CLASSIFICATION OF MANGROVE VEGETATION COMMUNITIES IN AYEYARWADY DELTA USING LANDSAT ETM+ DATA

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ABSTRACT

Mapping is an essential resource assessment for employing rational and sustainable use as well as for planning realistic conservation strategies of tropical forests. One of the most feasible ways for mapping of extensive forest areas is extracting thematic information from remotely sensed data. In this study, the utility of satellite borne remote sensing data (Landsat ETM+ data) was examined for mapping purposes, with special emphasis on the classification of mangrove vegetation in the Ayeyarwady Delta. Spectral characteristics of various mangrove types, their classification by means of visual and digital image processing techniques were evaluated. Using available aerial photographs and ground information, discrimination and mapping accuracy of mangrove vegetation communities at three different levels of details were studied. Results indicated that the incorporation of transformed image layers such as band ratios, principal components and Tasseled-Cap transformation into colour composites facilitates slightly better identification of some ambiguous and spectrally similar classes. Commonly used digital method 'Maximum Likelihood Classification' offered less satisfactory results. Some possible improvements for classification were suggested in this study. It was found that the spectral information alone is not sufficient to obtain acceptable accuracy, and adequate field knowledge on geo-physical and environmental condition of mangrove vegetation is indispensable in classification using remotely sensed data.

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1. INTRODUCTION

The mangal vegetation is found at three geographical locations along the coast of Myanmar, concentrated particularly in the delta of Ayeyarwady River. The Delta is the home of largest mangrove areas of the country (Saw Han, 1992) which are ecologically as well as economically vital to the nation. Like many other forested areas, this complex and unique ecosystem is gradually diminishing before it has been thoroughly surveyed and studied. Some 276,600 acres[1] in the Delta are classified as mangrove forests in 2001 but these stands are under severe pressure and are either widely degraded or totally denuded. The first step towards its rehabilitation, conservation and management should be the assessment and mapping of the extent and distribution of all vegetation communities including mangrove forests.

Both aerial photography and satellite-borne remote sensing data have been widely used to map mangrove areas in many parts of the world (FAO, 1994). The level of management determines the details of information required, upon which the choice of sensor in turn is primarily dependent. Whereas panchromatic black and white aerial photographs were the basis for the compilation of forest type maps of Ayeyarwady Delta in early 1980s, Landsat imageries were used for land use/ land cover mapping of the area conducted later. In an earliest study for change detection, Sit Bo (1992) used Landsat MSS and TM imageries to assess forest cover changes between 1974 and 1990. Three broad crown cover classes of mangrove forest were distinguished by means of visual interpretation of false colour composites (FCCs). Finer classification scheme was adopted for land use/ land cover mapping of the area in 1995. Despite mangrove areas were divided into six subclasses (Anon., 1995), only one floristic type (*Heritiera fomes* forests) could be visually identified on the band 453 FCCs. The rest are variants of heterogeneous and mixed mangrove types.

All of past studies in the Delta have focused on a range of land cover classes distinguishing only a few classes of mangrove forests. To plan a rational and sustainable use of forest resources as well as to materialize a practical conservation strategy, information on ecological composition of the region as a whole is also required. The structure and species composition of different mangrove vegetation classes may vary significantly in order that their ecological and economical values may not be identical.

Even though the practicality of Landsat data has already been proved, the discrimination capabilities of the sensor is still left to be tested for detailed classification and mapping of both floristic and physiognomic/ structural cover types. Past mapping operations primarily focused on the mangrove/ non-mangrove separation and the mangroves were treated as a single land cover type. Much attention was not paid to the discrimination of different mangrove vegetation classes.

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[1] Source: Remote Sensing and GIS Section, Planning and Statistics Division, Forest Department

Studies on the spectral responses of different cover types will give an insight into the relation between remotely sensed data and objects on the ground. Better understanding will lead to the determination of possibilities as well as limitations with regard to visual and digital classification of various vegetation communities. This issue becomes more crucial, since Landsat data are one of the most feasible remote sensing sources for mapping and other applications.

The present study, thus, aims specifically at the following objectives:

- to describe general floristic/ structural mangrove types observed in the area,
- to develop an appropriate classification scheme for mapping purposes,
- to study spectral characteristics of cover types, and discrimination capabilities of the sensor,
- to evaluate image enhancement techniques that can provide an understanding of the nature of mangrove vegetation communities, and
- to suggest suitable classification methodology for practical application.

2. MATERIAL

2.1. Study Area

Ayeyarwady Delta lies in the South and Southeast Asia region which has the largest areas (some 42%) of world's mangroves (Spalding et al., 1997). The Delta is situated in the southwestern part of the country, geographically between latitudes 15° 43′ and 17° 25′ North, and between longitudes 94° 30′ and 96° 0′ East. It had been built up by the Ayeyarwady river with its origin in the northern tip of the country.

The region has a tropical monsoon climate with a pronounced dry season of three to four months. The climatic condition is optimal for mangrove growth. The area receives more than 2,500 mm per annum of precipitation that occurs only within the rainy season from mid-May to mid-October. Total rainfall from November to May for seven months is only 3-7% of the annual precipitation. Absolute highest temperature is 39°-40° C recorded in March and April, and absolute lowest temperature is 12°-13° C in January and February. Humidity is very high throughout the year; 60% to nearly 100% is recorded[2]. Evaporation is relatively high from March to mid-May when the temperature reaches the peak and, at the same time there is virtually no precipitation.

Geologically, the region is termed as morphological sub-unit "Irrawaddy Delta Basin". Rocks encountered in the Delta area are of marine sediments of Miocene age. Regarding the tectonic situation of the region, Bender et al. (1983) stated that the Ayeyarwady Delta was essentially occupied by Recent to Sub-Recent fluviatile sediments and only a few shallow anticlines of Miocene rocks were visible southwest of Yangon. Major soil types of the area are classified as Thionic Fluvisols,

[2] Source: Meteorological Department of Myanmar

Gleyic Solonchaks and Arenosols[3]. Except along the sandy coast, the soils are of gley clay or clay loam types which are sticky and very plastic. A tendency of soil acidity was found and rich nutrient of soil is observed (Tin Tin Ohn & Sein Thet, 1991).

The topography of the most areas is flat, being of deltaic alluvial origin. During the gradual sedimentation process new islands appear in the rivers and newly accreted areas are formed in the sea close to the main land. These areas are divided and separated by rivers, creeks and cross channels, resulting in a host of coastal islands of various sizes. Due to the silt deposition into the sea, the Delta tends to extend seawards. Ba Kyi (1964, cited in Bender et al., 1983) reported that the Ayeyarwady Delta is building up in a seaward direction at maximum rate of 4.5 km/ 100 years. This gradual seaward extension is testified by sandy high ridges that can be easily identified in the satellite imagery, characterizing distinct linear features in east-west direction. They are occupied by settlements, orchards and home gardens. According to the recent studies, however, the seaward progression is negligible due to the balance between sedimentation and coastal erosion (Chong, 1992). The level of land is mostly very low and submerged at spring tides during the rains. The deposition of silt along the perimeter of the new island gradually rises the level so that the banks become slightly higher, for some 20-30 cm, than the land inside. Interior of the island, depression areas are formed in which tides flow regularly. Theses lower levels inside are submerged twice a day. This configuration of the ground is closely associated with the types and distribution patterns of vegetation, since the influencing factors such as inundation and tidal regimes are primarily dependent upon it.

