HIGH-RESOLUTION VEGETATION DATA FOR MANGROVE RESEARCH AS OBTAINED FROM AERIAL PHOTOGRAPHY

ANOUK VERHEYDEN[1,2*], FARID DAHDOUH-GUEBAS[2], KATRIEN THOMAES[2], WILLIAM DE GENST[3], SANATH HETTIARACHCHI[4] and NICO KOEDAM[2]

[1]*Research Assistant Fund for Scientific Research-Flanders (Belgium);* [2]*Research Group of General Botany and Nature Management, Mangrove Management Group;* [3]*Department of Geography, Center for Cartography and GIS, Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussel, Belgium;*
[4]*Department of Botany, University of Ruhuna, Matara, Sri Lanka*
*(*author for correspondence, e-mail: Anouk.Verheyden@vub.ac.be; fax: ++32 2 629 34 13; tel.: ++32 2 629 34 10)*

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Abstract. In this methodological study, the applicability of aerial photographs for monitoring mangrove vegetation dynamics at high resolution was investigated. Vegetation maps of three mangrove forests in Sri Lanka (Galle, Rekawa and Pambala) were produced based on visual analysis of aerial photographs. The visual analysis was aided by applying an interpretation key constructed during a first fieldwork mission. Image attributes used for the identification of individual trees included: gray values, texture, form and size of the crowns and the presence or absence of a shaded side. For the identification of species assemblages, the vegetation structure (i.e. the distribution of individual trees) appeared to be an important attribute. The accuracy and reliability of the vegetation maps were investigated during a second fieldwork mission. The aerial photographs proved to be very useful for the production of genus-based vegetation maps. The error analysis showed that density estimations (quantitative identification) based on aerial photography was not sufficiently accurate for the objectives of the study, but that the overall identification of vegetation assemblages (qualitative identification) coincided most satisfactory with the ground-truth data. In addition to the applicability of aerial photography in monitoring mangroves, the importance of aerial photography in the management of the mangrove ecosystem is clearly highlighted.

Key words: aerial photography, mangrove, remote sensing, Sri Lanka, vegetation mapping.

1. Introduction

Remote sensing provides valuable information for mapping vegetation and monitoring vegetation change. Aside from the information given by the local population, it is often the only information available about the forests' history. Within the literature, there is a tremendous emphasis on digital imagery and automated methods, despite the fact that in many cases, human interpretation of photographic images is the only method of obtaining information. Satellite imagery has been used to map and assess vast coastal areas such as mangroves (Aschbacher et al., 1995; Ravan and Roy, 1997; Ramachandran et al., 1998). However, the coarse resolution of these data sources rarely allows identification at the species or generic level,

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or the typology of assemblages necessary to detect changes within a mangrove forest (Holmgren and Thuresson, 1998). Aerial photographs still possess a much higher resolution and therefore give considerably more information, allowing a more detailed study of the local vegetation and floristics. For example, Blasco et al. (1998) and Smith et al. (1998) used multi-temporal aerial photographs to detect subtle seasonal changes in vegetation cover in a saltmarsh system. Holmgren et al. (1997) could estimate forest characteristics, such as timber volume, from digital high-altitude aerial photographs and the canopy dynamics of a tropical rainforest were investigated by Herwitz et al. (1998) with the aid of aerial stereopairs.

In addition to the higher resolution, aerial photographs also have the advantage of being available over a larger time range, compared to satellite imagery. Photographs of war or shortly post-war times (WWII) are generally the earliest available and will always be the only method of retrospective research extending far back into the 20th century. Time series of aerial photography give relevant information to study vegetation dynamics (Williams and Lyon, 1991; Miller et al., 1996; Dahdouh-Guebas et al., 2000). Both the high spatial and temporal resolution of aerial photographs make them very strong tools in management, because of the ability to detect changes in a forest that may require management. In mangrove forests, the early detection of changes on a species or generic level can be extremely important for the ecosystem, for associated ecosystems and for the human population that depends in many ways on the mangrove. Mangroves act, for instance, as a living dyke against the effects of the tides along many tropical coasts. The disappearance of a single species of mangrove may be the start of a chain reaction that leads to the inability of the ecosystem to fulfill its vital role against coastal erosion, threatening for instance coconut plantations (Van Campenhout, 1997; Van pottelbergh, 1999) and human settlements. The disappearance of mangroves also has direct consequences for associated ecosystems such as seagrass beds and coral reefs that will be affected by the process of sedimentation of suspended material (e.g. in river deltas) displaced from the mangroves to their vicinity. Local people depend on the mangrove as a resource for wood, and more important for food, since mangroves act as breeding, spawning, hatching and nursing grounds for many commercial and non-commercial marine animal species (Rönnbäck, 1999).

Mangrove forests have been studied worldwide and, at present, considerable research effort is put in the assessment of the state of mangroves on a large scale (Spalding et al., 1997; Dahdouh-Guebas, 2001; Kairo, 2001). This includes the study of mangrove dynamics in time and space, the increase or decrease in areal extent, changes in species richness, regeneration capacity, etc. (cf. Dahdouh-Guebas et al., 2000). The understanding of mangrove dynamics can lead to conservation and management directives, such as the establishment, protection and management of re-afforestation plots in the framework of regeneration and/or restoration projects, as described by Lee et al. (1996).

The main objective of this study was to investigate the applicability of aerial photographs in the production of detailed mangrove vegetation maps to be utilized in the study of vegetation dynamics on a species or generic level. This entailed a two-tier procedure: first, a reliable determination key was generated for the interpretation of the photographs, and second, the determination of typologies of different species assemblages was done making use of this key. Both the identification (qualitative identification) and density of the mangroves (quantitative identification) from the aerial photographs were compared with the field data and tested. The secondary objective of this study was to investigate the wider spatial applicability of the interpretation key and to evaluate the feasibility of its use for the interpretation of aerial mangrove photographs from the past.

2. Materials and methods

2.1. General approach

An overview of the scientific approach of the study is given in Figure 1 and can be summarized as follows:

- Phase I: Photographs were analyzed visually in search for useful image attributes to distinguish different assemblages.
- Phase II: The data collected during the first fieldwork mission were superimposed on the aerial photographs to allow identification of individual trees and species assemblages.
- Phase III: Using the information from the visual analysis and the fieldwork, a preliminary interpretation key was developed.
- Phase IV: Detailed vegetation maps were produced in a Geographic Information System (GIS) environment.
- Phase V: During the second fieldwork mission, data from representative areas of the forest were collected to ground-truth the vegetation maps.
- Phase VI: Error analysis and correction was performed, where necessary, on the vegetation maps and on the interpretation key.
- Phase VII: The interpretation keys of the different study sites were compared to determine the spatial applicability of the keys.

