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Qualitative distinction of congeneric and introgressive mangrove species in mixed patchy forest assemblages using high spatial resolution remotely sensed imagery (IKONOS)

Abstract This paper is a preliminary report of the ability of IKONOS multispectral satellite imagery with a very high spatial resolution of 1 metre to distinguish two mangrove species in Sri Lanka belonging to the same genus (*Rhizophora apiculata* and *R. mucronata*). Not only is this an advancement for the monitoring of forests, it is even more important considering their patchy nature in Sri Lankan mangroves (in contrast to classically zoned forests). Apart from congeneric distinction, introgressive species (*Acrostichum aureum*) can also be detected from IKONOS imagery, which is important in the early warning for cryptic ecological changes that may affect mangrove species composition (both floral and faunal) and functioning. The results tabulate the usage of various image composites, transformations and classifications, and indicate the danger of too much detail in remote sensing, and the need to apply an optimum resolution. We also highlight that the highest resolutions (as in pansharpened multispectral composites) remain invaluable for visual ecological investigations, which are not at all outdated by new digital satellite images of (sub)metre spatial resolution and their possibility for computer-aided analysis.

Key words mangrove, remote sensing, resolution, introgression, IKONOS, *Acrostichum*, *Rhizophora*, Sri Lanka

Introduction

The assessment of the condition of the Earth's surface and atmosphere is primarily based on air- and space-borne imagery and ground truth. Until the launch of the IKONOS sensor (24 September 1999), remote sensing-based research on the current status of, and the changes in, biodiversity and ecosystems was limited to delineation of large, homogeneous assemblages, or to recognition of higher taxonomic levels, either because of the spatial, or the spectral, resolution of the imagery (Dahdouh-Guebas, 2002). On one hand globally available multispectral satellite imagery had a spatial resolution of 10 m to 30 m, too coarse to distinguish individual trees. On the other hand, aerial photography had a very good spatial resolution (20–30 cm), but it was not multispectral. There are, however, some recent evaluations of the usefulness of the compact air-borne spectrographic imager (CASI) and of its applications (Mumby *et al.*, 1997, 1998; Green *et al.*, 1998), but this type of multispectral imagery is not globally available, and is very expensive to acquire (Mumby *et al.*, 1999). With the first commercial high-resolution satellite imagery from IKONOS, the first attempt was made to combine a very high spatial resolution (panchromatic: 1 m; multispectral: 4 m) with a good spectral resolution (panchromatic: 0.45–0.90 μm; blue: 0.45–0.53 μm; green: 0.52–0.61 μm; red: 0.64–0.72 μm; near-infra-red: 0.77–0.88 μm) on a global scale. In addition, IKONOS has a very high temporal resolution (*ca.* 2.9 day revisit time for data with the above qualities) and a high radiometric resolution (11 bit quantization). This paper deals with the 'taxonomic (or floristic) resolution', which we define as '*the taxonomic level to which biological identification can be performed using a remotely sensed image*'. This may be applied and extrapolated to a range between the distinction of large biomes or land-cover classes on global and regional scales on one hand, and ecosystems, assemblages, genera or even species and individuals on local scales on the other hand.

Here, we report, first, the invaluable distinction of congeneric species that contribute to complex mixed assemblages

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in the highly dynamic systems of tropical mangrove forests, and second, the delineation of introgressive species in the same ecosystem, as an innovative application of very high resolution IKONOS imagery.

Background

We and others have highlighted the major structural dynamics that may occur in mangroves on a temporal scale as short as two decades (Dahdouh-Guebas *et al.*, 2000). Qualitative floristic impoverishment in spite of a stable areal mangrove extent has been reported in different countries (Dahdouh-Guebas, 2002; Kairo *et al.*, 2002*a*). This indicates the need to focus repeated assessments of the state of this intertidal ecosystem and its unique biodiversity at a scale of species and individual trees, particularly in mixed and patchy assemblages. This is important in the light of the slow but adverse impacts that species shifts may have (Jayatissa *et al.*, 2002; Kairo *et al.*, 2002*a*).

