*, Vol. 8, No. 12, pp. 1767-1784

Nezry, E., Mougin, E., Lopes, A., Gastellu-Etchegorry, J.P., and Laumonier, Y. (1993): Tropical vegetation mapping with combined visible and SAR spaceborne data. *International Journal of Remote Sensing*, Vol. 14, No. 11, pp. 2165-2184.

ORSTOM (Institut Francais de Recherches pour le Development en Cooperacion) and INPA (Instituto Nacional de Pesquisa da Amazonia) (1988): *Conditions ecologiques et economiques de la production d'une ile de varzea: l'ile du Careiro*. Rapport Terminal, Paris, Manaus.

Pan, J.J. and Chang, Chein-I (1992): Destriping of Landsat MSS images by filtering techniques. *Photogrammetric Engineering and Remote Sensing*, Vol. 58, No. 10, pp. 1417-1423.

Paradella, W.R., Da Silva, M.F.F., Rosa, N.De A., and Kushigbor, C.A. (1994): A geobotanical approach to the tropical rain forest environment of the Carajas Mineral Province (Amazon region, Brazil), based on digital Landsat TM and DEM data. *International Journal of Remote Sensing*, Vol. 15, No. 8, pp. 1633-1648.

Pires, J.M. (1974): Tipos de vegetacao da Amazonia. *Brasil Florestal*. Vol. (V):17, pp. 48-58.

Pope, K.O., Rey-Benayas, J.M., and Paris, J.F. (1994): Radar remote sensing of forest and wetland ecosystems in the Central American tropics. *Remote Sensing Environment*, Vol. 48, pp. 205-219.

Poros, D.J. and Peterson, C.J. (1985): Methods for destriping Landsat Thematic Mapper images. A feasibility study for an online destriping process in the Thematic Mapper Image Processing System (TIPS). *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1371-1378.

Porto, M.L., Longhi, H.M., Citadini, V., Ramos, R.F., and Mariath, J.E. de A. (1976): Levantamento fitossociologico em area de 'mata-de-baixio' na Estacao Experimental de Silvicultura Tropical -INPA- Manaus, Amazonas. *Acta Amazonica*, Vol. 6, pp. 301-318.

Prance, G.T. (1978): The origin and evolution of the Amazon flora. *Interciencia*, Vol. 3, No. 4, pp. 207-222.

Prance, G.T. (1979): Notes on the vegetation of Amazonia 3. The terminology of Amazonian forest types subject to inundation. *Brittonia*, Vol. 31, No. 1, pp. 26-38.

- Prance, G.T. (1989): American tropical forests. In: Lieth, H. and Werger, M.J.A. (eds.): Tropical rainforest ecosystems. Elsevier Science Publishers B.V., Amsterdam, The Netherlands, pp. 99-132.
- Prance, G.T. and Schubart, H.O.R. (1978): Notes on the vegetation of Amazonia 1. A preliminary note on the origin of the open white sand campinas of the lower Rio Negro. *Brittonia*, Vol. 30, No. 1, pp. 60-63.
- Prance, G.T., Rodrigues, W.A., and da Silva, M.F. (1976): Inventário florestal de um hectare de mata de terra firme km 30 da estrada Manaus-Itacoatiara. *Acta Amazonica*, Vol. 6, No. 1, pp. 9-35.
- Putzer, H. (1984): The geological evolution of the Amazon basin and its mineral resources. In: Sioli, H. (ed.), The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 15-46.
- Quegan, S., Caves, R.G., and White, R.G. (1993): The structural content of ERS-1 images and its implications. In: Proc. Second ERS-1 Symposium: Final Results (Hamburg, Germany), pp. 623-628, 1993.
- Rasch, H. (1994): Mapping of vegetation, land cover, and land use by satellite - experience and conclusions for future project applications. *Photogrammetric Engineering and Remote Sensing*, Vol. 60, No. 3, pp. 265-271.
- Revilla Cardenas, J.D. (1981): Aspectos florísticos e fitosociológicos da floresta inundável (igapo) Praia Grande, Rio Negro, Amazonas, Brasil. Tese apresentada ao curso de pós-graduação da Universidade do Amazonas e Instituto de Pesquisas da Amazonia para o grau de mestre em ciências biológicas. Manaus.
- Riggan, P.J., Brass, J.A., and Lockwood, R.N. (1993): Assessing fire emissions from tropical savanna and forests of central Brazil. *Photogrammetric Engineering and Remote Sensing*, Vol. 59, No. 6, pp. 1009-1015.
- Ringrose, S., Matheson, W. and Boyle, T. (1988): Differentiation of ecological zones in the Okavango delta Botswana by classification and contextual analyses of Landsat MSS data. *Photogrammetric Engineering and Remote Sensing*, Vol. 54, No 5, pp. 601-608.
- Rosenfield, G.H. and Fitzpatrick-Lins, K. (1986): A coefficient of agreement as a measure of thematic classification accuracy. *Photogrammetric Engineering and Remote Sensing*, Vol. 52, pp. 223-227.