2.2. Description of the study sites

Three mangrove forests were selected for investigation, based on their relative undisturbed character and their location in different climatic zones of Sri Lanka (Mueller-Dombois, 1968). For a site to be classified as relatively undisturbed, the site had to show a continuity of mangrove cover over four decades. The choice of sites in different climatic zones enabled us to draw conclusions about the wider spatial applicability of the interpretation key, since different climatic zones show different vegetation compositions (De Silva and Balasubramaniam, 1985). The studied sites are located in Galle (06°01′N–80°14′E), Rekawa Lagoon (06°03′N–80°50′E) and Pambala (07°30′N–79°49′E).

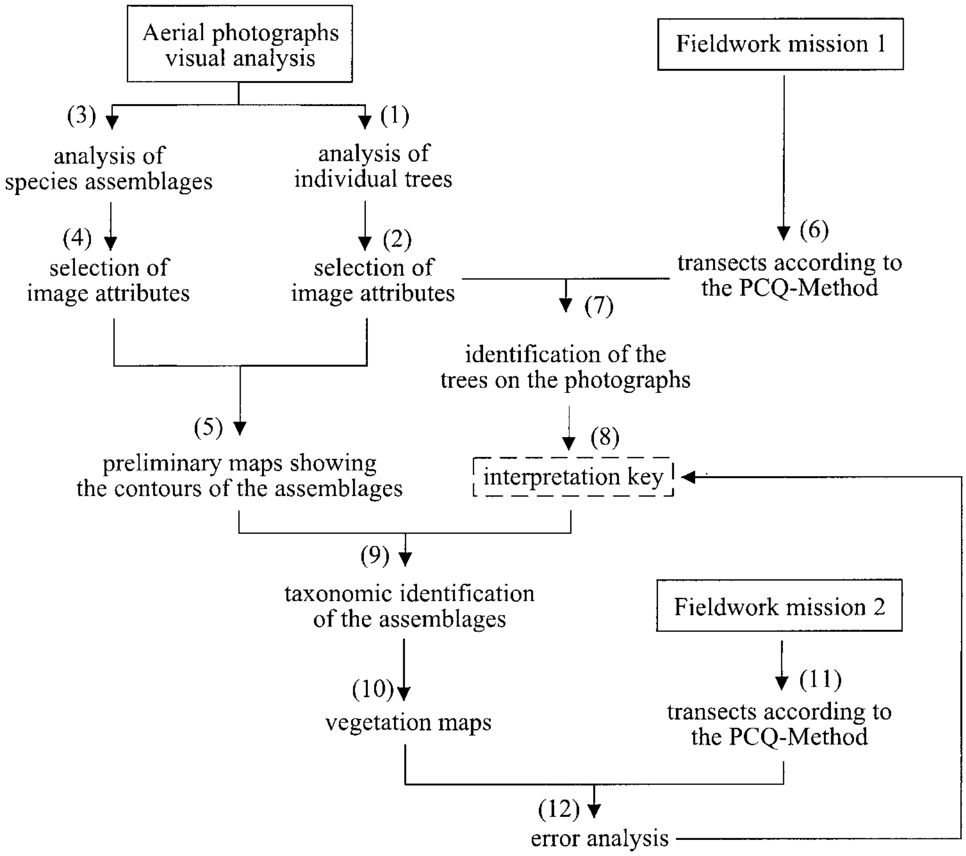


Figure 1. Flowchart of the methodological framework used in this study. The numbers between parentheses refer to detailed descriptions of the stages in the text.

The mangroves of Galle, sometimes referred to as the mangroves of Unawatuna, are located in the ‘wet’ climate zone of Sri Lanka (Figure 2). They cover an area of 1.5 km^2 and are of the basin type according to the typology of Lugo and Snedaker (1974). The forest is located approximately 600 m from the Indian Ocean shoreline. Two rivers run through the forest, the Thalpe Ela discharging into the ocean, and the Galu Ganga, a tributary of the Thalpe Ela. Interviews with the local population revealed that in 1982, the Galu Ganga was deepened and broadened and the sediment was used to construct an earthen road, which follows the river and continues through the mangrove forest. Furthermore, a dam was built where the Galu Ganga discharges in the Thalpe Ela in order to allow rice farming upstream.

Rekawa Lagoon is situated in the intermediate climatic zone (Figure 2) and can be classified as a fringe forest type (Lugo and Snedaker, 1974). The lagoon is about 3.3 km long and 0.9 km wide, with its long axis running parallel with the ocean, into which it discharges through a meandering creek of about 1.6 km in length.

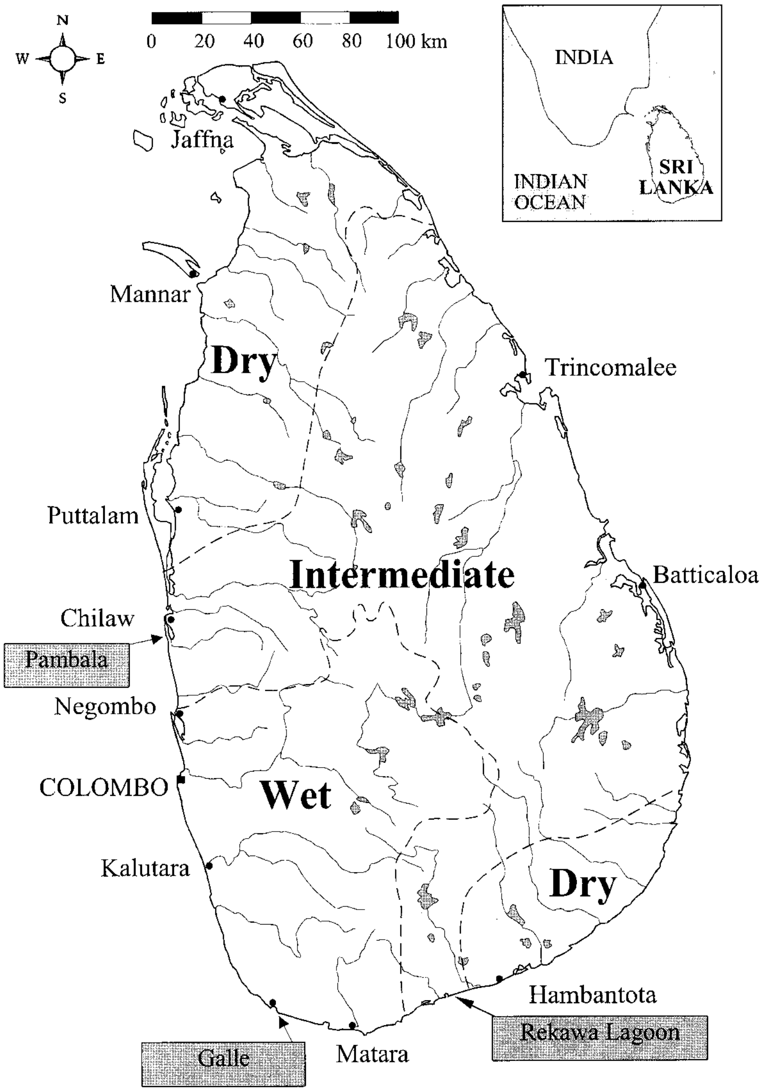


Figure 2. Location of the study sites in Sri Lanka and the distribution of the main climatic zones according to Mueller-Dombois (1968). Adapted from Jayatissa et al. 2002.