Airborne images have always offered the best spatial resolution in panchromatic imagery and their analysis is the only way to assess long-term (decadal) retrospective spatio-temporal dynamics at the level of assemblages and of individuals. The mapping of mangroves through aerial photography is often done through visual delineation of assemblages (Dahdouh-Guebas *et al.*, 2000; Verheyden *et al.*, 2002), and many studies on tropical coasts have recurrently emphasized the excellent potential of this imagery (Mumby *et al.*, 1997; Ramsey & Laine, 1997; Dahdouh-Guebas *et al.*, 1999, 2000; Manson, 2001; Chauvaud *et al.*, 2001; Lubin *et al.*, 2001), in spite of its intrinsic weaknesses such as the dependence on human interpretation.

Recent multispectral space-borne imagery with a spatial resolution of 1 m and less, such as IKONOS, EROS and QUICKBIRD images, constitute a new tool in the above-mentioned investigations (Tanaka & Sugimura, 2001). Often remote sensing analysis is used to subdivide geographic areas in large classes, which are limited to small scales or to large monospecific units (*e.g.* Franklin *et al.*, 2001). However, as the spatial and spectral resolution of remotely sensed images increase, this application can be upgraded to larger scales and mixed land classes. As alluded above, the underlying question in our study is 'Does the combination of a very high spatial and high spectral resolution generate a better taxonomic (floristic) resolution?'. It may be surprising to introduce a case-study on mangroves to investigate this, as mangrove forests are typically characterized by a tide-induced zonation of vegetation units largely dominated by single species or genera. However, many Sri Lankan mangrove areas, which are only influenced by little tidal activity, are an exception to this, and often display mosaic or at best partially zoned vegetation structures (Dahdouh-Guebas *et al.*, 2000; Dahdouh-Guebas & Koedam, 2002). Using panchromatic aerial photography, Dahdouh-Guebas *et al.* (2000) and Verheyden *et al.* (2002) succeeded in distinguishing between various mangrove genera on an individual and assemblage level. Can we do any better with IKONOS and distinguish between species within a genus, particularly in mixed forests?

Methods

We employed IKONOS imagery (January 2002) from a globally and locally species-rich mangrove forest in Sri Lanka (Pambala; for a detailed site description see Dahdouh-Guebas *et al.*, 2002), in order to distinguish elements such as land-cover, mangrove vegetation assemblages and species presence. Blue, green and near-infrared wavelengths were used to produce a multispectral false colour composite of the study area. This composite image and a panchromatic image (grey values), with their respective spatial resolutions of 4 m and 1 m, were merged using the forward-reverse principal components transformations (Chavez *et al.*, 1991) and the hue-intensity-saturation transformation (Carper *et al.*, 1990) to produce a pansharpened multispectral image of 1 m spatial resolution. Both methods combine the very high spatial resolution of the panchromatic image to transform the multispectral image in such a way that a multispectral image of 1 m spatial resolution is created.

In the first phase of the research that is reported here, the images were inspected for homogeneous and heterogeneous image objects, taking into account past expertise in visual interpretation of aerial photographs (Dahdouh-Guebas *et al.*, 2000; Jayatissa *et al.*, 2002; Kairo *et al.*, 2002*a*, *b*; Verheyden *et al.*, 2002; Dahdouh-Guebas *et al.*, 2004), but complemented by supervised and unsupervised image classifications. The latter are computer-aided interpretations of imagery primarily based on the spectral characteristics of the image, with (supervised) or without (unsupervised) the input of specific spectral signatures for various image classes. The usefulness of the various classifications is given in detail in the results section, but no mapped classification results are shown in this preliminary report.