As the research was focused on the various mangrove vegetation communities, a representative test sites were selected in which typical cover types can be found. Selected sites are located in Bogalay and Laputta Townships (Fig. 1).

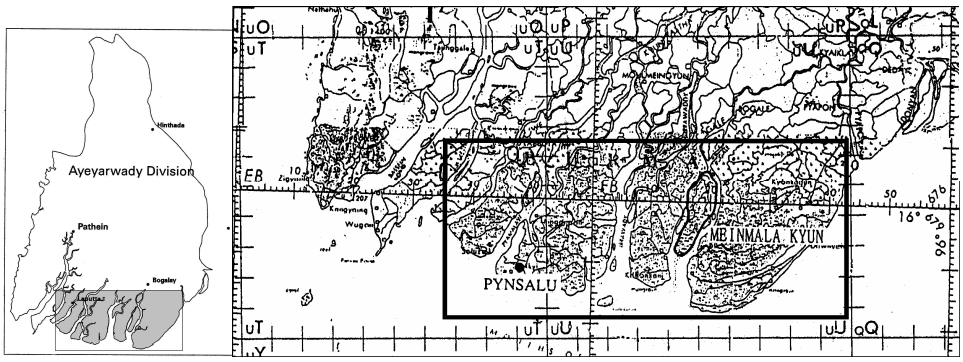


Figure 1: The study area

[3] Source: Soil Map of Myanmar by Land Use Division, Myanma Agriculture Service

Geographic location of the study area is approximately between latitudes 15° 43′ and 16° 10′ North, and between longitudes 94° 35′ and 95° 42′ East, encompassing an area of about 632,000 ha. The area is composed of nine reserved forests three townships. A considerable portion of mangroves in the area, however, has been already converted into cultivated land, and most of the mangroves are concentrated in Bogalay and Laputta townships. Encroachment into the mangroves is rampant even in the reserved forests.

General land cover pattern of the area can be described as three strata from North to South. The land has been completely turned into paddy fields in the North. The encroachment into the mangrove areas is minimum in the South because of high salinity of soil, higher tidal inundation and scarcity of land suitable for human settlements. More or less contiguous mangroves, therefore, can be seen there. In between the land is formed as a mosaic of paddy fields with various sizes and fragments of mangrove areas. There remain virtually no undisturbed natural mangrove areas and the existing stands are affected by degradation and depletion process.

2.2. Vegetation Communities

The South and Southeast Asia region, within which the Ayeyarwady Delta lies, has a relatively high diversity of mangrove species. Although all of mangrove species in the Delta have not yet been completely recorded, mangrove forests of the region can be regarded as one of the world's most diverse mangrove ecosystems with between 30 and 40 tree and shrub species. Kogo (1993) compiled a list of 29 mangrove trees, shrubs and ferns. Due to the deltaic nature and high levels of freshwater runoff, the salinity of water and soil is relatively low in the region, which probably causes different formation of vegetation communities and zonation patterns from those of coastal mangroves of the country.

In past working plans occurring forests were described based on six terrain classes (Tan Chein Hoe, 1952; Carappiett, 1957) that are comparable to the inundation classes proposed by Watson (1928). Two important classes were land flooded during spring tides that was the highest level for the true mangrove vegetation and land flooded during all high tides that was the true mangrove environment. Major mangrove type recorded in the old working plans was the *Heritiera fomes* (syn. *H. minor*) forest that ideally occurred in low intermediate levels of the Delta. Carappiett reported that the extent of this mangrove type was as much as 62% of the total forested area in Delta Forest Division. In mixed types dominated by *H. fomes*, the species was associated universally with *Ceriops decandra* and often with *Bruguiera gymnorhiza*. Other associated species were *Xylocarpus moluccensis*, *Xylocarpus granatum*, *Excoecaria agallocha* and *Cynometra ramiflora*. Other mangrove associations mostly confined to the low levels

flooded during all tides were *Rhizophora*, *Bruguiera* and *Sonneratia* stands that were distributed in patches or small extents.

Extensive utilization of the mangrove forests over a long period reduced them to severely degraded areas with little economic value. Original forms of vegetation communities without anthropogenic disturbances, as recorded in past working plans, cannot be found today. Most of the remaining forests are young regenerated stands that are often low and shrubby. Localized small patches of some species are occasionally found. Along the sides of creeks and rivers of some areas a thin belt of *Avicennia-Sonneratia* or *Rhizophora* often occurs on the fringe, while wider array of species are found landwards. This indistinct pattern, however, cannot be distinguished in the ETM+ imageries.

Chapman (1976, 1977) set out principal mangal associates that were generally recognized depending upon the floristic composition of the communities. The followings, however, are the vegetation types of the region that are based solely on the field observations of the present study and are adapted to the classes identifiable in the remotely sensed images.

Stands of Sonneratia spp. and Nypa fructicans

This type comprises of young successional mangrove formations that usually occur on newly accreted areas. Along prograding banks of large rivers, it forms long and narrow homogeneous strips of *Sonneratia* communities (usually *S. alba, S. caseolaris, S. griffithii* often together with planted *Nypa* stands). On small islands, the low and regularly flooded areas are usually recently colonized by these communities.

Planted Nypa fructicans Stands

Almost all of *Nypa* stands found today are planted rather than natural, and they usually fringe the banks of rivers and small creeks. Large plantations are also observed especially in Pyindaye Reserve.

Pure and mixed stands of Rhizophora, Bruguriera, Ceriops and Kandelia candel

These communities are, as recorded in the past working plans, usually confined to low levels of the area and are mostly found in localized patches of pure stands. *Rhizophora* often fringes banks of large rivers and creeks or it occurs at the inner depression areas that are locally known as *Byu-Byaiks*. Adjacent to these *Byu-Byaiks* where the terrain is slightly higher, *Bruguriera* and *Kandalia candel* are found in small gregarious groups or in mixed stands associated with *Rhizophora*. Although *Ceriops decandra* mostly occurs with other species, small patches of pure stands are also found.

Pure and mixed stands dominated by Avicennia

This type is widely distributed throughout the Delta. Many areas, however, are newly planted pure stands that usually form narrow strips along the banks of rivers. Mixed stands associated with other species such as *Ceriops decandra* and sporadic *Xylocarpus granatum* are also observed.