However, the discharge is often blocked by a sand bar, which is frequently cleared by local farmers in order to improve freshwater run-off from the upstream paddy fields. A wide sandflat with coconut palms, *Cocos nucifera* L., separates the bulk of the lagoon from the Indian Ocean. Near its discharge point, three rivers feed the creek: the Kirama Oya, Urubokka Oya and Rekawa Oya. Disturbances include some wood harvesting and tanbark collection.

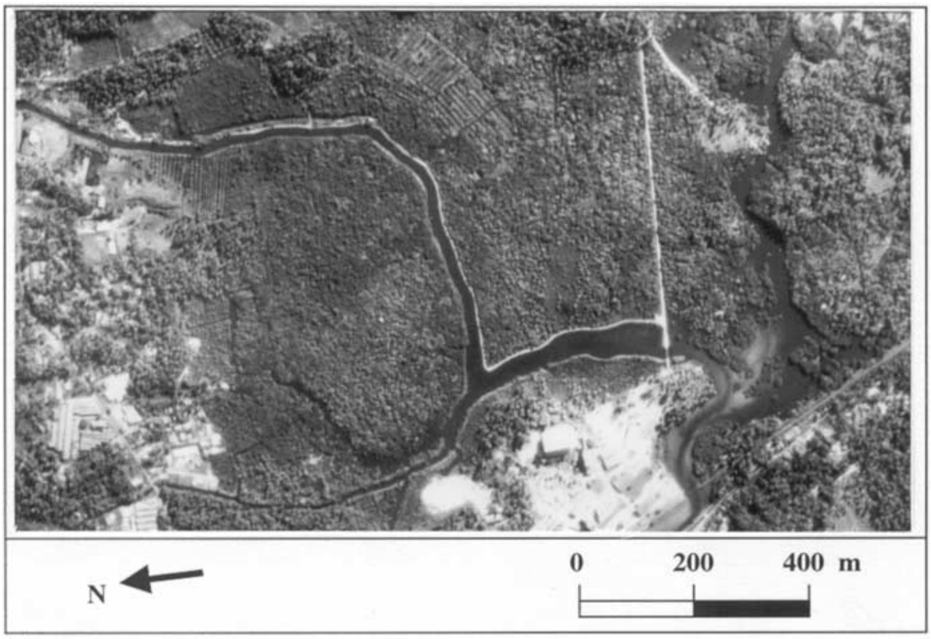
Pambala (Kakkapalliya) is situated in the intermediate climatic zone (Figure 2) and is part of Chilaw lagoon, which is about 5 km long and 2 km wide.

The mangroves in Pambala can be classified as a ‘hammock’ forest type (Lugo and Snedaker, 1974). The lagoon opens into the ocean at two sides, resulting in a daily influx of seawater into the lagoon. Pambala is recognized by the IUCN (1996) as a fairly undisturbed site.

Although Pambala and Rekawa are both located in the intermediate climatic zone (Mueller-Dombois, 1968), these two study sites are interesting for comparison. Pambala is situated in the northern section of the intermediate climatic zone and Rekawa in the southern (Figure 2). The mangroves of Pambala are thus separated from those of Rekawa by a ‘wet’ climatic barrier, along the coast.

2.3. VISUAL INTERPRETATION OF THE AERIAL PHOTOGRAPHS

Aerial black and white photographs of Galle and Rekawa (Figure 3a,b) were obtained from the Department of Geography at the University of Ruhuna, Matara, while those of Pambala (Figure 3c) were obtained from the Forest Department, Colombo. The most recent photographs were from 1994. The photographs originally had scales of 1 : 50,000 (1956) and 1 : 20,000 (1974 and 1994), but were photographically enlarged to facilitate investigation to 1 : 10,000 and 1 : 5000 respectively.



(a)

Figure 3. (a) Aerial photograph of the mangrove area in Galle (1994). (b) Aerial photograph of Rekawa lagoon (1994); the photograph shown is a combination of two photographs out of a series (c) Aerial photograph of the study site in Pambala (1994).

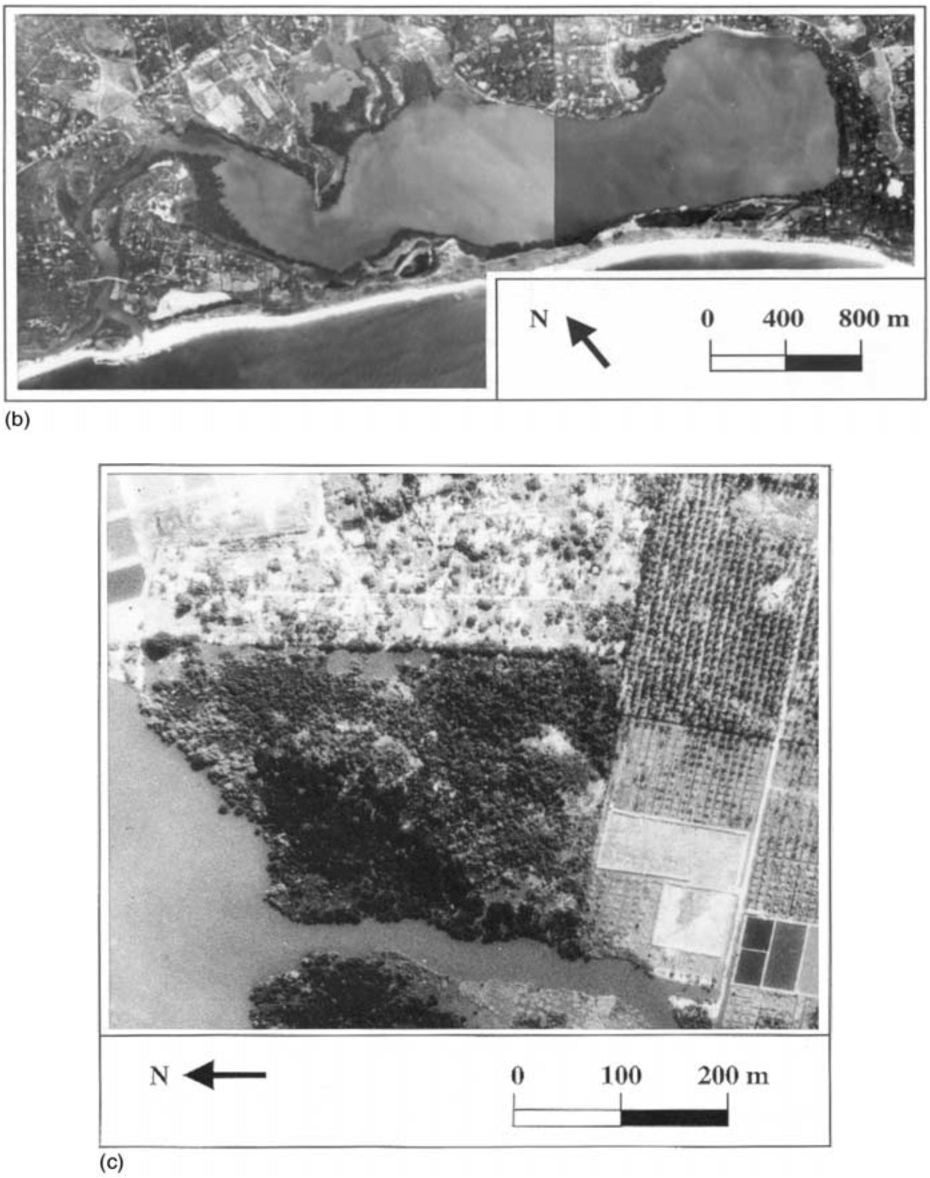


Figure 3. (*Continued*)

