

Capacity building in tropical coastal resource monitoring in developing countries: A re-appreciation of the oldest remote sensing method

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SUMMARY

Long-term decadal retrospection in spatio-temporal imagery analyses can only be carried out using aerial photographs, which are still the most detailed remotely sensed data available. Visual interpretation of such imagery is most efficient and inexpensive in the light of ecosystem monitoring research in developing countries, which are often unable to cope with the development or the cost of acquisition of commercial space-borne imaging (e.g. IKONOS, Quickbird). In this light, the present paper explicitly analyses the methodological use of image attributes of air-borne imagery from mangrove forests, and investigates the consistency and constraints of mangrove image attributes in visually interpreted air-borne imagery. Six image attributes are analysed, and their application is illustrated using various mangrove sites in Kenya and Sri Lanka. Comparison of identification keys reveals that minor attributes such as 'ecological position' are informative, and that image attributes for a particular species or genus are apparently less plastic and more widely applicable than formerly assumed. Emphasis on compulsory fieldwork is made and constraints related to reflection and interference, amongst others, are discussed.

INTRODUCTION

Mangrove forests are unique ecosystems at the edge of land and sea that have an essential ethnobiological and subsistence value for local people, particularly in (sub)tropical developing countries (Bandaranayake 1998; Ewel *et al.* 1998; Dahdouh-Guebas *et al.* 2000a). In addition, they fulfil a number of ecological roles, such as prevention of

coastal erosion, as breeding, spawning, hatching and nursery grounds, and for enhancement of fish biomass from adjacent coral reefs (Moberg and Rönnbäck 2003; Mumby *et al.* 2004¹). The highly threatened status of mangroves as a result of anthropogenic impacts suggests the need for urgent protection worldwide (Farnsworth and

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Ellison 1997; Dahdouh-Guebas 2002). Monitoring of coastal environments through remote sensing data is an efficient way to quantify and qualify their status (Zainal *et al.* 1993; Johannessen *et al.* 1993; Ramsey and Jensen 1996). Mangrove monitoring using remote sensing technology is often financially feasible for research institutions in developing countries, as a majority of governments execute aerial photography missions and make photographs available at a low cost. The expensive prices to be paid for new commercial satellite imagery (e.g. IKONOS, Quickbird), however, may constitute a limitation for developing countries². In addition, as elaborated below, satellite data may not be the best remote sensing data source to extract species-specific or socio-economic information from mangrove areas, as opposed to this use for urban areas, for instance (Jensen and Cowen 1999). It is therefore important to further research air-borne imagery of mangrove areas.

Air- or space-borne imagery provides common data for investigating natural resources remotely. Particularly in difficult, inaccessible and impenetrable habitats, such as mangrove forests, remote sensing is an efficient tool and provides preliminary results in a phase prior to compulsory fieldwork, or more or less final results on a scale larger than where the fieldwork is concentrated (Ramachandran *et al.* 1998; Chauvaud *et al.* 2001). The application of aerial photography has been shown to be successful in the study of mangrove floristics (Verheyden *et al.* 2002; Sulong *et al.* 2002) and mangrove vegetation structural dynamics (Dahdouh-Guebas *et al.* 2000b; Dahdouh-Guebas and Koedam 2002; Dahdouh-Guebas *et al.* 2004b³), allowing a more detailed study than is possible with satellite imagery (Blasco *et al.* 1998; Manson *et al.* 2001). Even as very high resolution satellite imagery from IKONOS and Quickbird becomes publicly available, the only long-term (> 3 decades) retrospective way of monitoring dynamics on a scale of assemblages or individuals is through sequential aerial photography (Herwitz *et al.* 1998; Dahdouh-Guebas 2002). Within the literature, there is a tremendous emphasis on digital imagery and automated methods (Brandtberg and Walter 1998; Kadmon and Harari-Kremer 1999), despite the fact that in many cases human eye interpretation of aerial photography images and the ability to integrate different image attributes intuitively is found to be one of the best ways of obtaining information.

In fact, visual interpretation of IKONOS or Quickbird imagery (spatial resolution: 1 m or higher) has also been found to be more appropriate for certain research purposes (Read *et al.* 2003; Clark *et al.* 2004). Even though visual interpretation may be time-consuming, it is not financially constrained by powerful image analysing software and GIS software (e.g. ArcGIS). This independence is once again beneficial to research institutions in developing countries, and warrants the pursuit of research on visual interpretation methodologies. In addition, the difficulty of explaining how the human eye integrates various image attributes to delineate or to identify an image object has not been tackled so far. Hence, visual interpretation is not always carried out, or at least described, in a streamlined and repeatable way (Sulong *et al.* 2002).

Identification keys to recognise certain species or vegetation assemblages are usually applied to well delineated forests, leaving a more detailed comparison of the consistency or plasticity of image attributes on a wider scale virtually unchallenged (Verheyden *et al.* 2002). The available range of image attributes and their limitations for visual interpretation have never been explicitly investigated for mangrove forests, which are characterised by particular features of zoned and mosaic vegetation structures in areas with lots of water and sand, all of which increase the complexity of interpretation.