Pure and mixed stands dominated by Heritiera fomes

Observed *Heritiera fomes* stands are secondary forests regenerated mostly from coppice shoots surviving from the prolonged overexploitation. Wherever the terrain is high enough *Phoenix paludosa* is present as undergrowth. Common associate species are *Ceriops decandra* and *Excoecaria agallocha*. The distribution of these forests are no longer widespread but are concentrated only in the strictly conserved areas such as Mainmahla island and the core of Kadonkani Reserve.

Degraded stands dominated by Phoenix paludosa

These are formerly *Heritiera fomes* stands. Due to successive cutting over a long period the forests are reduced to degraded stands dominated by *Phoenix paludosa*. When the dominating *H. fomes* were removed the gaps were filled by *Phoenix paludosa* sometimes in nearly pure stands although sporadic *H. fomes* trees are still present.

Severely degraded areas and thickets of shrubby vegetation

In some areas the original forests are so severely degraded that the remaining vegetation forms impenetrable dense thicket of *Acanthus* and *Agrostichum* in low areas or they are turned into *Phoenix paludosa* stands on higher ground. As natural regeneration of other species is not possible under this condition, these communities have little economic value. These areas are often burnt down and converted into rice fields.

Mixed stands with heterogeneous species composition

Apart from the above pure consociates or stands dominated by single or a few species, mixed communities are also observed. They are either transition types in the zone between two distinct associations, the ecotone, or heterogeneous stands that consist of most of the original mangrove species.

2.3. Remote Sensing Data

The earth observing instrument on Landsat 7, the Enhanced Thematic Mapper Plus (ETM+), replicates the capabilities of the highly successful Thematic Mapper (TM) instruments on Landsat 4 and 5. ETM+ is an eight-band multi-spectral scanning radiometer capable of providing high-resolution image information of the

Earth's surface. It detects spectrally-filtered radiation at visible, near-infrared, short-wave, and thermal infrared frequency bands from the sun-lit Earth. Spectral and spatial characteristics of the sensor are shown in Table 1.

Table (1) Spectral and Spatial Resolution of Enhanced Thematic Mapper Plus (ETM+)

Band Number	Spectral Range (μm)	Ground Resolution (m)
1	0.45 to 0.515	30
2	0.525 to 0.605	30
3	0.63 to 0.690	30
4	0.75 to 0.90	30
5	1.55 to 1.75	30
6	10.40 to 12.5	60
7	2.9 to 2.35	30
panchromatic	0.52 to 0.90	15

Landsat Worldwide Reference System (WRS) will be maintained with periodic adjustments for the life of the mission. The WRS catalogues the world's landmass into 57,784 scenes, each one being 183 km wide and 170 km long. The Ayeyarwady Delta is covered by the scene WRS 133/ 49. Most recent data available at the Remote Sensing and GIS Section of the Planning and Statistics Division (acquired on 1 January 2001) were used for present study. Sub-scene of the study area was extracted for further data analysis. Only optical bands (Band 1 to 5 and 7) were included in the data analysis. As the mangrove vegetation communities are situated on the lowlands the removal of topographic effects that would complicate digital image processing was not necessary. Aerial photographs (1 : 50,000 scale) taken in February 2002 were also used as reference data.

2.4. Acquisition of Ground Information and Field Verification

Acquisition of field data was carried out from January to April 2002. Separate field trips were made to collect ground truth for training samples and reference information for verification. Through careful inspection of on-screen display and hard copy of band 453 (RGB) colour composite, test sites covering a range of different mangrove types were selected. Sample positions within these test sites were then pinpointed in the image and they were located on the ground using topographic maps and a global positioning system. Homogeneous stands and consociates of single species with considerable area extent were also visited and their locations were recorded. Information on land cover type, general description of the site and overall crown density were collected. Mean stand density and average stand height were also measured.

2.5. Ancillary Information

Along with the aerial photographs, land cover maps of the area compiled in the past were used as ancillary data. Experiences and knowledge accumulated from the projects and operations conducted in the area and they served as ancillary information for the study. The floristic information of the mangrove vegetation, however, is lacking or very limited and the vegetation communities have been usually grouped into a few general mangrove classes.

3. METHODS

In classification and mapping with remotely sensed data, the basic requirement is that the spectrally separable classes in the image correspond to the classes of interest (or information classes) on the ground. Spectral responses and spatial characteristics in the image, analog as well as digital, are used as surrogate for the information classes. To test this implicit hypothesis and to determine the level of detail achievable with special relevance to the classification of mangrove vegetation in the delta, attention was focused especially on two basic and common methodologies, viz., visual interpretation of enhanced images and the pervasive supervised maximum likelihood classification. Associations between natural groupings in the image data, and the appearances in the imageries with the classes of interest were assessed. All image processing was performed using ERDAS Imagine on a personal computer at Remote Sensing and GIS Section of Forest Department.

3.1. Image Enhancement for Visual Interpretation

Visual interpretation continues to play a very important role in mapping operations of tropical forests. Almost all of the past compilations of land use/ land cover maps conducted by the Forest Department mainly relied on the visual image interpretation technique (Sit Bo, 1992; Anon., 1995; Anon., 1996). In some cases visual interpretation proved more satisfactory and enhanced image would reveal regional patterns previously unknown (Tuomisto et al., 1994).

3.1.1. Concept of visual interpretation

Visual interpretation is a process involving the visual analysis and examination of images in order to identify objects, to judge the significance of the objects, and consequently to obtain mostly qualitative information from the images. Using specific a priori and contextual knowledge, the interpreter observes the image elements and makes deductive and inductive mental processing of the observed facts in regard with the subject of investigation. The basic elements of interpretation are illustrated in Figure 2.

More than one plausible outcome of the interpretation process is often possible, and the specific background and knowledge of the interpreter become obviously significant in this case. The visual interpretation, thus, depends upon the interpretability (or visual perceptibility) of the image as well as the skill and knowledge of the interpreter. Its output is generally the thematic information in the form of either a thematic map or a digital presentation.