During visual analysis of the aerial photographs, individual trees (1) (the numbers between brackets refer to the different steps in Figure 1) were inspected for image attributes (gray value, texture, shape, etc.) (2). The attributes retained for the purpose of species identification were the following:

- Gray values: this attribute is regarded as a relative value, since light conditions can cause considerable differences. Neither the shaded side, nor the overexposed side of the crown is taken into consideration to determine the gray value (i.e. only the middle of the crown was used).

- Texture: here defined as the internal structure detected in one crown (e.g. smooth, grainy).
- The shape and size of the crown.
- The presence or absence of a shaded side, as an indication of the density and shape of the canopy.

The photographs were also analyzed for species assemblages (3), showing a typical typology. To define and recognize species assemblages the 'structure' attribute was added for visual analysis of the photographs (4). The term 'structure' is here defined as the way the tree canopies are distributed with respect to each other, and can be compared to Lillesand and Kiefer's (1994) 'pattern' attribute.

Once species assemblages were defined and localized, preliminary vegetation maps were constructed, showing only the contours of different assemblages without taxonomic identification (5). To construct these maps, the scanned aerial photographs and the contours of the different assemblages were digitized in a GIS (MapGrafix ComGrafix, Inc., USA).

2.4. FIELDWORK

The first fieldwork mission took place during January–February 1996, for Galle and Rekawa and February 1997, for Pambala. The second fieldwork mission was carried out in January 1997, for Galle and Rekawa and April–May 1998, for Pambala. A gap of two to four years separates the ground-truthing missions from the taking of the aerial photographs. The possibility of any discrepancies between the data collected during field inventories and the aerial photographs due to this time gap is small; however, it cannot be completely excluded.

Species presence was recorded on a number of transects using the point-centered-quarter method or PCQM (Cottam and Curtis, 1956, adapted by Verheyden, 1997) to detect the species assemblage (6). In this method, the closest tree was recorded in each of four adjacent 90° quadrants in different sample points, and tree's D_{130} was measured (term according to Brokaw and Thompson (2000), but formerly referred to as DBH, the diameter at breast height) for trees with a D_{130} greater than 2.5 cm. Mangrove tree species nomenclature is according to Tomlinson (1986). Attention was also given to the identification of individual trees (7), which could be easily located on the photographs (e.g. along the roads).

During the first fieldwork mission, one transect was investigated in Galle, seven in Rekawa, and five in Pambala, after which the preliminary interpretation keys were prepared. The second fieldwork mission included eight transects using the PCQM in Galle and a number of observational transects (visual determination of species presence and dominance of species) in Rekawa and Pambala, which allowed the verification of the vegetation maps. For the three sites, the relative density values were calculated for each species assemblage separately. For this purpose, transects crossing different assemblages were overlaid with the vegetation contours (from the preliminary vegetation maps). Transects were positioned on the maps using clearly identifiable landmarks (e.g. roads, dam, etc.). The transects were then split up and the sample points were attributed to the different vegetation assemblages for the calculation of the densities.

2.5. PRODUCTION OF THE VEGETATION MAPS

A preliminary interpretation key was constructed using the data collected from the first fieldwork mission and the image attributes selected during visual analysis (8). This key was used to taxonomically identify the species assemblages on the photographs (9) and produce the final vegetation maps (10).

2.6. ERROR ANALYSIS

The purpose of the error analysis is to investigate whether the information obtained from fieldwork can be obtained from (less time consuming) aerial photograph interpretation. More specifically, this research focuses on the recognition of the dominant tree species on one hand (qualitative identification) and their relative densities (quantitative identification) on the other. Using the data obtained during the second fieldwork mission (11), an error-analysis (12) was performed for the three vegetation maps. This analysis is threefold.

- The relative densities, as obtained from counting individual trees on the aerial photograph (‘observed’ values), were compared with those obtained from the fieldwork (‘expected’ values) for each of the vegetation assemblages using the G-test (Sokal and Rohlf, 1981).
- The dominant species present (obtained from ground-truthing data) within a species assemblage was compared with the dominant species determined from aerial photography analysis.
- Finally, the correct delimitation of the species assemblages was incorporated into the error analysis. To accomplish this, the data obtained from the transects were visualized in a GIS and superimposed on the vegetation maps. The resulting map was visually inspected for species assemblages detected during fieldwork but not on the photographs.

3. Results

3.1. THE INTERPRETATION KEYS

Figure 4a–c shows the final interpretation keys for Galle, Rekawa and Pambala, respectively. These do not show any fundamental difference from the preliminary keys produced after the first phase fieldwork missions, which is positive for the reliability of the keys. For Galle, a number of species could be added to the key after the second phase fieldwork missions. This was particularly due to the discovery of more species in the field when more transects were investigated. Image attributes show an overlap between the different species of the same site as well as between the different species of different sites (see discussion).