The objective of the present study is to apply a wider range of image attributes applicable to the visual interpretation of mangrove assemblages and attempt a comparison of their consistency and limitations in different mangrove lagoons bordering the Indian Ocean: Mida Creek and Gazi Bay in Kenya, and Rekawa Lagoon, Galle-Unawatuma Lagoon and Pambala-Chilaw Lagoon in Sri Lanka. It must be highlighted that the images are interpreted in the framework of long-term retrospective spatio-temporal vegetation structure dynamics on an assemblage level. This implies that we are interested in identifying species, or at least genera, within the mangrove ecosystem, and therefore need the very high spatial resolution of aerial photography. Our long-term retrospective approach (> 50 yrs) implies that only black and white aerial photographs were considered, and not space-borne or multispectral sensors, the discussion of which is therefore beyond the scope of this paper. However, we are aware of the recent

developments in the application of very high resolution satellite imagery such as general assessment of their use (Wang *et al.* 2004), investigation of mangrove health status (Kovacs *et al.* 2005) or the recognition of congeneric or introgressive species thanks to the combination of good spatial and spectral resolution (Dahdouh-Guebas *et al.* 2005a). The paper also serves to streamline the way image objects are delineated and identified by different researchers worldwide.

MATERIAL AND METHODS

The available material was aerial photographs with a resolution of about 30 cm from the respective study sites from 1972 (Kenya), 1974 (Sri Lanka), 1992 (Kenya) and 1994 (Sri Lanka), which were obtained from the Kenyan Survey Department and from the Sri Lankan Forest Department. The same photographs were used as basic or secondary material in earlier studies on mangrove ecology (Gang and Agatsiva 1992; Matthijs *et al.* 1999; Dahdouh-Guebas *et al.* 2000b; Obade 2000; Jayatissa *et al.* 2002; Kairo *et al.* 2002a; Dahdouh-Guebas and Koedam 2002; Verheyden *et al.* 2002; Dahdouh-Guebas *et al.* 2004a,b).

Our team ground truthed the aerial photographs during more than 15 fieldwork expeditions over a period of 10 years (1993–2003). Ground truthing was done using plot-based and plotless vegetation description techniques along geo-referenced transects, as well as by visual observations, as described below. The plot-based Braun-Blanquet relevé method (Westhoff and Van der Maarel 1978; Van der Maarel 1979) was used in 25-m² or 100-m² quadrats at 10 m to 100 m intervals between quadrats along a line transect (depending on the extent of the forest) to generate a qualitative description of the vegetation. The plotless and more quantitative Point-Centred Quarter Method or PCQM (Cottam and Curtis 1956), as described by Cintrón and Schaeffer Novelli (1984) and optimised by Dahdouh-Guebas and Koedam (2006b), was also applied along transects, sampling at 10 m intervals. The adult tree individual (i.e. tree larger than 1.3 m or with a $D_{130} > 2.5$ cm) closest to the sample point was identified and recorded in each of four quadrants, and its height and diameter D_{130} [130 cm height *sensu* Brokaw and Thompson (2000), formerly referred to as DBH, the diameter at breast height] were measured. The stem

diameter of mangrove species with aerial roots at 130 cm height was measured 30 cm above the highest roots. Other anomalies to the application of the PCQM (e.g. forking stems) were dealt with as described by Dahdouh-Guebas and Koedam (2006b). Along the transects, the total cover of the vegetation was estimated in percentages in the quadrats of the plot-based method, or in the 5 × 5 m quadrat nearest to the sampling point for the plotless method (the sample point thus formed the common corner point of the four quadrats located in the four quadrants). Visual observations were recorded as text and by ordinary photography, by walking through all vegetation assemblages, aided by a hard copy of the images and by GPS. Based on the above measured variables and observations, vegetation characteristics were described that could be used in testing the accuracy of the interpretations of aerial photographs. Considering that this paper focuses on the identification keys themselves, we refer to published papers by our team for details on the ground truth and on accuracy testing (Dahdouh-Guebas *et al.* 2000b, 2002; Dahdouh-Guebas and Koedam 2002; Jayatissa *et al.* 2002; Kairo *et al.* 2002a; Verheyden *et al.* 2002; Dahdouh-Guebas *et al.* 2004a, 2004b).

New identification keys were constructed for the mangrove sites of Gazi Bay and Mida Creek in Kenya, whereas, for the Sri Lankan lagoons of Pambala-Chilaw, Galle-Unawatuna and Rekawa, the information of formerly established identification keys (Verheyden *et al.* 2002) has been integrated and amended here, and consistently structured using the image attributes as defined and illustrated in Table 1 and Figures 1 and 2. These image attributes include tonality, texture, structure, tree and/or canopy size, shape, shade and, finally, position. Lillesand and Kiefer (1994) gave a number of examples of air-photo identification of landforms (bedrock, aeolian, glacial, fluvial and organic soils) and their interpretation keys. However, their introduction to air-photo interpretation was exclusively applied to systems in industrialised countries, and not to mangrove ecosystems or tropical ecosystems typical of developing countries. It must be recalled that it is difficult to explain what anyone's eye sees and integrates to identify something, and that image attributes vary according to the ecosystem. Particularly under the image attribute 'texture' this is evident, and comparative words such as 'cauliflower' were used to clarify a

Table 1 Definition of all the image attributes used in this paper. Figure 1 illustrates each of them schematically, Figure 2 is a real life example. Note that some of these attributes overlap with others