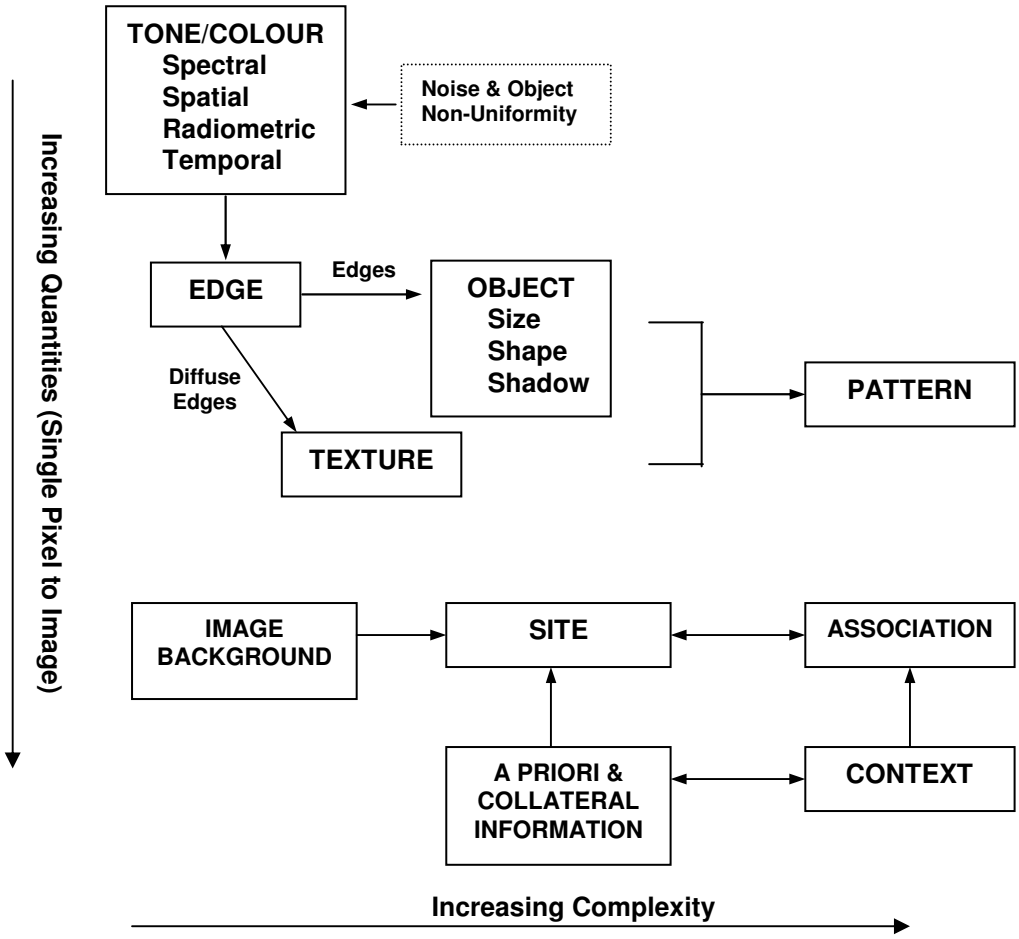


Figure 2: The elements of interpretation (Adapted from ANON., 1983)

3.1.2. Image enhancement techniques

The goal of image enhancement is to improve the visual perception and thus to increase interpretability of the image by means of enhancing spectral differences between the objects under study. Various enhanced colour composites were tested and their visual perception was evaluated in present study. The initial step was to

produce colour composites in which three original ETM+ bands were assigned to red, green and blue. As TM data are three-dimensional in character (Townshend, 1984), a combination of each band from visible, near infrared (NIR) and mid infrared (MIR) range is generally recommended (Benson & De Gloria, 1985; Jensen, 1996). For the selection of optimum triplet with maximum information, an objective and automated procedure suggested by Sheffield (1985) was used. Best three-band combination with maximum variance was determined using Sheffield's variance-covariance parameter, assuming that the variation of the data in specific image layers represent the contents of information.

Following the best triplet selection, the data were enhanced through several image transformations, namely, ratio enhancement, principal components analysis (PCA) and Tasseled-Cap Transformation (TCT). Ratioing bands for feature enhancement or combining ratios with original bands in colour composites can improve discrimination of vegetation classes with subtle differences. Selection of ratio combinations was based on the low correlation between corresponding band pairs and hypothesized spectral relationship among vegetation classes in the study area. A number of ratios along with Normalized Difference Vegetation Index (NDVI) were tested.

In PCA, strongly correlated original ETM+ bands are transformed into new image layers called principal components (PCs). It is, actually, a linear combination of six original bands, resulting new values re-projected on the statistically independent orthogonal axes. Eigenvectors mathematically derived from the covariance matrix of ETM+ bands are used as coefficients in the linear transformation of original data values into the component values. Each column of the eigenvector matrix describes a unit-length vector in spectral space, which shows the direction of the PC (Gonzalez & Wintz, 1977).

TCT is one of the most important and often used vegetation indices. It offers an optimized viewing of data structure for vegetation studies. Kauth and Thomas (1976) developed TCT initially for Landsat MSS data, and Crist and Cicone (1984) later extended the Tasseled-Caped concept to the simulated Landsat TM data. They found that the six-band TM data are dispersed into a three-dimensional space composed of three axes termed as *Brightness*, *Greeness* and *Wetness*. Of these three axes, *Greeness* is strongly related to the amount of green vegetation in the scene, being a contrast between the near infrared and visible bands. *Brightness* is a weighted sum of all bands, representing principal variation in soil reflectance, whereas *Wetness* relates to canopy and soil moistures.

Transformed image layers were first studied individually and the colour composites were then produced by means of combining three ratios, three PCs and three TCT layers. Following correlation analysis and thorough study of individual image layers, mixed composites were produced using all transformed layers along

with the original ETM+ bands. Roy et al. (1991) called them 'Hybrid Composites' and they have successfully used some hybrid composites for forest type mapping of a study area in India. Several common contrast stretches were applied to selected colour composites. Due to subtle differences among classes, powerful stretching is often necessary to distinguish various cover types.

3.2. Spectral Separability of Mangrove Vegetation Communities

In order to quantify the separation between a pair of density functions, statistical distances are usually used. These distances are referred to as measures of statistical separability of the probability distributions of the classes (Swain, 1978). Many multi-channel separability indices have been developed. The transformed divergence (TD) and the Jefferis-Matusita (J-M) distance are, among others, most commonly used for the purpose of category separation. Although these indices are usually used for feature selection, i.e. selection of a sub-set of best channels, they can be also used as measures of statistical separation between category response patterns for pairs of classes. The TD is a covariance-weighted distance between category means and TD values less than 1500 can be considered as spectrally similar classes (Lillesand & Kiefer, 2000)

Test areas for each classes mentioned in 2.2 were visually assessed and located in the image using on-screen display of the band 453 composite. Sample pixels were then extracted and training statistics were computed. The spectral separability of the classes was evaluated and training set was then refined.

3.3. Adopted Scheme for Classification

An appropriate classification scheme was derived from the close study on mangrove vegetation on the ground and evaluation of spectral separability of the classes. All classes of interest were carefully defined and included. Since desirable information classes did not cent percent match spectrally discernable classes of remotely sensed multi-spectral data, refining and re-categorizing classes based on spectral separability were inevitable. Attention is paid to the inclusion of classes relevant to the information categories into the final classification scheme.

Two aspects were taken into account here. Whereas ecologists are interested in floristic composition, structural and/or physiognomic classes describing general land cover pattern are of major interest for land use planners. An appropriate scheme should not only comprise of sufficient information categories but also be applicable to the classification using remotely sensed data. It was found that inclusion of all floristic communities was not possible. The primary restriction lies within the utility of the remote sensing data, but another important reason is the fact that a comprehensive classification of mangrove vegetation for the area is not yet available. Vegetation types mentioned in section 2.2 were considered as the basis for the

derivation of the scheme. Fourteen different classes shown in Table 2 were included at initial stage.