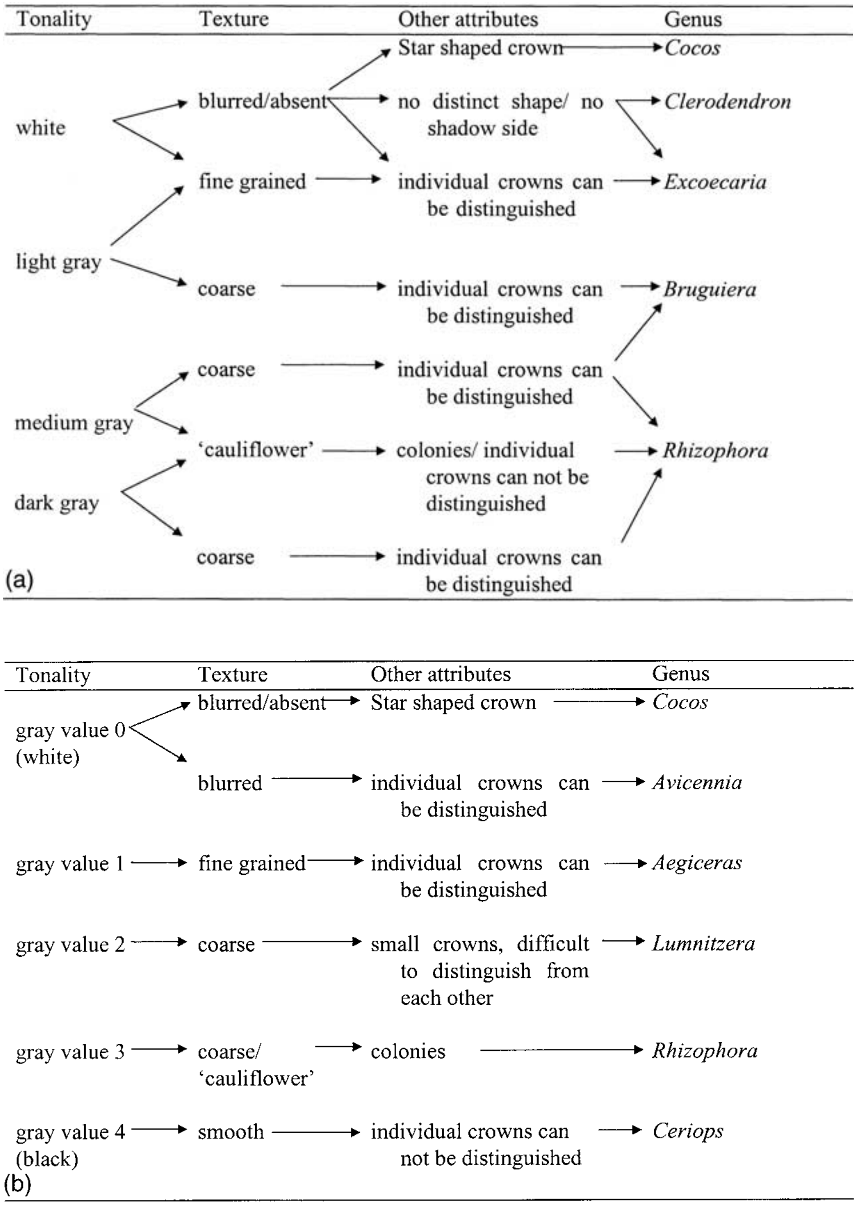


Figure 4. (*Continued*)

Tonality	Texture	Other attributes	Genus
white	blurred/absent	Star shaped crown	*Cocos*
light gray	coarse	individual crowns can be distinguished	*Avicennia*
	blurred	individual crowns can be distinguished	*Excoecaria*
medium gray	fine grained	small crowns, difficult to distinguish from each other	*Lumnitzera*
	coarse/ blurred	individual crowns are difficult to distinguished	*Bruguiera or Xylocarpus*
	blurred/absent	no distinct shape/ no shadow side	*Acrostichum or Acanthus*
dark gray / black	coarse/ 'cauliflower	individual crowns can sometimes be distinguished	*Rhizophora*

(c)

Figure 4. Interpretation keys for the mangroves of Galle (a) (adapted from Dahdouh-Guebas et al., 2000), Rekawa (b) and Pambala (c).

3.2. THE VEGETATION MAPS

Figure 5a–c shows the vegetation maps for Galle, Rekawa and Pambala, respectively. The maps focus on the mangrove vegetation. Terrestrial vegetation, rice farms and inhabited areas were all classified as non-mangroves. Plantations (e.g. coconut palms) and infrastructures (e.g. shrimp farms, roads) close to the mangroves, or interacting directly or indirectly with the mangrove ecosystem were added to the maps, since these could be important when studying dynamics. On the photographs, a distinction could be made between homogenous assemblages (composed of one dominant genus and some individuals of other genera) and heterogeneous or mixed assemblages, in which two or more genera are co-dominant. In some cases, the absolute density of some stands could be distinct. An obvious example is the recognition of open areas within the forest. These 'open' areas are usually not completely bare of vegetation, but contain very sparse individuals or young trees, the latter being hardly, or not visible on the photographs. A less obvious example of difference in absolute density was the distinction between sparse and dense *Excoecaria* assemblage in Galle. This distinction was based on the relative distance between crowns, and thus it was based on the attribute 'structure'. Pambala and Rekawa show a higher species diversity than Galle, which is expected due to the different climatic zone they are situated in (De Silva and Balasubramaniam, 1985).

3.3. Error analysis

Table I displays the relative densities for each assemblage as obtained from visual analysis of the photographs and from fieldwork measurements in Galle. From Table I, it can be deduced that the dominant genera were successfully identified in most of the cases. However when comparing the relative density values, the G-test showed non-significance in most of the cases.