Image attribute	Definition	Example
(A) Tonality	The colour or grey value of a single image object, in this case, often one crown or an aggregation of crowns	From very low to very high grey values (Fig. 2a). In colour photographs tonality also encompasses colour, possibly divided over different categories of wavelengths [multispectral imagery such as the Compact Airborne Spectrographic Imager or CASI (Mumby <i>et al.</i> 1998)]
(B) Texture	The internal pattern of a single image object	This can be absent (plain texture, no internal variation), blurred (Fig. 2b1), finely (Fig. 2b2) or coarsely grained (Fig. 2b3), or defined as perceived [e.g. 'cauliflower texture' in Dahdouh-Guebas <i>et al.</i> (2000b) and Verheyden <i>et al.</i> (2002)]
(C) Structure	The way different image objects are ordered with respect to each other	This is reflected by the consistent order as in 'regularly planted trees' (Figs 2c1, c2), but also in the continuity of the canopy. Note that a 'discontinuous canopy' implies that crowns are separately visible, but a 'continuous canopy' does not imply that separate crowns cannot be distinguished (Fig. 2c3)
(D) Size	Size of the canopy	Some canopies are significantly smaller or larger than those of surrounding trees (Fig. 2d)
(E) Shape	Shape of the outline of a crown	Round, elliptic or of a particular shape, such as the star-shaped coconut trees (Fig. 2e)
(F) Shade	Tonality and shape of the stem and/or canopy shade on the floor	A light shade indicates that (sun) light penetrates through the canopy (such as for the typical palm leaves of coconut trees). The darker the shade, the higher the leaf density, stopping light from penetrating. Note that also the shape of a tree or canopy can be detected from its shade, and that the shade is not always to be found on the floor (on water, on other vegetation) (Fig. 2f)
(G) Position	Ecologically relevant location of the tree	For ecological reasons (proximity to resources, tolerance, competition), some species may be located in particular areas such as along creeks (Fig. 2g1) or in the landward back of mangrove (Fig. 2g2)

type of texture in the past (Dahdouh-Guebas *et al.* 2000b).

The five resulting standardised identification keys were then used to further investigate the species that are recognisable as vegetation assemblages. It should be recalled here that the use of a mangrove species' name as an identification tag in the keys should be considered as a vegetation assemblage dominated by a certain species rather than as a pure stand. Species listed as 'mangrove species', according to Jayatissa *et al.* (2002), and present in at least three out of the five sites, were then compared in their image attributes and a 'compromise key' was drafted. In the latter, the most common non-mangrove identification classes were included as well.

RESULTS AND DISCUSSION

In the light of publication space, only one identification key per country has been shown (Table 2), whereas the entire set of keys has been made available as online supplementary material (see Table 2).

The most common non-mangrove image objects are water, sand, coconut trees (*Cocos nucifera* L.), terrestrial vegetation and human infrastructure (Table 2 and online supplementary material). They are present in a majority of the sites and are characterised by unambiguously recognisable features within the photographic 'context'. Human infrastructure includes constructions (houses, buildings, industrial facilities) and tracks (railways,