Table (2) Initial Classes Considered in the Development of a Suitable Scheme

Classes	Code
1. *Rhizophora*	Rhz
2. *Bruguiera/ Kandelia*	Brg/Kdl
3. *Sonneratia/ Nypa*	Snr/Npa
4. Planted *Nypa* Stands	Npa
5. *Avicennia* Stands	Avc
6. Mixed *Avicennia* Stands	AvcMxd
7. Mixed Mangrove Stands	Mxd
8. *Heritiera* (Low Stand Height)	HerLow
9. *Heritiera* (Medium Stand Height)	HerMed
10. *Heritiera* with *Phoenix paludosa*	HerPnx
11. Degraded Stands with *Phoenix paludosa*	DegPnx
12. Degraded Mixed Stands (Open Canopy)	DegOpn
13. Degraded Mixed Stands (Sparse Canpopy)	DegSpr
14. Degraded Stands with Thickets	DegTkt

3.4. Visual Interpretation of the Selected Colour Composites

Selected colour composites were displayed on the computer screen and their interpretability was inspected. Band 453 composite with histogram equalized stretch was used as bench-mark in the comparison. Discrimination among the vegetation classes was paid special attention. An independent inspection was also carried out by a second interpreter, and the evaluation results of two interpreters were later on compared.

3.5. Supervised Digital Classification

Maximum likelihood classification (MLC) is the most common supervised classification algorithm used with remotely sensed data (Richards, 1993). According to the Bayes' classification, the conditional probability of a class or category to which a pixel at a location $\boldsymbol{x}$ belongs is:

$P(\omega_i \mid \boldsymbol{x})$, i = 1, … , M where 'M' is total number of classes.

Classification is performed according to:

$\boldsymbol{x} \in \omega_i$ if $P(\omega_i \mid \boldsymbol{x}) > P(\omega_j \mid \boldsymbol{x})$ for all $j \neq i$,

which is also known as 'Bayes minimum error rule' (Hand, 1981). Since $P(\omega_i \mid \boldsymbol{x})$, the likelihood that the correct class is ω_i for a pixel at position $\boldsymbol{x}$, is unknown, the following relationship is used.

$$P(\omega_i \mid \boldsymbol{x}) = P(\boldsymbol{x} \mid \omega_i)\, P(\omega_i) / P(\boldsymbol{x})$$

The classification rule will be:

$\boldsymbol{x} \in \omega_i$ if $P(\boldsymbol{x} \mid \omega_i)\, P(\omega_i) > P(\boldsymbol{x} \mid \omega_j)\, P(\omega_j)$ for all $j \neq i$

The probabilities $P(\boldsymbol{x} \mid \omega_i)$ are estimated from training data and the $P(\omega_i)$ are also known or can be estimated from the analyst's knowledge of the image. The following prerequisites, therefore, must be satisfied for the successful application of MLC:

- Training data must truly represent the whole classes in the image.
- A priori probabilities $P(\omega_i)$ must be known or estimated.
- The probability distributions for the classes are of the form of multivariate normal models.

4. RESULTS

4.1. Image Enhancement

4.1.1. Selection of best triplet using original bands

The correlation matrix of ETM+ bands (Table 3) shows strong relationship among band 1 to 3 (visible bands), and between two MIR bands, i.e. Band 5 and 7. The correlation between NIR and MIR bands is moderate whereas the relationship between NIR and visible bands is relatively low. This obviously indicates the fact that the data are three-dimensional in character.

Table (3) Correlation Matrix

Band	ETM+2	ETM+3	ETM+4	ETM+5	ETM+7
ETM+1	0.97	0.79	-0.59	-0.05	0.10
ETM+2		0.87	-0.51	0.01	0.15
ETM+3			-0.16	0.42	0.54
ETM+4				0.65	0.52
ETM+5					0.98

Resulted best three triplets according to Variance-Covariance Parameter are 345, 347 and 245. Band 4 is contained in all triplets in hierarchy, even at the expense of excluding band 5. The result agrees with generally recommended combination of each band from visible, NIR and MIR region in the electromagnetic spectrum. As the best triplet for overall information content may not be the best for conveying the specific information desired, other band combinations, i.e. 347 and 245, were also considered. After in-depth investigation of the composites, the combination of ETM+4, ETM+5 and ETM+3 (assigned to red, green and blue respectively) was finally selected as best band triplet.

4.1.2. Image transformations

Ratio Enhancement

Five ratios along with NDVI have been considered based on the criteria mentioned in 3.1.2, of which four ratios were thoroughly investigated for image enhancement. Ratio of band 2 and 7 highlights discrimination between vegetation and non-vegetation classes, but suppresses differences among vegetation types. The appearance of the ratio of band 4 and 3 or NDVI image is very similar to that of band 4. The correlation coefficient is high (0.95), indicating that no extra information can be obtained from these image layers. Ratio of band 4 and 5 also enhances the contrast between vegetation and non-vegetation classes and it offers better differentiation among some specific classes, e.g. between degraded stands with *Phoenix paludosa* and Stands with closed canopy. Ratio of band 4 and 7 has a very similar appearance, but it contains more noise than the ratio of band 4 and 5 does. Due to the fact that band ratioing generates contrast as well as noise, and ratioed images are intensity blind, combining three ratio images in a colour composite would degrade rather than enhance the contrast and appearance of the composite. Consequently, ratios were used to produce hybrid composites (see 4.1.3).

Principal Component Analysis

Table 4 shows the eigenvalues of the components. It is obvious that the component 1 (PC1) contains most of the variation, accounting for 73.2% of total variance within the entire six-band ETM+ data set. Component 2 (PC2) and 3 (PC3) explain 22.4% and 4.0% of the remaining variance, respectively. The first three PCs altogether, thus, account for about 99.5% of the total variance. Eigenvector matrix (Table 5) indicates the factor loadings of the original bands for the principal components. Band 5 has relatively strong negative influence on PC1. PC2 is affected negatively by the NIR band, whereas PC3 is negatively related to band 3.

Table (4) Eigenvalues of the Principal Components

Components	Eigenvalues	Percent
1	3038.5	73.16
2	930.8	22.41
3	164.0	3.95
4	13.5	0.33
5	4.6	0.11
6	1.7	0.04

Table (5) Eigenvector Matrix

	PC1	PC2	PC3	PC4	PC5	PC6
ETM+1	0.022	0.259	-0.209	0.685	0.138	-0.632
ETM+2	0.014	0.321	-0.343	0.436	0.156	0.752
ETM+3	-0.127	0.536	-0.609	-0.538	-0.062	-0.180
ETM+4	-0.456	-0.669	-0.572	0.101	-0.082	-0.009
ETM+5	-0.750	0.172	0.305	-0.060	0.558	-0.001
ETM+7	-0.462	0.255	0.216	0.193	-0.797	0.052

In PC1, water bodies and swamp areas are distinct in dark tones due to the negative influence of MIR bands (band 5 and 7). Although the contrast between vegetation and non-vegetation is highlighted, the differences among non-vegetation classes are suppressed. It provides moderate enhancement of structural variation of vegetation classes, especially among the classes with different stand densities and canopy structures. The discrimination of the classes with medium stand density, however, is relatively weak in the image. To the contrary, non-vegetation classes such as bare land, fallow and barren land are clearly outlined in the PC2. But the image is less useful for vegetation study, since the vegetated areas are in dark tone. PC3 enhances subtle differences among vegetation types but provides poor differentiation between vegetation and non-vegetation.