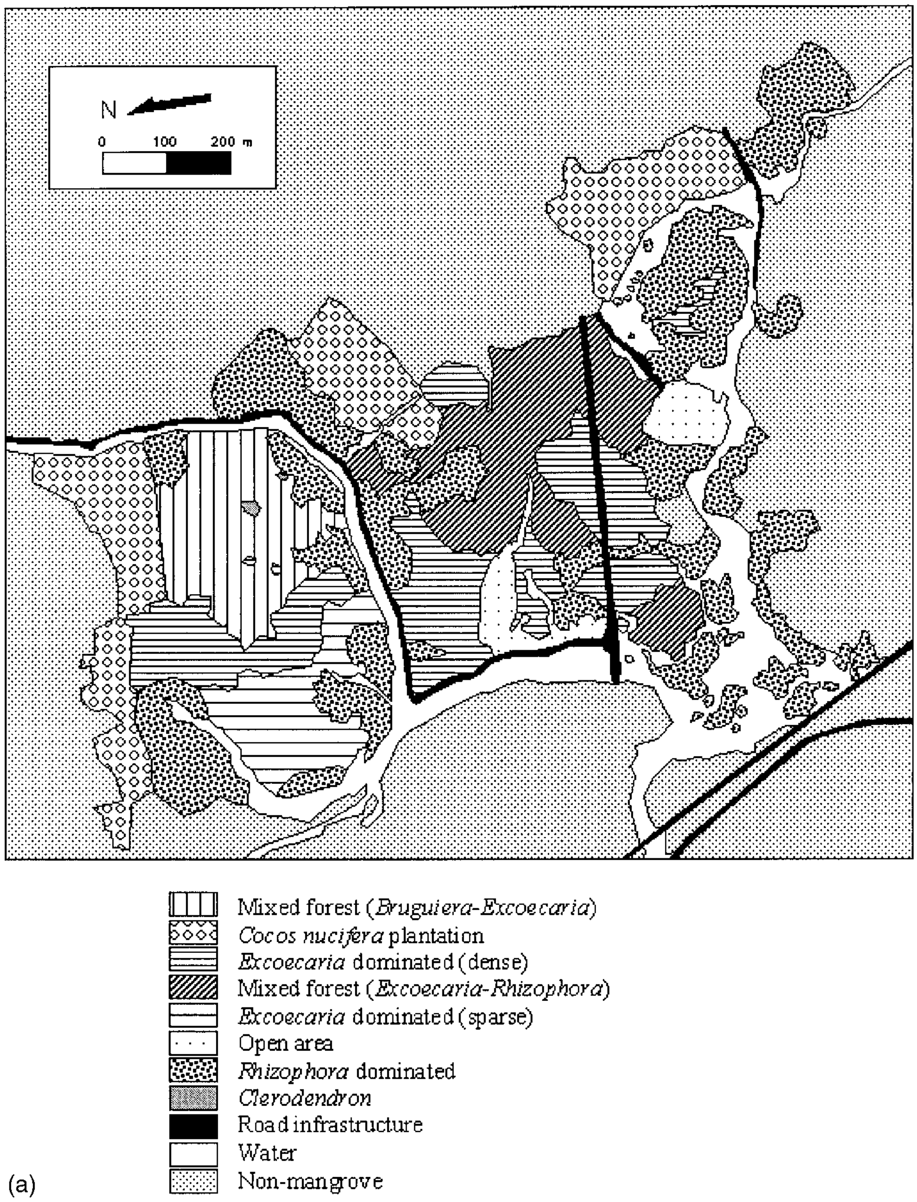


Figure 5. Vegetation maps of 1994 for the mangroves of Galle (a), Rekawa (b) and Pambala (c).

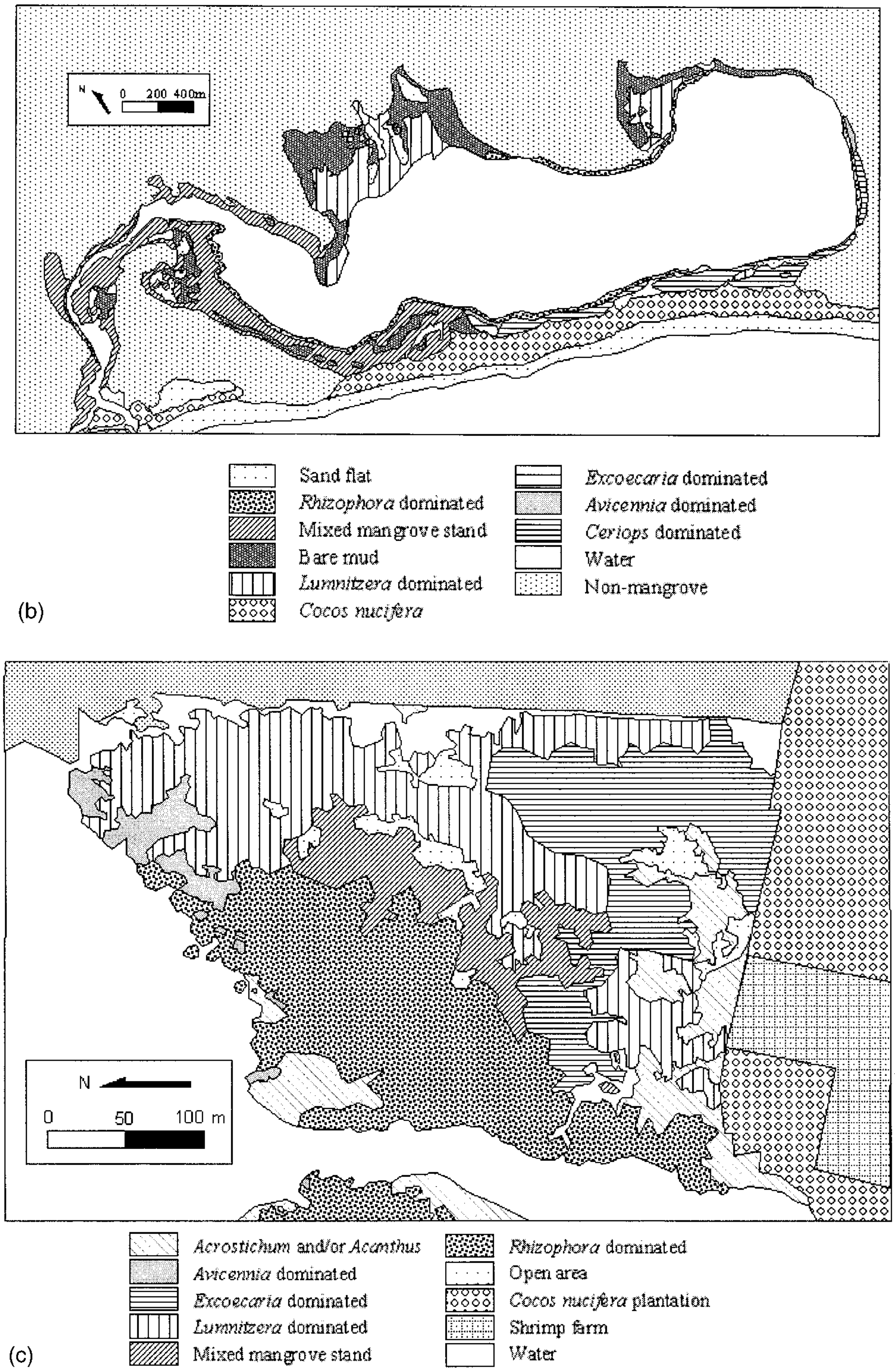


Figure 5. (*Continued*)

TABLE I. Relative density values (in number of trees per total area) for the different assemblages as obtained from the visual analysis of the photographs (Obs.) and from the fieldwork (Exp.) for the different species assemblages using the G-test.

Assemblage (dominant genus)	Genera present	Obs.	Exp.	G-value	d.f.	p-value
Rhizophora	*Rhizophora*	76	34	1.787	2	n.s.
	Excoecaria	53	25			
	Bruguiera	0	1			
Excoecaria (dense forest)	*Rhizophora*	99	27	59.035	3	$p < 0.001$
	Excoecaria	531	129			
	Bruguiera	0	14			
	Heritiera	0	6			
Excoecaria (low density forest)	*Rhizophora*	0	0	1.746	1	n.s.
	Excoecaria	100	23			
	Bruguiera		1			
Mixed *Rhizophora*–*Excoecaria*	*Rhizophora*	116	26	59.375	2	$p < 0.01$
	Excoecaria	171	11			
	Bruguiera	0	1			
Mixed *Excoecaria*–*Bruguiera*	*Rhizophora*		8	Not computable		
	Excoecaria		19			
	Bruguiera		19			
Open area	*Rhizophora*	14	8	8.269	2	$p < 0.02$
	Excoecaria	61	70			
	Bruguiera	0	5			

G-values, degrees of freedom (*d.f.*) and p-values are shown.

TABLE II. Percentage proportions of the sample points containing a certain species (columns) for each of the main vegetation assemblages (rows) as detected from the aerial photograph in Galle, Rekawa and Pambala.

