International Journal of Remote Sensing
Vol. 32, No. 6, 20 March 2011, 1635–1650

Taylor & Francis
Taylor & Francis Group

Assessment of mangrove vegetation based on remote sensing and ground-truth measurements at Tumpat, Kelantan Delta, East Coast of Peninsular Malaysia

BEHARA SATYANARAYANA*†‡§, KHAIRUL AZWAN MOHAMAD†, INDRA FARID IDRIS†, MOHD-LOKMAN HUSAIN† and FARID DAHDOUH-GUEBAS‡§

†Institute of Oceanography, University Malaysia Terengganu, 21030 Kuala Terengganu, Malaysia

‡Complexité et Dynamique des Systèmes Tropicaux, Département de Biologie des Organismes, Faculté des Sciences, Université libre de Bruxelles (ULB), Campus du Solbosch, CP 169, Avenue Franklin D. Roosevelt 50, B-1050 Bruxelles, Belgium

§Biocomplexity Research Focus c/o Laboratory of Plant Biology and Nature Management, Mangrove Management Group, Faculty of Sciences, Vrije Universiteit Brussel (VUB), Pleinlaan 2, B-1050 Brussels, Belgium

(*Received 20 August 2008; in final form 23 November 2009*)

The lower reaches of River Kelantan form a vast delta (1200 ha) consisting of bay, mangrove and estuary on the northeast coast of Peninsular Malaysia. The present study was conducted to assess the mangrove vegetation at Tumpat based on ground-truth and remote sensing measurements. The mangroves are composed of several species including *Nypa fruticans*, *Sonneratia caseolaris*, *Avicennia alba*, *Rhizophora apiculata*, *R. mucronata* and *Bruguiera gymnorrhiza*, in order of dominance. The point-centred quarter method (PCQM) was used to estimate the stem density (number of stems/0.1 ha) and basal area (m^2/0.1 ha) at selected sites on the ground. Recent high-resolution multispectral satellite data (QuickBird 2006, 2.4 m spatial resolution of the multispectral image) were used to produce land-use/cover classification and Normalized Differential Vegetation Index (NDVI) mapping for the delta. The area statistics reveal that mangroves occupy 339.6 ha, while coconut plantation dominates the vegetation (715.2 ha), followed by settlements (621.6 ha), sandbar (148.4 ha), agriculture (89 ha) and aquaculture (42.7 ha). Although the relationship between the spectral indices and dendrometric parameters was weak, we found a very high significance between the (mean) NDVI and stem density ($p = 1.3 \times 10^{-8}$). The sites with young/growing and also mature trees with lush green cover showed greater NDVI values (0.40–0.68) indicating healthy vegetation, while mature forests under environmental stress due to sand deposition and/or poor tidal inundation showed low NDVI values (0.38–0.47) and an unhealthy situation. Overall, a combination of ground survey and remote sensing provided valuable information for the assessment of mangrove vegetation types (i.e. young/growing or mature forest) and their health in Tumpat, Kelantan Delta.

*Corresponding author. Email: satyam2149@gmail.com

International Journal of Remote Sensing
ISSN 0143-1161 print/ISSN 1366-5901 online
http://www.tandf.co.uk/journals
DOI: 10.1080/01431160903586781

1. Introduction

Mangroves are highly productive ecosystems with a rich diversity of flora and fauna in the intertidal zones of tropical and subtropical coastlines (Abeysinghe *et al.* 2000, Jennerjahn and Ittekkot 2002, Twilley and Rivera-Monroy 2005, FAO 2007). They are considered of great ecological importance in shoreline stabilization, reduction of coastal erosion, sediment and nutrient retention, storm protection, flood and flow control, and water quality (Dahdouh-Guebas *et al.* 2005b, Giri *et al.* 2007, Alongi 2008, Bahuguna *et al.* 2008), besides their regular economic benefit through various forest products (Kathiresan and Rajendran 2006, Zhang *et al.* 2006, Gilman *et al.* 2008, Walters *et al.* 2008). During the past decades, however, the situation with regard to the mangrove forests has been deteriorating because of increased demand for land to be allocated to food and industrial production and rural and/or urban settlements (Blasco *et al.* 2001, Dahdouh-Guebas *et al.* 2005b, Duke *et al.* 2007, FAO 2007). It has been estimated that loss of the mangroves may reach 60% by 2030 (Valiela *et al.* 2001, Alongi 2002, UNEP 2006, Simard *et al.* 2008). The changes in the mangrove forests therefore need continuous monitoring through research on spatial–temporal dynamism in the coastal land-use/cover patterns (Souza Filho *et al.* 2006, Chauhan and Dwivedi 2008).