Tasseled-Cap Transformation

Brightness (BRT) layer contains variation affected by the structural characteristics and inundation of stands. The appearance of *Greeness* (GRN) image is similar to that of band 4 or NDVI image, representing the variation in amount of green vegetation. The *Wetness* (WET) image reflects the degree of moisture of the objects. It is found to be not useful for the vegetation study, since poor representation of vegetation classes introduces difficulties in recognizing and identifying different mangrove types.

4.1.3. Colour composites and interpretability

After careful investigation of various color composites, the followings were finally selected for the comparison of interpretability (assigned red, green and blue respectively).

- Best combination of original bands: ETM+4, ETM+5, ETM+3
- Combination of principal components: PC1, PC2, PC3
- Combination of Tasseled Cap Transformation: GRN, BRT, WET
- Hybrid Combinations: (1) ETM+4, ETM+5, PC3; (2) GRN, PC1, PC3

4.2. Discrimination of Thematic Classes

4.2.1. Classification scheme

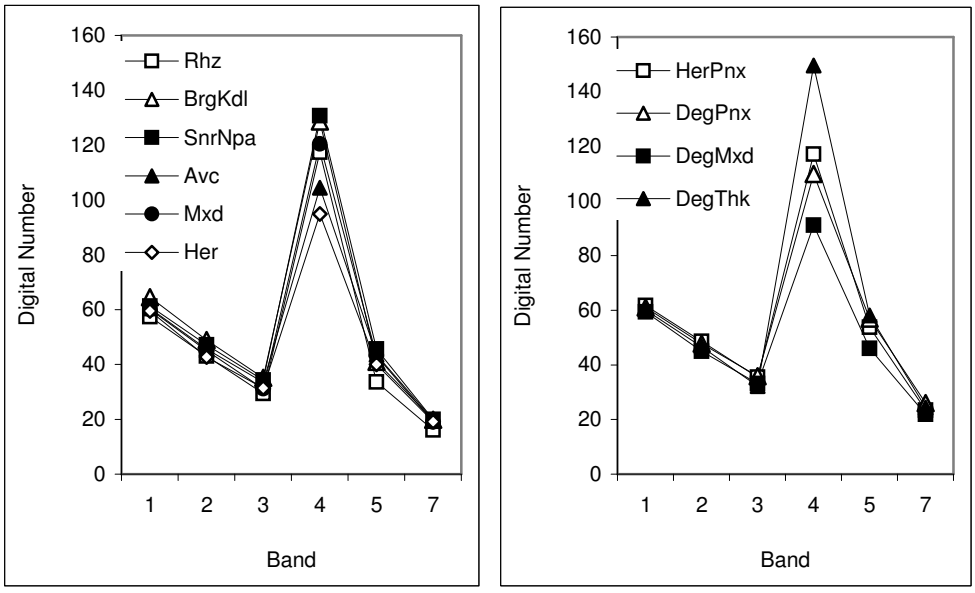
The resulted classification scheme is hierarchical at three different levels of detail (Table 6). At level 3, all classes mentioned in 3.3 were considered, from which ten classes, mostly floristic ones, were derived. Due to very close similarity of spectral patterns, some pairs of classes needed to be fused into one. The scheme at level 2 is, hence, a mixture of floristic and structural or physiognomic types. More generalized classes, primarily based on structural characteristics of the stands, were defined at level 1.

Table (6) Hierarchical Classification Scheme

Level 3	Level 2	Level 1
1. *Rhizophora* (Rhz)	1. *Rhizophora*	1. *Rhizophoraceae*
2. *Bruguiera/ Kandelia* (BrgKdl)	2. *Bruguiera/ Kandelia*	
3. *Sonneratia/ Nypa* (SnrNpa)	3. *Sonneratia/ Nypa*	2. *Sonneratia/ Nypa*
4. *Avicennia* (Avc)	4. Mixed Stands	3. *Heritiera/* Mixed Stands
5. Mixed Stands (Mxd)		
6. *Heritiera* (Her)	5. *Heritiera*	
7. *Heritiera* with *Phoenix paludosa* (HerPnx)	6. Degraded Stands with *Phoenix paludosa*	4. Degraded Stands with *Phoenix paludosa*
8. Degraded Stands with *Phoenix paludosa* (DegPnx)		
9. Degraded Stands (Deg)	7. Degraded Stands	5. Degraded Stands
10. Degraded Stands with Thickets (DegThk)	8. Degraded Stands with Thickets	6. Degraded Stands with Thickets

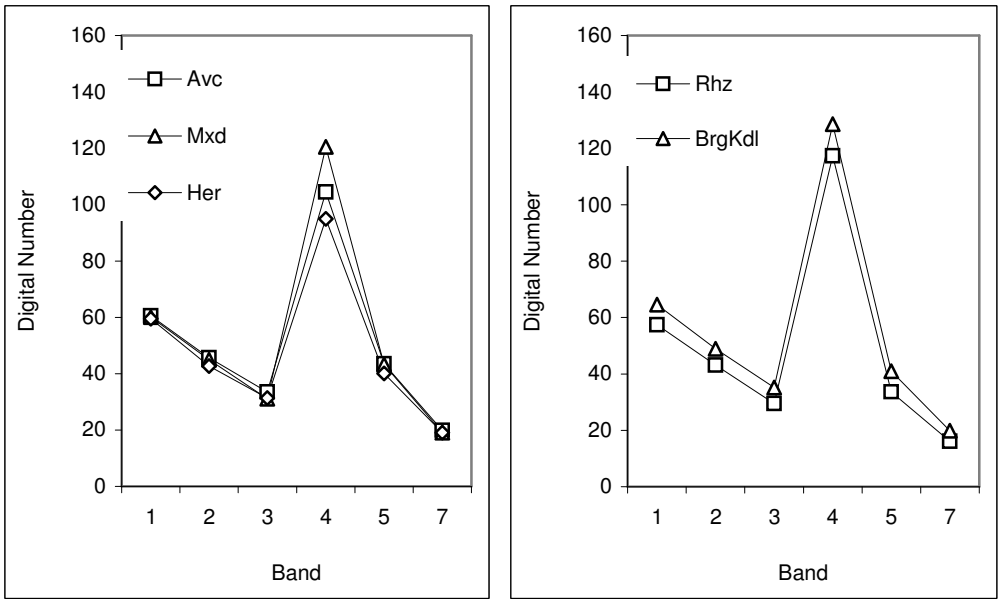
4.2.2. Spectral separability of classes

Mean values of training pixels (Figure 3) illustrate spectral responses of mangrove vegetation types. Marked differences among classes can be observed mainly in band 4 and 5. Degraded stand with thicket has the highest digital number (DN) value in NIR band, probably due to the presence of dense undergrowth. Reflection patterns of most of the closed stands with considerable canopy closure are more or less spectrally similar (Figure 3-a), whereas degraded mangrove classes, except between two stands dominated by the palm *Phoenix paludasa*, show remarkable differences (Figure 3-b).