Ground-truth data with respect to adult trees were available from several fieldwork expeditions (1997, 1998, 1999 and 2002). A stratified sampling design aided by global positioning system (GPS) technology and identification of the location of individual trees was used, and sample field data were traced on the georeferenced satellite images. All features on an assemblage level, visible from a printed pansharpened blue/green/near-infrared false colour composite, were visited in October 2002 and details on species compositions and individuals recorded (qualitatively). In addition, parallel and orthogonal transects covering the mangrove belt (regardless of the assemblages) were sampled using the point-centred quarter method (Cottam & Curtis, 1956), as described by Cintrón & Schaeffer Novelli (1984), and applied to adult trees taking into account the possible ambiguous situations that may occur (*loc. cit.*; Dahdouh-Guebas & Koedam, 2001). These data were used in a qualitative way to complement the above ground-truth (*cf.* Dahdouh-Guebas *et al.*, 2000).

Results

A general assessment of the IKONOS satellite image with respect to its usefulness and its analysis methods on an assemblage and species level shows that pansharpened false colour composites generate a high degree of spatial detail, texture and structure (Table 1).

	Spatial resolution	Assessment of the applicability
(a) Raw data		
blue (B), green (G), red (R), near-infrared	4 m	not useful as separate images and too coarse
panchromatic image (PAN) (NIR)	1 m	as good as aerial photography
(b) Image composites and transformations		
true colour composite (B/G/R-image)	4 m	average colour contrast
false colour composite (B/G/NIR-image)	4 m	– high colour contrast – less obvious spatial detail, texture and structure – useful for a first delineation of image objects
pansharpened images (= resolution-merge of the B, G, R and NIR image using the PAN-image) : PB, PG, PR, PNIR	1 m	solely used to further construct composite images
false colour composite of the pansharpened images (PB/PG/PNIR-image)	1 m	– high colour contrast – high degree of spatial detail, texture and structure – too detailed for a first delineation of image objects – can be used for a refinement of digitised polygons
Thematic Mapper (TM) Tasselled Cap (TC) transformation of the pansharpened images	1 m	no useful results
Multispectral Sensor (MSS) TC-transformation of the pansharpened images	1 m	3 useful bands : 'brightness', 'greenness' and 'yellowness'
Principal Component (PCA) transformation of the pansharpened images	1 m	3 to 4 useful bands according to the ordination classes
false colour composite of the 3 MSS-TC-bands	1 m	– high colour contrast – less obvious spatial detail, texture and structure – useful for a first delineation of image objects
false colour composite of the 3 PCA-bands	1 m	– high colour contrast – unclear spatial detail, texture and structure – useful for a first delineation of image objects
(c) Supervised classifications		
'parallelepiped classifier' applied to the original pansharpened images, in which unclassified and overclassified pixels were further classified using the 'Bayesian classifier'	1 m	good result when compared to visual (manual) interpretation
'parallelepiped classifier' applied to the original pansharpened images, in which unclassified and overclassified pixels were left as such	1 m	unclassified and overclassified pixels obscure the interpretation
'Bayesian classifier' applied to the original pansharpened images	1 m	very good result when compared to visual (manual) interpretation
'minimum distance to mean classifier' applied to the original pansharpened images	1 m	large differences when compared to visual (manual) interpretation
'Bayesian classifier' applied on the MSS-TC-transformed pansharpened images	1 m	results comparable to those obtained for the original pansharpened images
'Bayesian classifier' applied on the PCA-transformed pansharpened images	1 m	results comparable to those obtained for the original pansharpened images
(d) Unsupervised classifications (isodata algorithm)		
applied to original pansharpened images without masking a priori the non-mangrove area	1 m	image classes can be translated fairly well to information classes
applied to the mangrove area of the original pansharpenend images (a priori masking of the non-mangrove area)	1 m	image classes cannot easily be translated to information classes

Table 1 Assessment of the usefulness of various images and analysis methods with respect to IKONOS satellite imagery for a mangrove forest (Pambala, Sri Lanka) on an assemblage and species level.