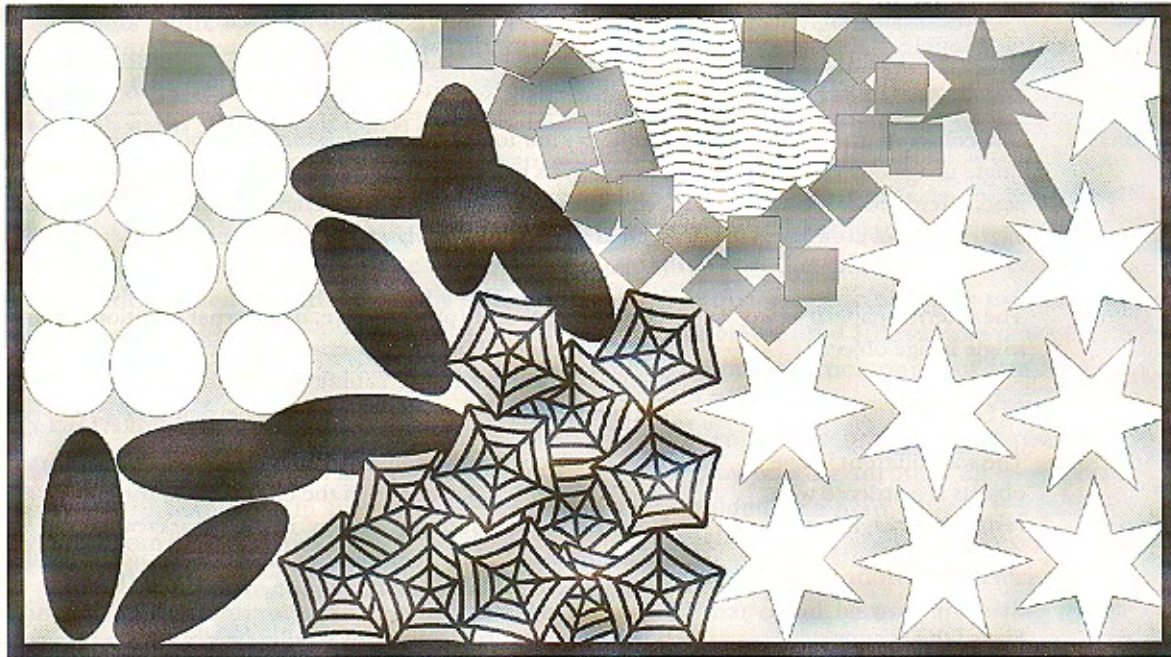


Figure 1 Schematic representation of an aerial photograph of a forest with different tree crowns differing in several image attributes defined in Table 1. The forest has a water body (indicated with waves), the image attributes of which will not be taken into account. The tree crowns have a *black*, *white* or *grey* tonality, and only two texture types: *plain* or *'web'* texture. When combining tonality with texture, the canopies are thus typified as 'plain white', 'plain grey', 'plain black', or 'grey web'. The structure image attribute is *regularly spread*, *less consistently spread* or *at random*, and they have a *circular*, *elliptic*, *squared*, *star* or *pentagon* shape; note that the *at random* structured canopies may be either *continuous* ('web grey pentagons') or *discontinuous* ('plain black ellipses'). In order not to complicate the schematic, the tree shade is only indicated for two trees; note that the shape of the tree crown seen from the side may confirm the shape seen from above (e.g. the star-shaped canopy, which, together with the long stem, are a typical feature of *Cocos nucifera*), or may reveal extra details (e.g. the house-shaped form of the trees with a circular canopy). The trees with grey, squared crowns are obviously *clustered around the water body*, which illustrates the image attribute 'position'

paths, roads and bridges). Other clearly recognisable man-made features are agricultural fields such as rice fields or coconut plantations, which are often found adjacent to mangrove areas. The 'compromise key' (Table 3) represents five common mangrove genera and, when compared with the original identification keys (Table 2 and online supplementary material), it shows that for a particular species none of the image attributes displays a strong plasticity. However, as indicated in the discussion below, certain limitations need to be taken into consideration.

Although identification keys are not meant to be applied to aerial photographs of regions that are not familiar (e.g. in other geographic units, in more or less diverse sites), the present study suggests that, for mangroves, they might be less plastic and possibly more widely applicable than formerly assumed. Apart from the basic image attributes, tonality, texture and structure, it appears that for the vegetation

classes particularly, spatial information (ecological 'position') can greatly help in their identification and, in certain cases, can even be decisive in the identification of vegetation assemblages that do not differ in tonality, texture or structure (see Table 2d in online supplementary material). Even in situations in which zonation is not or only poorly present, spatial information is very useful. However, compared to image interpretation of features with well-defined consistent locations (e.g. human anatomy imagery), the position of ecosystem elements remains rather unpredictable. Information with respect to crown shapes or height relative to the surrounding vegetation, for instance, can also help. All the above is further aided if knowledge about the species composition of a certain site exists (Verheyden *et al.* 2002). It is also imperative to get access to correct information with regard to species composition, as erroneous species lists may lead to wrong interpretations in the framework of remote