(a) **(b)**

Figure 3: Mean plots of mangrove vegetation classes (a) Closed stands with considerable canopy closure and (b) Degraded stands (For the code of classes see Table 6).



(a) **(b)**

Figure 4: Mean plots of floristically different but structurally similar classes (For the code of classes see Table 6).

The similarity or differences in spectral responses are attributed to two stand characteristics, primarily to the canopy structure and to some extent to the floristic composition. *Heritiera*, *Avicennia* and mixed stands, for instance, have very similar spectral patterns (Figure 4-a) because they are similar in terms of stand height, density and canopy structure. The differences are apparent only in NIR band, in which variations within the class are relatively high. Considerable commissioning of errors, hence, should be expected between these classes at classification stage. *Rhizophora* and *Bruguiera/ Kandelia* stands are also similar in structure in order that general pattern of spectral responses is similar, even though the difference in magnitude of reflection is considerably significant (Figure 4-b). Degraded stands and stands dominated by *Phoenix paludosa*, on the other hand, are spectrally different despite of similarity in structure. The difference is probably attributed to the dominance of the palm in degraded mixed stands or in degraded *Heritiera* stands. Consequently, the degraded types can be fairly accurately differentiated from the stands with considerable canopy closure.

4.3. Interpretability of Colour Composites

Overall separation of all selected composites was fair to good, although they did not provide satisfactory discrimination of Level 3 classes. Combinations of PCs and TCT images did not offer better interpretability than the best triplet of original bands (ETM+453) did. The contrast between degraded classes and closed stands, however, was improved in the composite of PCs. To the contrary, the combination of *Brightness*, *Greeness* and *Wetness* did not improve overall separability. Hybrid combination 1 offered slightly better discrimination of vegetation and non-vegetation classes, especially in identification of classes with various moisture contents. Discrimination of a few ambiguous classes such as *Bruguiera/ Kandelia* and *Sonneratia/ Nypa* was slightly better in this composite. Hybrid composite 2 also offered better differentiation of some specific classes, and its overall discrimination was as good as band 453.

Histogram equalization stretch gained better contrast than other tested stretching methods. Distinct patterns were obtained with this stretch, and thus it was useful for the differentiation of degraded stands from other classes. However, it should be noted that the strong stretching techniques not only enhance the contrast but also suppress variation of closely similar classes. As the linear stretch maintained subtle tonal differences in the image, it provided slightly better separation of classes with various stand densities and structures.

4.4. Accuracy of Supervised Digital Classification

In Table 7, overall accuracies derived from self-classification of training pixels are compared with those of independent verification of MLC results. Relatively high accuracy of self-classification at all levels indicates that the training samples used in present study are sufficiently homogeneous. By contrast, overall accuracy of independent verification is much lower at all levels of detail. Acceptable accuracy can be achieved only when the classes are generalized at level 1. It is thus obvious that the results from self-classification of training pixels should not be taken as a general indication of classification accuracy.

Table (7) Comparison of Overall Accuracy

Level	Self-Classification	Independent Verification
3	87.4%	63.3%
2	91.0%	71.0%
1	93.9%	80.6%

Accuracy assessment with independent reference information shows much lower results (Table 8). Even at level 1, accuracy for a specific class is as low as 63%, because confusion between *Sonneratia/ Nypa* and *Rhizophoraceae* is still considerable. At level 2, error of omissions and error of commissions are high, although moderate overall accuracy is achieved. Noteworthy result is that significant classification error occurs between pairs of classes, despites their training pixels showed relatively high separability in terms of 'Transformed Divergence'. This proves the fact that the quantitative indices extracted from training samples do not sufficiently represent the actual separability of classes over the whole scene. Accuracy at level 3 is not satisfactory in all aspects, owing to close spectral similarity of some classes defined in the classification scheme.

Table (8) Accuracy derived from independent verification of classification results

Level	Overall Accuracy (%)	KHAT	Minimum Producers' Accuracy (%)	Minimum Users' Accuracy (%)
3	63.3	0.51	37.5	44.2
2	71.0	0.60	41.7	57.7
1	80.6	0.72	66.0	63.3

5. DISCUSSIONS

5.1. Image Enhancement Techniques

Since mapping by means of ground survey is not feasible for extensive areas, remotely sensed data, both photographic and non-photographic, are mostly used to prepare or update maps. Satellite remote sensing becomes an alternative methodology especially for preparation of small-scale land cover maps. Landsat TM/ ETM+ data, among others, have been widely used for mapping of extensive tropical forests including mangrove areas. For vegetation studies NIR and MIR bands are particularly useful.

Out of the wide range of image analysis options, two primary types are of interest to forest and natural resource management, namely, image enhancement and data classification. The aim of image enhancement is to increase the contrast between the selected features. Each of image enhancement techniques produced unique outputs that should carefully be evaluated and interpreted. Results of present study reveal that the utility of band ratios is limited because ratioing not only enhances some scene features but also suppresses some specific contrast at the same time. Spectral and/ or biophysical relationships of vegetation classes under study are essential for the identification of meaningful band ratios. In present study the ratios of NIR and MIR bands were found more useful than commonly used NDVI image. By combining one of these ratios with other appropriate image layers in a colour composite, discriminating specific classes with subtle spectral variation is improved.

PCA often reveals certain features obscured and masked by more dominant patterns in the original bands, which was the rationale of incorporating the PCA into the image enhancement of the present study. As expected, it proved to be useful visual enhancement of the image. A visual inspection, however, is required to assign particular features to specific components. As the PCs are re-projected results of original ETM+ bands on the mutually independent orthogonal axes, the component values are no longer associated with general spectral characteristics of features on the ground. Furthermore, the PCA is scene dependent in order that the results of a particular study are not transferable to other scenes with different land cover situation. Utility of TCT in present study is approximately identical to that of PCA.

Enhanced image layers can then be combined to form a colour composite for visual interpretation. In present study, an objective approach was used to define and select most useful composites for evaluation. Theoretically, composites containing transformed layers such as ratios or PCs have the advantage of combining data from more than three bands. According to the results of this study, however, the composites of PCs or TCT images did not prove significant improvement in overall discrimination of classes. The best triplet of original bands provides the same interpretability. This indicates the fact that scene variation is not definitely associated

with the separability of classes. Still, hybrid composites are slightly better in discriminating classes with subtle spectral variation.