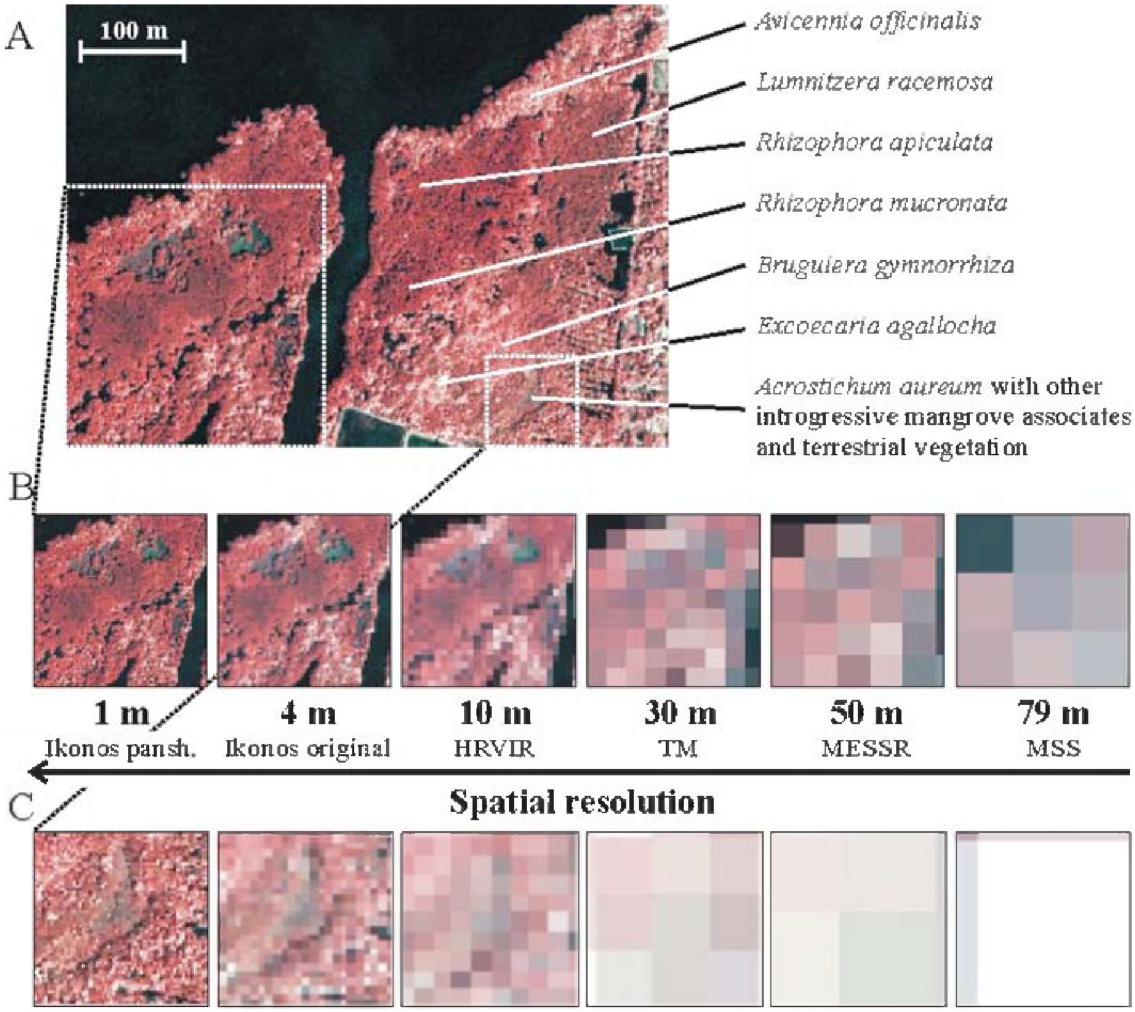

Figure 1 (A) Main vegetation assemblages in Pambala (Chilaw Lagoon), the most species-diverse mangrove forest along the Sri Lankan SW coast, in a pansharpened IKONOS blue/green/near-infrared false colour composite generated and ground-truthed in 2002. The nearly black areas correspond to 'water surfaces'. The white lines approximately point to the centre of the assemblages. A single individual represents the introgressive species, yet clearly discernible. (B) Comparison of the ability to distinguish the physiognomically similar congeners *Rhizophora apiculata* (light red) and *R. mucronata* (dark red) in a selected mangrove area in January 2002 as a function of the spatial resolution as given by