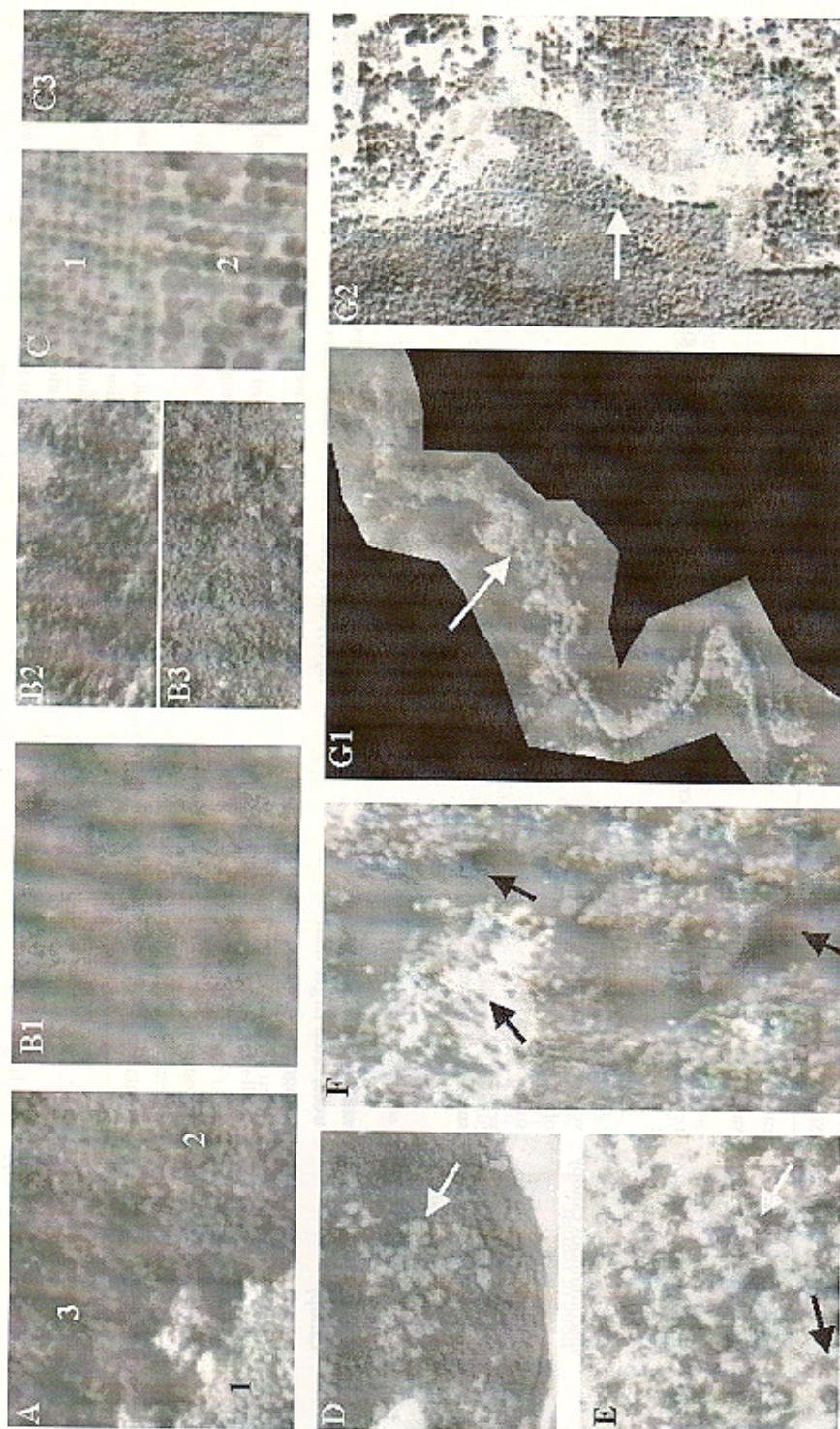


Figure 2 Illustration of the seven image attributes. (A) **Tonality** (Gazi Bay): (1) white *Avicennia marina*, (2) light grey *Ceriops tagal*, (3) dark grey *Rhizophora mucronata*. (B) **Texture**: (1) blurred *C. tagal* (Gazi Bay), (2) fine grain *Lumnitzera racemosa* (Pambala-Chilaw), (3) coarse grain *Avicennia officinalis* (Pambala-Chilaw). (C) **Structure** (Gazi Bay): (1) *Cocos nucifera*, and (2) *Mangifera indica* regularly planted, (3) more continuous canopy of *Rhizophora mucronata*. (D) **Size** (Gazi Bay): the white arrow points to *A. marina* canopies that are significantly larger and higher than the surrounding (darker) *R. mucronata* trees. (E) **Shape** (Gazi Bay): star-shaped *C. nucifera* (white arrow). Also note the star-shaped form of the shade (black arrow). (F) **Shade** (Galle): note three different shade types (black arrows). (G) **Position**: *A. marina* at the creekward side in Gazi (1) and at the landward side in Mida (2). See Table 2 and online supplementary material for illustration of textual identification keys

Table 2 Selected keys for the identification of vegetation in mangroves: Gazi Bay in Kenya (a), and Panbala in Sri Lanka (b). The entire set of identification keys is available as supplementary material from <http://www.vub.ac.be/APNA/staff/FDG/aerphoto2.html>. Note that the identification tag should always be considered as a vegetation assemblage *dominated* by a certain species, rather than as a pure stand. The vegetation map resulting from the key for Gazi can be consulted in Dahdouch-Guebas et al. (2004a)

(A) GAZI (04° 25' S - 39° 30' E)

Tonality	Texture	Structure	Size	Shape	Shade	Position	Identification
white	plain or irregular irregular	plain or irregular irregular	rather large variable	variable variable	none variable	variable often clearly man-made	sand infrastructure (tracks, constructions) <i>Cocos nucifera</i> (coconut)
	coarse grain and/or blurred	discontinuous canopy	regular	star-shaped crown	light shade	sparse and regular distribution landward	<i>Avicennia marina</i>
light grey	coarse grain	discontinuous canopy	very large crowns, often higher than surrounding vegetation	variable	surrounding vegetation may be shaded intermediate to dark	water side	<i>Avicennia marina</i>
	fine grain	discontinuous canopy or continuous canopy with crowns hard to distinguish	small-sized crowns	variable	light	landward side	<i>Avicennia marina</i>
	variable	often discontinuous canopy	variable, but in case of trees, often larger than mangroves	variable	none (herbaceous layer), dark (often for trees) or variable	landward side or outside reach of mangrove vegetation	terrestrial vegetation
dark grey	fine grain and blurred	continuous canopy crowns not separately visible	small-sized crowns, lower than surrounding vegetation	circular canopy	light	landward side or mid-mangrove	<i>Ceriops tagal</i>
	coarse grain 'peluche' texture	discontinuous canopy	regular	circular canopy	intermediate to dark	amongst terrestrial vegetation	<i>Mangifera indica</i> (mango)
	coarse grain	discontinuous canopy	very large crowns	variable	dark	sparse and regular distribution always at water side large-sized canopy	<i>Sonneratia alba</i>
very dark grey or black	fine or coarse grain	continuous canopy with crowns hard to distinguish	often large-sized aggregating crowns	variable	intermediate to dark	often at water side wide spatial range	<i>Rhizophora mucronata</i>

(B) PAMBALA (07° 30'N – 80° 00'E)