5.2. Visual vis-à-vis Digital Classification

The results show that both visual and digital methods facilitate easy differentiation between vegetated and non-vegetated land covers. The visual interpretation, however, is found probably the simplest and most reliable method in order to delineate vegetated mangrove cover types and non-vegetation classes. Incorporating transformed image layers into colour composites further enhance the separation between spectrally similar classes. Significant advantage is more apparent when the spatial features such as texture and pattern are used in the interpretation process. These features are especially essential for the identification of classes with distinct spatial pattern (e.g. sandy rises with orchards and settlements, not included in the classification scheme) that cannot be mapped accurately by means of digital classification. Low to moderate mapping accuracy of MLC confirmed that classification using the spectral information alone does not yield accurate mapping of various mangrove vegetation communities. The reason may be the fact that some classes markedly depart from the premise of MLC mentioned in 3.5.

The success of visual interpretation, on the other hand, strongly relies upon the skill and experiences of the interpreter. Subjective judgments thus are inevitable and inconsistent results are to be expected when more than one interpreter is involved in the mapping operation. Further disadvantage is the fact that it is time and labour intensive if large areas are to be mapped.

5.3. Possible Improvements for Classification

Simple and practical improvement in terms of accuracy and efficiency would be refining training samples for digital classification. Clustering approach can be used for more meaningful selection of training samples. Another prospect of improvement is combining visual and digital methods in which the interpreter's knowledge can be effectively combined with processing power of the computer. Using advanced techniques like rule-based expert classification and other non-parametric algorithms may be an alternative to conventional methods used in this study. The application of these complicated methods would be difficult for most mapping operations in the tropical region, because simple and straightforward method is first and foremost desirable in practice. Employing layered classification would be simplest way of incorporating ancillary information into the digital classification.

6. CONCLUDING REMARKS

Extraction of mangrove floristic information using ETM+ data was found not accurate at detailed level. Even panchromatic aerial photography in 1 : 50,000 scale did not offer reliable identification of specific floristic types. Yet, ETM+ data proved useful for classification of mangrove vegetation at more generalized level of details. NIR and MIR bands are especially useful in discriminating mangrove stands with different structural characteristics.

In regard with mapping techniques, results showed advantages of visual method over commonly used MLC algorithm. Subjectivity is often considered as a disadvantage of visual interpretation. Subjective judgments is, however, also inevitable in training sample selection of supervised digital classification.

In both cases, either visual interpretation or digital classification, the analyst should be equipped with the knowledge of scene to be mapped. The best results could be achieved if the user takes part in the classification process by cooperating with the image analyst. This would be more critical if the analyst have little or no field knowledge and experiences.

Appendix I

Common Mangrove Species Distributed in Ayeyarwady Delta[#]

Family	Myanmar Name	Botanical Name	Remarks
Acanthaceae	c<m (]zL)	*Acanthus ebracteatus*	Distributed as undergrowth.
	c<m (r\rf:)	*Acanthus ilicifolius*	- ditto -
	c<m (óG<f)	*Acanthus volubilis*	- ditto -
Avicenniaceae	orJhjuufwuf	*Avicennia alba*	Distributed in depression areas in localized patches.
	orJh]zL	*Avicennia marina*	Distributed along the banks with high salinity, and in muddy areas, occurred usually in narrow strips or as associate species.
	orJhjuD:	*Avicennia officinalis*	Distributed in slightly higher terrain.
Euphorbiaceae	oa\m	*Excoecaria agallocha*	Distributed as associate species.
Leguminosae	]rif:u	*Cynometra ramiflora*	Distributed as associate species.
Meliaceae	yifv<ftkef:	*Xylocarpus granatum*	Distributed as. associate species.
	use	*Xylocarpus moluccensis*	Distributed as associate species in sandy and higher terrain than *Xylocarpus granatum*.
Palmae	"ed	*Nypa fruticans*	Mostly planted stands
	oifabmif:	*Phoenix paludosa*	Occurred dominantly or distributed as undergrowth.
Pteridaceae	iSufjuD:awmif (juD:)	*Acrostichum aureum*	Distributed as undergrowth.
	iSufjuD:awmif (ao:)	*Acrostichum speciosum*	- ditto -

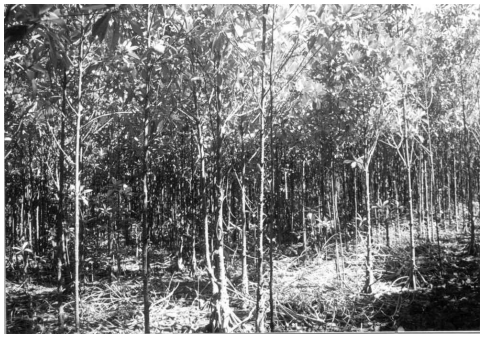
Rhizophoraceae	]AL:0g:judwfvdrf	*Bruguiera cylindrica*	Distributed as associate species, often dominated.
	]AL:tkyfaqmif:	*Bruguiera gymnorhiza*	- ditto -
	óSH]AL:	*Bruguiera parviflora*	- ditto -
	]AL:juufwuf	*Bruguiera sexangula*	- ditto -
	r'r	*Ceriops decandra*	Distributed as. associate species.
	r'rarsm	*Ceriops tagal*	- ditto -
	]AL:bddkif:a'gifhfh	*Kandelia candel*	- ditto -
	]AL:acsaxmuf (zdk)	*Rhizophora apiculata*	Occurred dominantly.
	]AL:acsaxmuf (r)	*Rhizophora mucronata*	- ditto -
Sonneratiaceae	vrJh	*Sonneratia alba*	- ditto -
	uefhyvm	*Sonneratia apetala*	Occurred often sporadically mixed with Aviccenia officinlis.
	vrk	*Sonneratia caseolaris*	Occurred dominantly.
	vb	*Sonneratia griffithii*	- ditto -
Sterculiaceae	uepdk (a\)	*Heritiera fomes*	- ditto -
	uepdk (ukef:)	*Heritiera littoralis*	- ditto -

[#] Complete survey of the flora in Ayeyarwady Delta has not yet been carried out. The list is compiled based solely upon the field observations.

Appendix II:

Some Mangrove Vegetation Communities Observed in the Study Area

Pure *Rhizophora* stand



Bruguiera/ Kandelia Stand

Pure *Avicennia officinalis* stand

Pure *Avicennia marina* stand

Heritieria fomes stand

Degraded mixed stand

Severely degraded mixed stand

Degraded stand dominated by *Phoenix paludosa*

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CLASSIFICATION OF MANGROVE VEGETATION COMMUNITIES IN AYEYARWADY DELTA USING LANDSAT ETM+ DATA

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