Assemblages	n	*A. cor*	*A. off*	*B.* spp.	*C. tag*	*E. aga*	*H. lit*	*L. rac*	*R.* spp.	*X. gra*	Nil
Galle	666										
EA	322	—	—	9.94	—	60.56	1.86	—	13.04	—	14.60
EA + B	50	—	—	32.00	—	34.00	0.00	—	12.00	—	22.00
R	165	—	—	5.45	—	24.85	0.00	—	52.12	—	17.58
O	129	—	—	3.10	—	52.71	0.00	—	5.43	—	38.76
Rekawa	116										
LR	39	17.95	10.26	—	0.00	2.56	—	61.54	0.00	—	7.69
R	39	5.13	7.69	—	5.13	2.56	—	28.21	38.46	—	12.82
O	38	0.00	0.00	—	0.00	0.00	—	13.16	0.00	—	86.84
Pambala	484										
LR	139	0.00	7.19	3.60	—	7.19	—	74.10	1.44	0.72	5.76
R	261	0.38	3.83	11.88	—	1.15	—	5.36	71.65	0.00	5.75
O	84	1.19	2.38	3.57	—	3.57	—	26.19	22.62	10.71	29.76

Assemblages dominated by: B = *Bruguiera* spp.; EA = *Excoecaria agallocha*, L.; LR = *Lumnitzera racemosa* Willd.; R = *Rhizophora* spp.; O = open area. Species: *A. cor* = *Aegiceras corniculatum* (L.) Blanco; *A. off* = *Avicennia officinalis* L.; *B.* spp = *Bruguiera* spp.; *C. tag* = *Ceriops tagal* (Perr.) C.B. Robinson; *E. aga* = *Excoecaria agallocha*; *H. lit* = *Heritiera littoralis* Dryand.; *L. rac* = *Lumnitzera racemosa*; *R.* spp. = *Rhizophora* spp.; *X. gra* = *Xylocarpus granatum*; Köenig; Nil = empty quadrant.

To further test the identification of the dominant species in the main vegetation assemblages, the percentage of sample points containing a certain species in each assemblage was investigated in Galle, Rekawa and Pambala (Table II). For the majority of the assemblages, the dominant species was correctly identified,

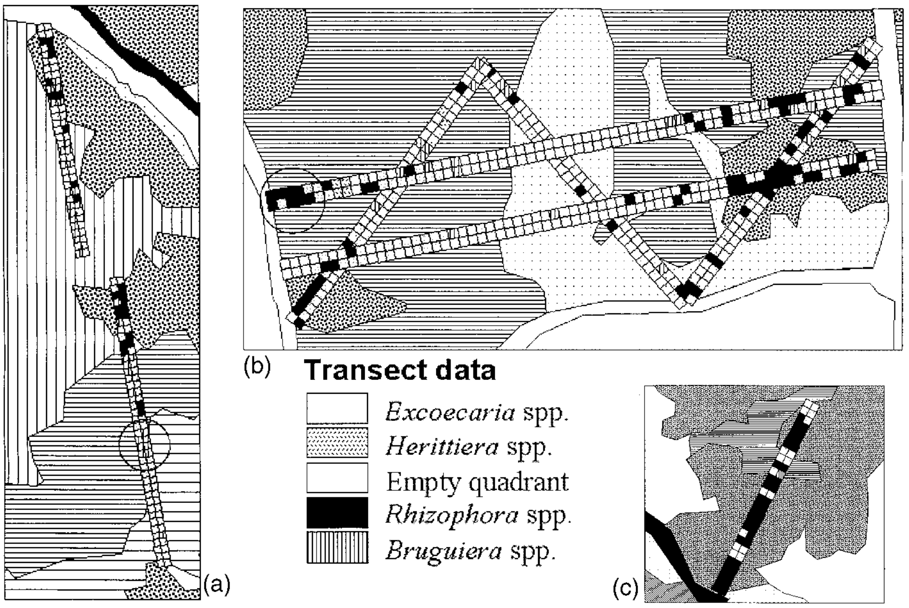


Figure 6. Different species assemblages in the Galle area (1994) with transects of the second fieldwork mission (1997) superimposed (adapted from Dahdouh-Guebas et al., 2000). Encircled are small assemblages, detected during the fieldwork, but not during visual analysis. See Fig. 5a for Vegetation map legend.

only the proportion of the open area in Galle and in Pambala, presumed to have predominantly empty sample points (= open area), has a rather unexpected high proportion of *Excoecaria agallocha* L. and *Lumnitzera racemosa* Willd. respectively. Figure 6a–c shows the overlay of the transects with the vegetation map. Each compartment on the transect represents one tree, measured according to PCQM (the measured distance is not represented). Shifts of a maximum of 20 m occur between the boundaries of the species assemblages as obtained from interpretation of the photographs and those visible from the overlaid transect data. On two occasions, small clusters of trees were noticed during the fieldwork (Figure 6a,b), differing from those that were predicted to be the dominant species or genus. One is a *Bruguiera* cluster and the other is a *Rhizophora* cluster, both in an *Excoecaria*-dominated area.

4. Discussion

The objective of this study was to investigate the applicability of aerial photographs to mangrove vegetation research and hence to determine whether information such as species assemblage, species composition of assemblages and relative densities of species could be obtained by interpretation of aerial photographs.

4.1. IMAGE ATTRIBUTES

For the identification of individual trees, the following image attributes were retained: gray values, texture, form and size of the crowns and the presence or absence of a shaded side. However, not all attributes were useful for the identification of each species. The presence or absence of a shaded side, for example, was in Galle, useful to distinct the shrub *Clerodendron* from *Excoecaria*, but it was not useful for other genera. Depending on the species encountered in the study site, one might have to redefine or add image attributes. Overlap of these image attributes caused some problems to identify certain individuals. This was the case for the identification of *Bruguiera*. *Bruguiera* individuals overlap considerably in their image attributes with those of *Excoecaria* as well as with those of *Rhizophora*. For this reason *Bruguiera* trees were not detected when individual trees were counted. If only identification of individual trees is considered, the *Bruguiera-Excoecaria* mixed stand would have been mistaken for an *Excoecaria–Rhizophora* mixed stand. Using ‘structure’, a clear difference was noticed: *Rhizophora–Excoecaria* stands display connected crowns with greater height differences, while *Bruguiera–Excoecaria* stands are characterized by a loose canopy and a more uniform tree height. This appeared unrelated to the ages of the trees.

In mangrove forests, plant species richness is often low when compared to neighboring terrestrial vegetation. Moreover, the species are often grouped in monospecific zones or patches. The importance of the structure-attribute seemingly increases when species show clear groupings and cannot be applied when a very homogeneous forest is investigated. In Sri Lanka, the mangroves seldom show a clear zonation, however, the forest shows patches of dominant species.

4.2. Error analysis

Although the quantitative analysis (relative density) did not give good results, the qualitative analysis of the photographs (dominant genera, delimitation of the assemblages) appeared very satisfactory.