Tonality	Textures	Structure	Size	Shape	Shade	Position	Identification
white	plain or irregular	plain or irregular	rather large	variable and complex shape	none	none	sand or grassy plain
light grey	blurred	discontinuous canopy	regular	star-shaped crown	light	sparse and regular distribution	<i>Cocos nucifera</i> (coconut)
	coarse grain	discontinuous canopy	often larger than surrounding vegetation	circular	dark	land or water side	<i>Avicennia</i> spp.
intermediate grey	blurred	discontinuous canopy	variable	variable	variable	not spatially bound	<i>Excoecaria agallocha</i>
	very fine grain	continuous canopy with many crowns	very small crowns	circular	none	landward side	<i>Lumnitzera racemosa</i>
	coarse grain and /or blurred	crowns hard to distinguish	medium to large, but never very large	circular	variable	none	<i>Bruguiera</i> spp. <i>Xylocarpus</i> spp.
	plain or blurred	none or regular	small	circular	none	none	<i>Arrostichum aureum</i>
	plain or blurred	none or regular	small	variable	none	at water side	<i>Arrostichum aureum</i> or <i>Avicennia bicolor</i>
dark grey	coarse	continuous canopy crowns separately visible or not so, often higher than surrounding vegetation	medium to large aggregating crowns	variable	dark	often at water side wide spatial range	<i>Rhizophora</i> spp.

Table 3 'Compromise key' to identify some common species and features from aerial photographs of mangrove areas based on five mangrove lagoons in Kenya and Sri Lanka. See Table 1 for the consistency of the features. Note that the identification tag should always be considered as a vegetation assemblage dominated by a certain species, rather than as a pure stand

Species	Tonality	Texture	Structure	Size	Shape	Shade	Position
<i>Avicennia</i> spp.	white or light grey	coarse grain	often discontinuous canopy	very large at seaside, variable small to medium at landward side	variable	light at landside, medium to dark at seaside	mostly along water side, but can also occur landward
<i>Brauguiera</i> spp.	light or intermediate grey	coarse grain/ blurred	(dis)continuous canopy	never very large crowns	circular	variable	not spatially bound
<i>Ceriops tagal</i>	intermediate or dark grey	fine grain/ blurred	continuous canopy crowns not visible separately	lower than surrounding vegetation	circular	light to dark	mostly landward
<i>Excoecaria agallocha</i>	white or light grey	fine grain/ blurred	discontinuous canopy	variable	variable	medium to dark	not spatially bound
<i>Rhizophora</i> spp.	intermediate or dark grey	coarse grain 'cauliflower' texture	continuous canopy, with sometimes distinguishable crowns	aggregating crowns	variable	dark	often at water side, wide spatial range
<i>Cocos nucifera</i>	white/ light grey	blurred	discontinuous canopy	regular	star-shaped crown	light grey shade	sparse and regular landward distribution
sand	white	plain or irregular	plain or irregular	small to large	simple to complex	none	variable
water	black, but sometimes light grey	plain or irregular	plain or irregular	often massive or extended	complex	none	waves can be present
human infrastructure	white/ light grey	irregular	irregular	variable, to be interpreted in photographic context	variable, to be interpreted in photographic context	variable, to be interpreted in photographic context	often clearly man-made

sensing (Jayatissa et al. 2002, Dahdouh Guebas et al. 2005b,c).

Verheyden et al. (2002) highlighted, for *Excoecaria agallocha* physiognomic differences between Galle and Rekawa caused by the plasticity in tonality of this species. Although technical photographic differences are always a possible cause for observed differences in image attributes, in particular in tonality (see below), the underlying basis of the above observation is probably the location of these sites in different climatic zones, and the leaf-shedding behaviour of *E. agallocha*, which is quite rare for a tropical mangrove species. Temperature and humidity conditions and their close association with soil salinity, are also known to affect mangrove height and, together with environmental factors, the vegetation structure of a forest (Dahdouh-Guebas and Koedam 2001; Dahdouh-Guebas et al. 2004a). This has a direct influence on the attribute 'structure' in aerial photography, such as for *Avicennia marina* (Forsk.) Vierh. in Gazi Bay (Table 2a), which are very large at the seaward side, and display a dwarf growth form at the landward side (Dahdouh-Guebas et al. 2004a). Regardless of the site, *Avicennia* species always display one of the lightest tonalities, whereas *Rhizophora* species display the darkest ones. This observation can also be taken beyond the oceanic or continental borders, and is for instance valid for *Avicennia* and *Rhizophora* species in Malaysia, Egypt, Mauritania and the USA (Stafford-Deitsch 1996; Colas 1997; Sulong et al. 2002; USGS 2003). For *Rhizophora* species, it seems also that local environmental conditions may be more important than differences induced by climate. A continuous canopy is characteristic for this genus in all sites, yet within the mangrove area of Galle (see Table 2d in online supplementary material), *Rhizophora* species may feature different 'structure' attributes. This within-site variability may be due to the variability of micro-environmental settings, such as topography. In Galle, the latter is influenced to a high degree by the mangrove mud lobster *Thalassina anomala* Herbst, which forms small islands and ponds. *Excoecaria agallocha* trees are always established on these islands whereas *Rhizophora apiculata* Bl. is located on the edges of the islands and is in part standing in the water. Hence, the general topography, whether or not anthropogenic (e.g. from abandoned coconut plantations), influences the 'structure' component, and the burrowing

activity of *T. anomala* is one biotic factor that further shapes this image attribute. The 'texture' seems to be little influenced by local environmental conditions, but is instead characteristic of a particular species.