Satellite remote sensing is an efficient tool that has been adopted increasingly for the detection, description, quantification and monitoring of the Earth's natural resources (Green *et al.* 2000, Kovacs *et al.* 2004, 2005, Chauhan and Dwivedi 2008). It provides timely and cost-effective data over inaccessible areas (Everitt *et al.* 1991, Green *et al.* 1996, Mumby *et al.* 1999), complementing field surveys, which are of higher information content but are more difficult to carry out, especially in the case of mangroves (Green *et al.* 1997, Satyanarayana *et al.* 2001, Kovacs *et al.* 2004, Giri *et al.* 2007). In this context, a combination of remote sensing and ground-truth measurements, analysed within a geographic information systems (GIS) platform, is found to be highly advantageous (Dahdouh-Guebas *et al.* 2005a,b, Souza Filho *et al.* 2006, Satyanarayana 2007). Several authors have used aerial and (optical) satellite images to study the mangrove ecosystems (e.g. Dahdouh-Guebas *et al.* 2000, Satyanarayana *et al.* 2001, Lucas *et al.* 2002, Fromard *et al.* 2004, Satyanarayana 2007), while others have used synthetic aperture radar (SAR) to examine the terrain's physical (macro-topography, slope, roughness) and electrical properties (Proisy *et al.* 2000, Souza Filho and Paradella 2002, Souza Filho *et al.* 2003, 2006, Simard *et al.* 2008). The selection of remotely sensed images (from different sensors and at different resolutions) differs according to the purpose/requirement of the user, and may involve, for example, species-level classification, biomass, understory events and land-use/cover (Chauhan and Dwivedi 2008). The use of high-resolution satellite images such as those collected by the QuickBird Satellite sensor for mapping mangrove forestation and to provide a baseline database for their future monitoring has been discussed by Wang *et al.* (2004), Saleh (2007) and Neukermans *et al.* (2008).

In remote sensing analysis, vegetation indices (e.g. the Normalized Differential Vegetation Index, NDVI) are often used to highlight wetlands (Ozesmi and Bauer 2002). Ramsey and Jensen (1996) explained the relationship between the NDVI and leaf area index (LAI) for the mangroves at southwest Florida. Green *et al.* (1997) and Kovacs *et al.* (2004, 2005) have also worked on similar aspects in the Turks and Caicos Islands (British West Indies) and Agua Brava Lagoon (Mexico), respectively. Bartholy and Pongracz (2005) used the NDVI to represent climate variability and vegetation productivity for the Atlantic-European region and the Carpathian Basin. More recently, Giri *et al*. (2007) used the NDVI to represent mangrove canopy closure and patterns of change in the forest's density/condition at Sundarbans, covering India and Bangladesh. The NDVI also stands as proxy for the above-ground biomass, primary productivity and vegetation health (Seto *et al.* 2004, Jiang *et al.* 2006, Walters *et al.* 2008, Anaya *et al.* 2009, Zomer *et al.* 2009). Overall, a positive relationship between NDVI and ground-based measurements has been established by previous investigations.

Although Malaysia possesses the second largest mangrove cover (about 11.7%) in Southeast Asia (FAO 2007), studies using remote sensing in mangrove forests remain scarce in the scientific literature. In Kelantan Delta, a few closely guarded interior (inaccessible) areas support some luxuriant mangrove vegetation. Sulong *et al*. (2001) were perhaps the first to describe the Kelantan mangroves using aerial photographs. Later, Kasawani (2003), Sulong *et al*. (2005) and Kasawani *et al*. (2006) focused on satellite images to develop maps for mangrove species distribution and forest types. Mohd-Suffian *et al*. (2004) and Karthigeyan (2008) worked on the coastal morphology and shoreline changes in this region.

The current study aimed primarily to assess the mangrove vegetation at Tumpat (Kelantan Delta), based on remote sensing and ground-truth observations. The specific objectives were to map and quantify the current status of the mangrove and adjacent land-use categories (i.e. area statistics), and to evaluate the potential relationship between vegetation indices (e.g. NDVI) derived from satellite imagery and mangrove dendrometric (e.g. tree density and basal area) parameters estimated on the ground.