- Rosenfield, G.H. and Melcy, M.L. (1980): Application of statistics to thematic mapping. *Photogrammetric Engineering and Remote Sensing*, Vol. 46, pp. 1287-1294.
- Rosenfield, G.H., Fitzpatrick-Lins, K., and Ling, H.S. (1982): Sampling for thematic map accuracy testing. *Photogrammetric Engineering and Remote Sensing*, Vol. 48, pp. 131-137.
- Rosenholm, D. (1993): Land use and vegetation mapping by satellite: SSC Satellitbild experiences 1987-1993. *ITC Journal*, Vol. 1993-3, pp. 251-260.
- Royer, A., Vincent, P., and Bonn, F. (1985): Evaluation and correction of viewing angle effects on satellite measurements of bidirectional reflectance. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 12, pp. 1899-1914.
- Sader, S.A. (1987): Digital image classification approach for estimating forest clearing and regrowth rates and trends. *Proceedings of IGARSS '87 Symposium*, Ann Arbor, 18-21 May, 1987.
- Sader, S.A., Stone, T.A. and Joyce, A.T. (1990): Remote sensing of tropical forests: an overview of research and applications using non-photographic sensors. *Photogrammetric Engineering and Remote Sensing*, Vol. 56, No. 10, pp.1343-1351.
- Salati, E. (1985): The climatology and hydrology of Amazonia. In: Prance, G.T. and Lovejoy, T.E. (eds.) (1985): *Key environments. Amazonia*. Pergamon Press, Oxford-New York-Toronto-Sydney-Frankfurt, pp. 18-48.
- Salati, E. and Marques, J. (1984): Climatology of the Amazon region. In: Sioli, H. (ed.), *The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin*. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 85-126.
- Salo, J. and Räsänen, M. (1989): Hierarchy of landscape patterns in western Amazon. In: Holm-Nielsen, L.B., Nielsen, J.C., and Balslev, H. (eds.) (1989): *Tropical forests. Botanical dynamics, speciation and diversity*. Academic Press, London-San Diego-Boston-New York-Sydney-Tokyo-Toronto, pp. 35-45.
- Saxena, K.G., Tiwari, A.K., Porwal, M.C., and Menon, A.R.R. (1992): Vegetation maps, mapping needs and scope of digital processing of Landsat Thematic Mapper data in tropical region of south-west India. *International Journal of Remote Sensing*, Vol. 13, No. 11, pp. 2017-2037.
- Scorer, R.S. (1990): *Satellite as microscope*. Ellis Horwood, New York - London - Toronto - Sydney - Tokyo - Singapore.

- Shimabukuro, Y.E., Holben, B.N., and Tucker, C.J. (1994): Fraction images derived from NOAA AVHRR data for studying the deforestation in the Brazilian Amazon. *International Journal of Remote Sensing*, Vol. 15, No. 3, pp. 517-520.
- Singh, A. (1987): Spectral separability of tropical forest cover classes. *International Journal of Remote Sensing*, Vol. 8, No. 7, pp. 971-979.
- Sioli, H. (1965): Bemerkungen zur Typologie amazonischer Flüsse. *Amazoniana*, Vol. 1, No. 1, pp. 74-83.
- Sioli, H. (1984): The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin. Dordrecht Lancaster, 763 pp.
- Soil Taxonomy (1975): A basic system of soil classification for making and interpreting soil surveys. Soil Conservation Service, U.S. Department of Agriculture. Agriculture Handbook No. 436, Washington, U.S.
- Sombroek, W.G. (1984): Soils of the Amazon region. In: Sioli, H. (ed.), The Amazon. Limnology and landscape ecology of a mighty tropical river and its basin. Dr. W. Junk Publishers, Dordrecht, Boston, Lancaster, 1984, pp. 521-535.
- Srinivasan, R., Cannon, M., and White, J. (1988): Destriping of Landsat data using power spectral filtering. *Optical Engineering*, Vol. 27, No. 11, pp. 939-943.
- Stehman, S.V. (1992): Comparison of systematic and random sampling for estimating the accuracy of maps generated from remotely sensed data. *Photogrammetric Engineering and Remote Sensing*, Vol. 58, No. 9, pp. 1343-1350.
- Sternberg, H.O'Reilly (1975): The Amazon river of Brazil. Franz Steiner Verlag GmbH, Wiesbaden, 74 pp.
- Stone, T.A., Schlesinger, P., Houghton, R.A., and Woodwell, G.M. (1994): A map of the vegetation of South America based on satellite imagery. *Photogrammetric Engineering and Remote Sensing*, Vol. 60, No. 5, pp. 541-551.
- Story, M. and Congalton, R.G. (1986): Accuracy assessment: a user's perspective. *Photogrammetric Engineering and Remote Sensing*, Vol. 52, pp. 397-399.
- Takeuchi, M. (1961a): The structure of the Amazonian vegetation. 2. Tropical rain forest. *Journal of the Faculty of Science, University of Tokyo, Section 3, Botany*, Vol. 8, Parts 1-3, pp. 1-26.
- Thomas, I.L. and Allcock, G.McK. (1984): Determining the confidence level for a classification. *Photogrammetric Engineering and Remote Sensing*, Vol. 50, pp. 1491-1496.