The unsatisfactory outcome of the G-test, concerning the detection of the species composition quantitatively, might reflect the unsuitability of the PCQM, which is directed towards measuring stem characteristics (stem density, basal area), while features observed on the photographs are rather crown directed. This difference in measured features could have played an important role especially in *Rhizophora* mixed stands. In Galle, *Rhizophora* clusters to form large colonies, giving them the typical ‘cauliflower’ structure, in which individual crowns were subjectively recognized. In mangrove forests, where different species within the adult vegetation layer of an assemblage show large height differences (this is seldom the case in Sri Lanka), the discrepancy between aerial photography interpretation and field method is larger because of over-topping of the trees. Nevertheless, the PCQM has other advantages such as the fast investigation of large areas.

The good results obtained for the qualitative analysis (Table II) proves the suitability of aerial photography for the identification of assemblages. Although in the case of the open area in Galle, the highest proportion of sample points was occupied by *E. agallocha* trees, a closer look to the field situation showed that this was mainly the result of relatively young individuals. The very low density of trees, however, supports the justification for the classification. A similar situation is found in Pambala.

Correct delimitation of the species assemblages was investigated visually by overlaying transect data with the vegetation maps. Small shifts of the boundaries between both data sets can be attributed to interpretation errors, digitizing errors, lack of unequivocal reference points for the orientation of our transects, a discontinuous scale due to parallax, deviations in the true length of the transects due to a poor estimation of the dimension of impenetrable *Rhizophora* colonies or finally because of small changes which occurred in the period between the taking of the aerial photographs (1994) and the fieldwork (1996–1998). These shifts, of maximum 20 m, show the accuracy of the position of our boundaries.

From the two clusters of species detected during fieldwork, only the *Rhizophora* cluster could be recognized to a certain extent, when the aerial photograph was re-inspected, suggesting an error of oversight. However, due to the absence of an unequivocal situation for the above recognition, and the introgression of *Excoecaria* in the same area, we preferred to stick to the identification as an *Excoecaria*-dominated forest patch. The undetected *Bruguiera* cluster is greatly due to the overlap of image attributes and to the fact that the clusters are too small to show a clear differentiated structure on the photograph.

4.3. SPATIAL APPLICABILITY OF INTERPRETATION KEYS

Between the different study sites, the interpretation keys differ because of physiognomic variations for certain species and because of the relative aspect of certain image attributes. For example, *E. agallocha* appears almost white on the aerial photographs of Galle, while it is darker on the photographs of Rekawa lagoon and Pambala, on which, *Avicennia marina* (Forsk.) Vierh. appears white instead. A physiognomic difference of *E. agallocha* between these two sites can in fact also be observed in the field. This suggests that the interpretation keys should only be used locally, if high accuracy is the objective. The term ‘locally’ implies that the keys can be used in similar geographic units, in which the floristic composition of the forest resembles the one on which the key is based on. When used on a different geographic unit, the keys presented here can give preliminary results about the species possibly present. If white crowns are detected, with blurred texture and no distinct shape, the detected individual could be an *Excoecaria*, an *Avicennia* or a *Lumnitzera*. But if information about the species present in the area is available, a correct identification is possible. Basically, all information is useful for photo interpretation. Since mangroves often show a clear zonation, the position of the species in relation to the sea can be very important as well. As clear zonation is virtually absent in Sri Lanka, this feature was not considered in this research. If a high degree of accuracy of the vegetation maps is required, the interpretation key should either be used only locally or for forests with similar species composition, or be calibrated for each new area.

With the aid of recent photographs and the interpretation key, mangrove vegetation dynamics can be studied using sequential aerial photography (cf. Dahdouh-Guebas et al., 2000). The photographs in a time series display differences in quality and sometimes in scale. These differences increase the difficulty of interpreting older photographs using the interpretation key, which is based on the most recent photograph only. However, a 'calibration' of the key for universality in time, as opposed to universality in space, is very easy to achieve in most circumstances.

For the calibration of the interpretation key, unchanged areas of the forest are compared on the different photographs. The available original photograph of Galle taken in 1974, for example, is very dark as compared to the one of 1994. The key can easily be calibrated when the attributes of unchanged areas, or areas showing minor changes are compared. Unchanged areas can be recognized on the photograph by using equiformity of the contours of the species assemblages as an indication. The resultant calibrated key will allow identification of assemblages in the more disturbed areas of the forest.

This calibration technique incorporates one assumption: the fact that the species composition remains the same in the forest over time. The problem does not emerge from the genera currently present, since these can be observed during fieldwork, but locally extinct genera will not be comprised in the interpretation key and will not be identified on the photograph. To assure there were only minor changes in the forest and to enable calibration of the key one should make use of sequential aerial photography with the least possible time gaps. In this respect high-resolution satellite imagery would be very appropriate for the future.

The rapidly advancing technology of satellite imagery gives hopeful results concerning the development of the acquisition of such data (McGraw et al., 1998). However, in a recent remote sensing study that compared airborne and spaceborne (e.g. SAR technology) data sources, the airborne data from imaging spectrometer (AISA), airborne ranging radar (HUTSCAT) and aerial photographs (1 : 20,000) were the most accurate data sources in the retrieval of forest stand attributes (Hyyppä et al., 2000). Recently available imagery that could challenge aerial photography for the future (not for the past) are the IKONOS space-born image (launched in September 1999) with a 1 m resolution (Corbey, 2000) and the EROS A1 (launched in December 2000) with a 1.0–1.8 m resolution (ImageSat International, 2001).

The changes, which can be monitored with high reliability using sequential aerial photography, are increase and decrease in area of each species assemblage and changes in the boundaries of the vegetation.

In addition to the high value of aerial photographs in producing vegetation maps of mangroves with identification of species composition up to the generic level, sequential aerial photography has a high value for studying mangrove dynamics. The power for management issues, and consequently for the protection of the coastal zone as outlined in the introduction, resides in the early detection of changes that may lead to the destruction of mangroves, and the ability for proper management to avoid degradation. Due to the relative low species richness of mangrove forests, this positive evaluation may not be extrapolated to floristically or structurally more diverse forests.

5. Conclusion

This study showed that aerial photographs constitute a most valuable tool in producing accurate vegetation maps of mangrove forests with identification up to the generic level. Most individual trees could directly be recognized from the aerial photograph using the following image attributes: gray values, texture, crown form and size, presence or absence of a shaded side. Overlap of the image attributes of different genera caused some problems during interpretation of the photographs. In this case, the generic composition of a species assemblage could indirectly be identified using the attribute 'structure'. Although the quantitative analysis (relative density) did not give good results and should therefore be investigated in the field only, the qualitative analysis of the photographs (dominant genera, delimitation of the assemblages) appeared very satisfactory. The interpretation keys show basic differences between locations and should therefore only be used locally or in mangrove areas with similar floristic composition. In addition to the applicability of aerial photography in monitoring mangroves, the importance of aerial photography in the management of mangrove ecosystems is clearly highlighted.

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