2. Materials and methods

2.1 *Study area*

The mangroves at Tumpat are located in the River Kelantan Delta on the northeast coast of Peninsular Malaysia (6° 11′ to 6° 13′ N; 102° 9′ to 102° 14′ E) (figure 1). This rich but fragile ecosystem has undergone serious alterations largely induced by human

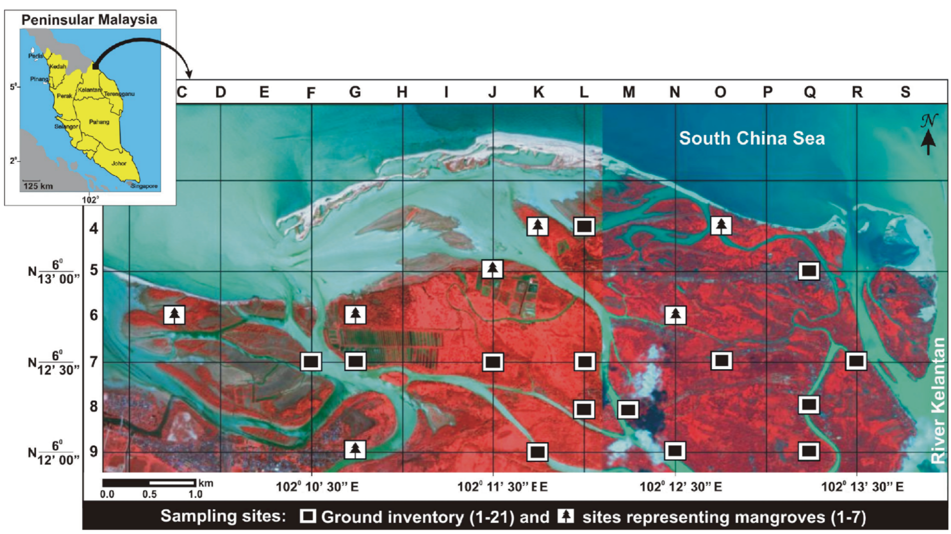

Figure 1. River Kelantan Delta showing Tumpat mangroves on the northeast coast of Peninsular Malaysia (sampling sites: 1–21) (background: QuickBird satellite imagery dated 29 April 2006).

activity in recent years. Besides its wide catchment area (7456 km^2), the delta possesses prominent features such as a bay, mangrove and estuarine environments separated by sandbar and other physical gradients. The delta covers approximately 1200 ha (Shamsudin and Nasir 2005), and the mangroves are represented by *Avicennia alba* Bl., *Bruguiera gymnorrhiza* Lamk, *Nypa fruticans* (Thunb.) Wurmb., *Rhizophora apiculata* Bl., *R. mucronata* Lamk. and *Sonneratia caseolaris* (L.) Engler (classification based on Tomlinson (1994)). Mangrove associates such as *Acanthus ilicifolius* L., *Acrostichum aureum* L. and *Derris trifoliata* Lour. are also found in this locality. The climate of Kelantan and its surrounding environs is strongly influenced by their location in the tropics, with a mean annual temperature of 26.8°C and high humidity (unpublished data).

Altogether, 21 stations based on a predetermined grid (at 1-km intervals) were selected for the ground-truth and floristic inventory (figure 1). The sampling sites were reached with the help of a global positioning system (GPS Garmin 45, Garmin International, Lenexa, KS, USA), and in some cases (i.e. inaccessible sites) were approached up to their nearest accessible location. Of the total 21 sites, only seven represented mangroves proper (sites C6, G6, G9, J5, K4, N6 and O4), and the rest agriculture, aquaculture, terrestrial/coconut vegetation and rural settlements (table 1). In addition to the grid-based locations, another 194 sites (randomly selected) were visited for ground-check in the mangrove and non-mangrove areas. Both *N. fruticans* and *S. caseolaris* were abundant and distributed throughout the forest, while *A. alba* and *R. mucronata* were exclusive to the bay–mangrove periphery (sites C6 and G6). *B. gymnorrhiza* and *R. apiculata* were observed in the forest interior, away from the main flooding channel/bay waters.