There are also a number of factors that may bias the visual identification of aerial photography, or that interfere with the interpretation, and they are illustrated below.

First, *reflection* of sunlight on shiny surfaces such as roofs, sand and water masses may generate a light tonality (Figure 3a1). This is important to consider since water often displays black (Figure 3a2, b2). Comparable objects also do not always reflect in a similar way. Water, for instance, may reflect a lot (Figure 3a1), a bit (Figure 3b1) or not at all (Figure 3a2, b2), depending on the angle of the light, the turbidity, the depth and the underwater substrate (sandy, muddy). Reflection is often obvious, but for low or sparse vegetation on a sandy substrate it may actually render the plants visible or not visible at all (Figure 3c).

Second, *interference* may lead to misinterpretations. One tree may have a black tonality and another tree may display white, but located one next to the other, they may display as a single grey object (Figure 3d). This has been observed for *Excoecaria agallocha* (white) and *Rhizophora apiculata* (dark grey) in Galle (Fig. 3d), where they displayed as one grey canopy such as that of *Bruguiera*, with which confusion is then likely to occur (Verheyden et al. 2002).

Third, *shade* might actually help in identifying the tree, but may equally make it difficult to identify trees and to delineate canopy edges. Shade is dependent on the latitude and the time of day a photograph is taken. Near the equator (Kenya, Sri Lanka), shades may be small or located just beneath objects, making them often invisible. However, in the morning or evening, or at higher latitudes, trees with a luxurious canopy display dark grey or black shades (e.g. *Rhizophora* spp.), while vegetation with a less developed canopy displays light grey shades (e.g. *Cocos nucifera*). This may lead to a number of misinterpretations: a dark crown in the form of a circle might be recognised as an elliptic crown because of the shade, or even as two crowns; the area of vegetation zones might be overestimated due to shades at the edge of a zone; or vegetation might be invisible because of the shade falling on them (Figure 3e).