different satellite sensors with the same spectral resolution (0.45–0.90 μm). (C) Comparison of the ability to distinguish the introgressive *Acrostichum aureum* in the same image (see Fig. 2 for physiognomic and assemblage details of this species). pans. = pansharpened; HRVIR = High Resolution Visible and Infrared; TM = Thematic Mapper; MESSR = Multispectral Electronic Self-Scanning Radiometer; MSS = Multi Spectral Scanner.

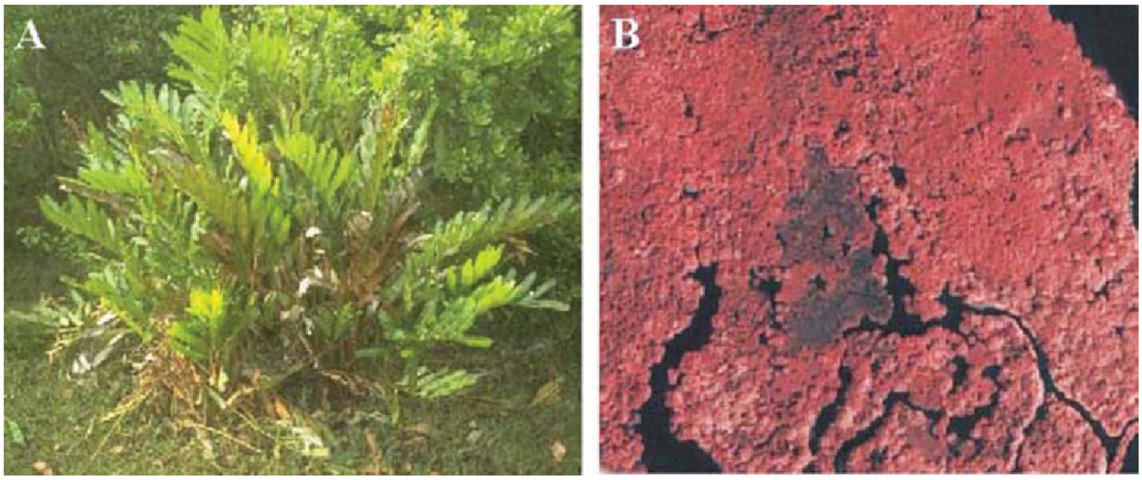

Figure 2 Physiognomy of an individual of *Acrostichum aureum*, the mangrove fern (A), and the appearance of a large stand of this species in the middle of the figure (B). Note its typical dark tonality (purple) on the pansharpened blue/green/near-infrared false colour composite.