2.2 *Ground data collection*

The fieldwork in Kelantan Delta was conducted in October 2007. The point-centred quarter method (PCQM; Cottam and Curtis 1956, Cintron and Schaeffer Novelli 1984, Dahdouh-Guebas and Koedam 2006) was used at each mangrove site to estimate the stem density (number of stems/0.1 ha) and basal area (m^2/0.1 ha) as parameters. In this context, a maximum distance of 100 m transect was covered at each location to measure tree height (m), stem diameter D_{130} (cm) (term according to Brokaw and Thompson (2000) to represent the diameter at breast height, DBH), and the distance (m) between the transect line and the nearest tree in each quadrant at 10-m intervals. This procedure allows an understanding of the mean stem diameter of each mangrove species and their relative importance in structuring the mangrove forest at Tumpat. Moreover, the PCQM can be used as a ground-truth method for remote sensing studies in a combinatory investigation (see Dahdouh-Guebas and Koedam (2006)). However, there are only seven sites in the delta that represent mangrove vegetation (mentioned earlier) and for suitability of PCQM (figure 1). The data on the mangrove associates and other terrestrial vegetation in the vicinity were recorded from non-mangrove sites. At each point, the coordinates were obtained from GPS and those features were photographed. All these findings (ground inventory) were used to develop a final land-use/cover map for Kelantan Delta.

2.3 *Satellite data analysis*

Very high-resolution (2.4 m) multispectral satellite data (QuickBird dated 29 April 2006) represented largely by the mangrove vegetation/sampled area in Kelantan Delta

Table 1. Ground-truth observations (at 1 km grid intervals) in Kelantan Delta.

No.	Site no.	Latitude (N)	Longitude (E)	Vegetation	Remarks
1.	C6	6° 12′ 50″	102° 09′ 51″	*Avicennia alba*, *Nypa fruticans*, *Rhizophora mucronata* and *Sonneratia caseolaris*	Mangrove site
2.	F7	6° 12′ 25″	102° 10′ 32″	*A. alba*, *N. fruticans*, *R. mucronata*, *Bruguiera gymnorrhiza* and *S. caseolaris*	Mixed mangrove plantation
3.	G6	6° 12′ 50″	102° 10′ 42″	*A. alba*	Mangrove site
4.	G7	6° 12′ 28″	102° 10′ 53″	*Acrostichum aureum, N. fruticans* and *S. caseolaris*	Abandoned aquacultural ponds
5.	G9	6° 12′ 01″	102° 10′ 50″	*N. fruticans*	Mangrove site
6.	J5	6° 13′ 03″	102° 11′ 30″	*N. fructicans* and *S. caseolaris*	Mangrove site
7.	J7	6° 12′ 22″	102° 11′ 30″	Coconut	Non-mangrove site
8.	K4	6° 13′ 13″	102° 11′ 41″	*N. fructicans* and *S. caseolaris*	Mangrove site
9.	K9	6° 12′ 06″	102° 11′ 39″	Terrestrial/elevated ground	Non-mangrove site
10.	L4	6° 13′ 10″	102° 11′ 55″	*Acr. aureum*, *Acanthus ilicifolius* and *Derris trifoliata*	Non-mangrove site
11.	L7	6° 12′ 33″	102° 12′ 05″	Terrestrial/elevated ground	Non-mangrove site
12.	L8	6° 12′ 07″	102° 12′ 03″	Terrestrial/elevated ground	Non-mangrove site
13.	M8	6° 12′ 07″	102° 12′ 16″	Coconut	Non-mangrove site
14.	N6	6° 12′ 45″	102° 12′ 28″	*N. fructicans* and *S. caseolaris*	Mangrove site
15.	N9	6° 11′ 59″	102° 12′ 32″	Banana/coconut	Non-mangrove site
16.	O4	6° 13′ 09″	102° 12′ 36″	*N. fructicans* and *S. caseolaris*	Mangrove site
17.	O7	6° 12′ 36″	102° 12′ 49″	Terrestrial/elevated ground	Non-mangrove site
18.	Q5	6° 13′ 00″	102° 13′ 18″	Coconut	Non-mangrove site
19.	Q8	6° 12′ 14″	102° 13′ 12″	Coconut	Non-mangrove site
20.	Q9	6° 12′ 05″	102° 13′ 20″	Coconut	Non-mangrove site
21.	R7	6° 12′ 30″	102° 13′ 29″	Coconut	Non-mangrove site

(6° 11′ 70″ to 6° 13′ 50″ N; 102° 09′ to 102° 14′ E) were selected for the present study (figure 1). This image was pre-processed by applying radiometric and geometric corrections at the Malaysian Remote Sensing Agency (formerly known as MACRES, Kuala Lumpur). The land-use/cover map of Kelantan Delta (including mangroves) was produced by supervised maximum likelihood classification (using ERDAS Imagine version 8.5, ERDAS, Inc., Norcross, GA, USA), the most commonly used technique for mapping wetlands (Ozesmi and Bauer 2002). Each class (e.g. mangrove, aquaculture, settlements, etc.) was determined through training sets, that is the selection of pixels with the same pattern. In total, 10 classes were assigned, including two areas of densely populated mangrove species, namely *A. alba* and *S. caseolaris* + *N. fruticans*. The other classes were represented by coconut plantations, terrestrial vegetation, agricultural fields, aquacultural ponds, settlement areas, exposed mud banks, sandbars and water. To evaluate the accuracy of the land-use/cover map, a confusion matrix (e.g. Congalton 1991) was produced using a minimum of 50 reference (ground-check) points for each major class (Jensen 1996).