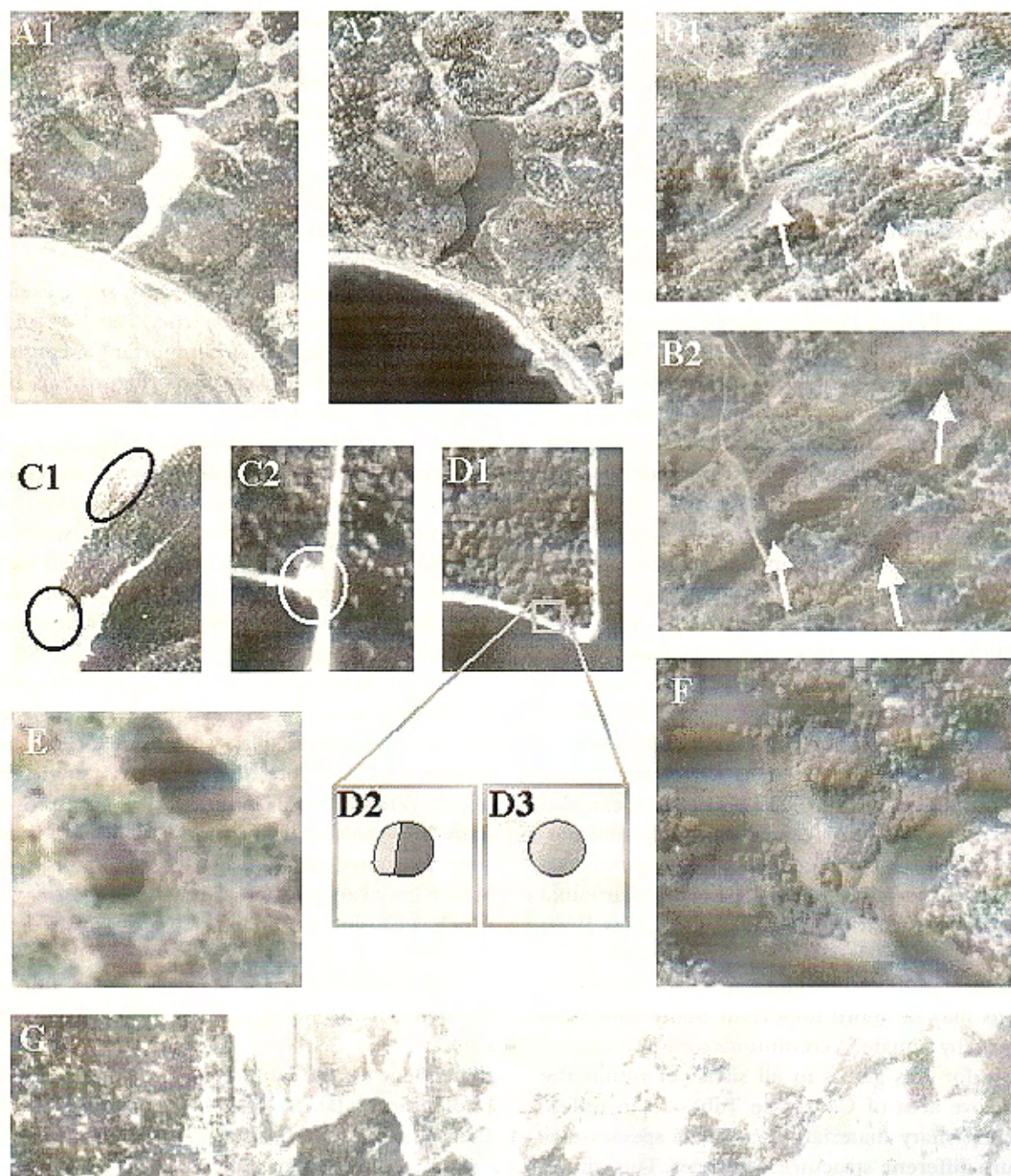


Figure 3 Illustration of possible misinterpretation problems. **Reflection:** (A) water reflected in white (1) and in black (2) in Dondra Lagoon (Sri Lanka); (B) water reflected in grey values (1) and in black (2) in Gazi (the three arrows point to the same water bodies in each of the photographs); (C) sand reflection makes low and sparse vegetation difficult to detect in Mida Creek for *Avicennia marina* (1) and in Galle for young mangrove trees and mangrove associates (2) (encircled areas indicate the presence of mangrove vegetation and associates). (D) **Interference:** adjacent *Excoecaria agallocha* (light) and *Rhizophora apiculata* (dark) individuals (D1) can be misinterpreted as a single *Bruguiera* spp. tree (usually intermediate grey) with an illuminated and a shaded side (D2). (E) **Shade** of trees in Gazi can make edge detection more difficult. (F) **Estimation of forestry parameters** like number of trees is impossible in aggregating, multiple-stemmed trees such as riverine *Rhizophora apiculata* colonies in Galle. (G) **Photographic artefacts** such as the generally darker tonality on the left side of this photograph as compared to the right side (Pambala-Chilaw) make interpretation impossible

Fourth, *estimation of forestry parameters*, such as the proportion of species, and consequently their density or other parameters, is dangerous when based on a photograph. For one reason, canopies may not be representative for stems because of possible overtopping of one species by another, such as large *Avicennia marina* overtopping almost equally large *Rhizophora mucronata* observed by Dahdouh-Guebas et al. (2004b) in a study on vegetation structure dynamics. Silvicultural studies concentrating on exploitable wood, for instance, and thus interested in ground reality in the field rather than in canopies, may therefore be misled by remote sensing imagery. For the same reason, colony formation also cannot be estimated, particularly in mangroves. *Rhizophora* spp. is known to be a multiple-stemmed tree, but in its canopy it is difficult to delineate single individuals (Figure 3f). *Bruguiera gymnorhiza* or *B. sexangula*, on the other hand, often consists of a single stem, but may form distinct sections in its canopy that may be interpreted as multiple individuals. The relative importance of species should therefore be estimated solely from fieldwork.

Fifth, *photographic artefacts* may appear when, for instance, lighter areas appear along certain sides of a single photograph, which do not correspond at all with differences in vegetation (Figure 3g). Usually these differences in tonality are obvious because they do not correspond with biological or ecological logic. Also, the greater distortion at the edge of photographs may lead to changes in shape of objects.

Even though the present study was carried out in five sites in two countries, the disadvantage, which is independent of the number of sites, is that each forest is unique in vegetation structure, number of species, species dominances, and so forth (cf. Dahdouh-Guebas et al. 2002). However, in the framework of capacity building in long-term tropical coastal resource monitoring in developing countries, there is no better alternative than to summarize and streamline the methods of visual interpretation of aerial photographs. From our study performed over the past decade, it seems that identification keys for the interpretation of aerial photographs of a certain mangrove area can be

applied to another one in a preliminary phase, provided species compositions are, at least in part, overlapping. Fieldwork is a compulsory next phase, but due to the small variability of the image attributes, it can probably be carried out in a relatively small area. Species identification from air-borne imagery can then be linked to data that may be important in the management of the area, such as exploitable wood (Kairo et al. 2002b) or carbon stocks (Omasa et al. 2003). The latter is, for instance, relevant in the establishment of methodologies for estimating the carbon stocks of forests in a global context (Kyoto Protocol), which also requires individual trees to be identified (*loc. cit.*). Notwithstanding the importance of continued research into air-borne imagery of mangrove forests, attention should be drawn to the fact that fieldwork alone can overcome factors obscuring the interpretation of aerial photographs. The new ecological concept of 'cryptic ecological degradation' (Dahdouh-Guebas et al. 2005b) emphasizes that what a Forestry Department perceives based on remote sensing and on inappropriate definition 'mangrove species' can be the opposite of what really occurs in the field (qualitative degradation masked by an increase in aerial extent). This significantly affects the functionality of a mangrove forest as was observed during the 2004 tsunami disaster (Dahdouh-Guebas et al. 2005c; Dahdouh-Guebas 2006). Future research should also investigate to what extent visual interpretation weighs up to automated classification of new very high resolution space-borne sensors, and to what extent the results from visual interpretation are researcher-dependent.

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Editor's Note: Since submission of this paper there have been several new developments: rather than change the whole paper new references are added as superscripts in the text and reference list.

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