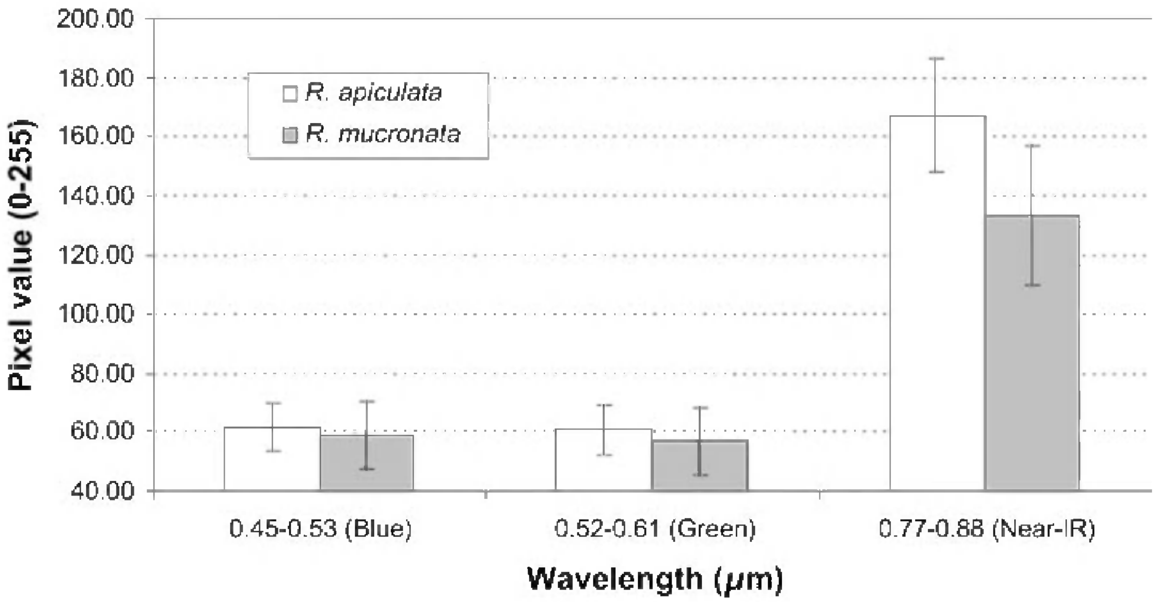

Figure 3 Average pixel value (± SD) as a measure for the differential signatures of *Rhizophora apiculata* ($n = 375$ pixels) and *R. mucronata* ($n = 350$ pixels) for the blue, green, and near-infrared band of the false colour composite in Fig. 1. The light and dark red patches in Fig. 1B illustrate how these differential signatures can be detected visually.

Our results show that IKONOS imagery, aided by its multispectral features, allows for a distinction of all major and dominant species present. These can be discriminated based on tonality, texture and position (Fig. 1A), with *Avicennia officinalis* L. and *Excoecaria agallocha* L. having a typical lighter tonality, and the former found near the water edge whereas the latter is found at higher elevations. *Lumnitzera racemosa* Willd. displays a medium red tonality, a typical very finely grained texture and is located landward.

In addition, for the first time, space-borne remote sensing imagery allows the distinction between two species from a single genus (congeneric species) at an assemblage level (Fig. 1B), and of (terrestrial) mangrove associate species that intrude into the true mangrove vegetation (introgressive species) (Figs 1C, 2). Both observations are evidenced by comparing IKONOS imagery with lower spatial resolutions, as emerges from satellite sensors that have, however, the same spectral resolution (Fig. 1B, C).

Within *Rhizophora*, the most typical, vulnerable and valuable mangrove genus worldwide, we were able to distinguish *Rhizophora apiculata* Blume from *Rhizophora mucronata* Lam. (Fig. 1B), both visually and based on spectral signatures (Fig. 3). The edges between the light and dark red areas in Fig. 1B were visited in the field, where it was further evident that it represented the edge between these two congeneric species. We stress that this distinction is floristic, and not physiognomic. The remotely sensed physiognomy of both congeners is virtually the same in the area investigated (see canopies in Fig. 1B).

Our study also shows that satellite imagery can now be applied to detect *Acrostichum aureum* L. in mangroves, which, likewise, can only be distinguished in IKONOS or other imagery with submetre spatial resolution (Fig. 1C). Our ground-truth expedition revealed that only one specimen was visible in the open area; a single individual can be as tall as 2.5 m (Fig. 2A). *Acrostichum aureum* is also very distinct in its tonality, which becomes more evident as the patches of aggregated individuals become larger (Fig. 2B).