- Townshend, J., Justice, C., Li, W., Gurney, C., and McManus, J. (1991): Global land cover classification by remote sensing: present capabilities and future possibilities. *Remote Sensing Environment*, Vol. 35, pp. 243-255.
- Townshend, J.R.G. and Justice, C.O. (1986): Analysis of the dynamics of African vegetation using the normalized difference vegetation index. *International Journal of Remote Sensing*, Vol. 7, No. 11, 1435-1445.
- Townshend, J.R.G. and Tucker, C.J. (1984): Objective assessment of Advanced Very High Radiometer data for land cover mapping. *International Journal of Remote Sensing*, Vol. 5, No.2, pp.497-504.
- Townshend, J.R.G., Justice, C.O. and Kalb, V. (1987): Characterization and classification of South American land cover types using satellite data. *International Journal of Remote Sensing*, Vol. 8, No. 8, pp. 1189-1207.
- Tucker, C.J., Holben, B.N. and Goff, T.E. (1984): Intensive forest clearing in Rondonia, Brazil, as detected by satellite remote sensing. *Remote Sensing of Environment*, Vol. 15, pp. 255-261.
- Tuomisto, H., Linna, A., and Kalliola, R. (1994): Use of digitally processed satellite images in studies of tropical rain forest vegetation. *International Journal of Remote Sensing*, Vol. 15, No. 8, pp. 1595-1610.
- Turcotte, K.M., Kramber, W.J., Venugopal, G., and Lulla, K. (1989): Analysis of regional-scale vegetation dynamics of Mexico using stratified AVHRR NDVI data. 1989 ASPRS/ACSM Vol. 3, April 2-7, Baltimore, pp. 246-257.
- Veloso, Henrique Pimenta, Antonio Lourenco Rosa Rangel Filho, and Jorge Carlos Alves Lima (1991): *Classificacao da vegetacao Brasileira, adaptada a um sistema universal*. Ministerio da Economia, Fazenda e Planejamento. Fundacao Instituto Brasileiro de Geografia e Estatistica - IBGE. Diretoria de Geociencias. Departamento de Recursos Naturais e Estudos Ambientais. Rio de Janeiro, 123 pp.
- Wegener, M. (1990): Destriping multiple sensor imagery by improved histogram matching. *International Journal of Remote Sensing*, Vol. 11, No. 5, pp. 859-875.
- Welch, R., Jordan, T.R., and Ehlers, M. (1985): Comparative evaluations of the geodetic accuracy and cartographic potential of Landsat-4 and Landsat-5 Thematic Mapper data. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1249-1262.
- Westin, T. (1990): Filters for removing coherent noise of period 2 in SPOT imagery. *International Journal of Remote Sensing*, Vol. 11, No. 2, pp. 351-357.



- White, R.G. (1991): Change detection in SAR imagery. *International Journal of Remote Sensing*, Vol. 12, pp. 339-360.
- Wooding, M.G. and Attema, E. (eds.) (1993): South American Radar Experiment SAREX-92. Proceedings of the SAREX-92 Workshop at ESA Headquarters, Paris, 6-8 December 1993. ESA wpp-76. European Space Agency, Paris, France, 246 pp.
- Wooding, M.G. and Attema, E. (1994): South American Radar Experiment (SAREX-92). *Earth Observation Quarterly*, No. 44, pp. 18-20.
- Wooding, M.G., Zmuda, A.D., and Attema, E. (1993): An overview of SAREX-92 data acquisition and analysis of the tropical forest environment. In: Wooding and Attema 1993, pp: 3-14.
- Worbes, M. (1983): Vegetationskundliche Untersuchungen zweier Überschwemmungswälder in Zentralamazonien - vorläufige Ergebnisse. *Amazoniana*, Vol. 8, No. 1, pp. 47-65.
- Worbes, M. (1985): Lebensbedingungen und Artengefüge zentralamazonischer Überschwemmungswälder. Dissertation zur Erlangung des Doktorgrades. Georg-August Universität, Göttingen, FRG.
- Worbes, M., Klinge, H., Revilla, J.D., and Martius, C. (1992): On the dynamics, floristic subdivision and geographical distribution of varzea forests in Central Amazonia. *Journal of Vegetation Science*, Vol. 3, pp. 553-564.
- Wrigley, R.C., Hlavka, C.A., Card, D.H., and Buis, J.S. (1985): Evaluation of Thematic Mapper interband registration and noise characteristics. *Photogrammetric Engineering and Remote Sensing*, Vol. 51, No. 9, pp. 1417-1425.