Discussion

Before the availability of satellite imagery with (sub)metre spatial resolution, a high degree of spatial detail, texture and structure could only be detected from aerial photography, even though these were often panchromatic (Dahdouh-Guebas, 2002). As shown above, the general 'tonality' and 'structure' image attributes are comparable to aerial photographs, in which for instance *Avicennia* and *Excoecaria* also display a light tonality, and in which *Lumnitzera* also displays a fine grained texture (Verheyden *et al.*, 2002). The congeneric distinction of *Rhizophora apiculata* and *R. mucronata* resulting from this study is conducive to the inventorying of plant biodiversity and the monitoring of biodiversity changes. In the light of these two *Rhizophora* species having differential traditional and medicinal uses (Bandaranayake, 1998), the distinction of locally occurring congeners is also an important ethnobotanical and socio-economic support. There is no doubt that the signatures are overlapping with that of other species. However, through combinations between physiognomic characteristics, in which *Rhizophora* species differentiate from other mangrove species, and within *Rhizophora*-dominated assemblages, such distinctions are made more easily. Further research will explore the ability to detect the limits between congeners in a wider area, but it will evidently depend on the degree of zonation or of mixture between tree species.

The detection of a single *Acrostichum aureum* specimen is another advancement, which opens doors to the early warning for introgressive species in mangroves. *Acrostichum aureum*, the mangrove fern, is known to penetrate into the mangrove, and to form large stands that may affect original species composition (Srivastava *et al.*, 1987), which can decrease the biodiversity or functionality of the original vegetation. It is therefore considered a pest, rather than a mangrove, in many countries, and often its (expensive) removal is required prior to mangrove rehabilitation efforts (Field, 1998; Ellison, 2000). Early detection of *Acrostichum* introgression into mangrove stands therefore has not only an ecological importance, but also an economical one. Although promising as a preliminary result, it cannot yet be acknowledged how universal *A. aureum* can be detected from very high resolution imagery. It must be highlighted that remote sensing is still limited to the canopy layer, particularly in dense forests, and cannot reveal processes of introgression in the understorey.

Despite IKONOS' high detail for specific features (distinction of congeneric species, distinction of introgressive specimens), the general delineation of assemblages may benefit from a reduction in spatial detail, in view of the available spectral detail (Table 1b). In other words, a too detailed image results in tree canopies of a single species being represented by heterogeneous image pixels (upper side, lower side, sun-side, shade-side), and the delineation of an entire assemblage or the classification of an entire image may be easier for images that are more coarse (comparable to the original spatial resolution of the multispectral bands). Apart from image classification of large areas in the light of mapping or monitoring, the detailed features visible from panchromatic or pansharpened imagery also provide ecological information, such as mortality of individual trees (Clark *et al.*, 2004) or the introgression reported above.

A high floristic resolution is needed to detect gradual and minor changes, which may be caused by, or indicative of, environmental changes. Much as in the debate on the floristic introgression into the tree layer of the Amazonian under various scenarios of glacial and interglacial climate change (Colinvaux *et al.*, 1996), rather than to view major forest-grassland vegetation shifts through floristic introgression in sequential historical analyses, high resolution remote sensing is required to monitor such changes in 'real-time'. Gradual and therefore cryptic ecological changes, such as the terrestrialization of an intertidal mangrove forest by introgressive species, can then be pinpointed in an early phase.

Although the results reported in the present paper are from mangroves, the fields of application reach far beyond the limits of mangrove forests, and possibly to other disciplines in which edge-detection between adjacent elements are essential. Automated delineation of tree crowns(Brandtberg & Walter, 1998), and texture analysis in monospecific forests (Franklin *et al.*, 2001) could now be applied to more complex systems developing an algorithm that integrates all benefits from new digital satellite imagery, i.e. a very high spatial resolution, a good spectral resolution, and a high temporal and radiometric resolution, which may result in an even higher taxonomic resolution than the innovation reported here. However, the information from very high spatial resolution remote sensing is not necessarily extracted using computer-aided interpretation. Even with IKONOS or QUICKBIRD imagery of submeter resolution, visual analysis is not outdated, and may prove most appropriate for specific ecological research and management purposes (Read *et al.*, 2003; Clark *et al.*, 2004). Although the combination between pixel-based (spectral) and object-based (texture) analysis indicates a high potential for future identification techniques, the ecological reality (physiognomy, distance to certain ecological resources or physico-chemical environmental conditions) assessed through visual interpretation, remains invaluable in the interpretation of remotely sensed imagery.

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