The NDVI, one of the commonly used vegetation indices derived from satellite images, has been shown to represent the amount of greenness or biomass of mangroves, which in turn can reflect their health or photosynthetic activity (Bartholy and Pongracz 2005, Kovacs *et al.* 2005, LeMarie *et al.* 2006, Seto and Fragkias 2007). Values of this index are calculated from the reflected solar radiation in the near-infrared (NIR) (760–900 nm) and red (R) (630–690 nm) bands using the formula NDVI = [(NIR) − R]/[(NIR) + R], which usually varies between −1 and 1. A value close to zero represents no vegetation and a value close to +1 indicates a high density of green leaves (Jensen *et al.* 1991, Jensen 1996, 2000, Bartholy and Pongracz 2005, Seto and Fragkias 2007).

The mangrove locations were entered into a spatial database (using ArcView GIS 3.2, ESRI, Inc., Redlands, CA, USA) as rectangles of roughly 100 m × 10 m, which corresponds to the actual dimensions of our PCQM transect (1000 m^2 or 0.1 ha). The mean value of the area covered by each transect (rectangle) was extracted from the NDVI image, and then compared with the mangrove tree density and basal area through the analysis of simple linear regression. This hypothesis was interpreted using the coefficient of determination (R^2) with a significance at $p < 0.05$.

3. Results and discussion

3.1 *Mangrove structural attributes*

The study of forest structure or the management of a forest for silvicultural purposes requires plant structural parameters such as density, basal area and biomass (Saenger 2002, Dahdouh-Guebas and Koedam 2006). The results based on PCQM (table 2)

Table 2. Mangrove structural parameters (based on PCQM) in Kelantan Delta.

	Site						
	C6	G6	G9	J5	K4	N6	O4
Total tree density (stems/0.1 ha)	89	79	132	112	125	129	136
Total basal area (m^2/0.1 ha)	1.72	1.82	0.14	4.90	0.35	2.25	2.87
Mean NDVI	0.47	0.38	0.40	0.46	0.48	0.66	0.68

indicated that the total mangrove tree density at Tumpat varied between 79 and 136 stems/0.1 ha (sites G6 and O4), while the basal area varied from 0.14 to 4.9 m^2/ 0.1 ha (sites G9 and J5). In general, tree density and basal area are the important variables used to assess the 'young/growing' or 'mature' nature of the vegetation (i.e. stem densities in general correlated negatively with stand biomass or wood volume) (Satyanarayana *et al.* 2002, Satyanarayana 2005). Among others, site G9 (solely consisting of *N. fruticans*) represented a growing forest (density 132 stems/0.1 ha; basal area 0.14 m^2/0.1 ha), while J5 (dominated by *S. caseolaris*) a mature stand (density 112 stems/0.1 ha; basal area 4.9 m^2/0.1 ha). Sites C6 (89 stems; basal area 1.72 m^2/0.1 ha), G6 (79 stems; basal area 1.82 m^2/0.1 ha) and N6 (129 stems; basal area 2.25 m^2/0.1 ha) had relatively low stem densities and high basal areas, indicating their mature nature. Site K4 (125 stems; basal area 0.35 m^2/0.1 ha), located at the bay–mangrove periphery, represented a young/growing lush green forest. The high basal area at site O4 (2.87 m^2/0.1 ha) is due to its inaccessibility and distance from major transportation channels.

3.2 *Supervised classification*

Figure 2 shows the land-use/cover map of Kelantan Delta. All (10) classes (different land-use/cover patterns) were well demarcated, in agreement with the ground-truth observations. Kasawani *et al.* (2006) previously reported 10 mangrove forest types in this region, including *Avicennia*-*Sonneratia*, *Acanthus*-*Sonneratia*, *Acanthus*-*Nypa*, *Hibiscus*-*Acrostichum*, mixed *Acanthus*, mixed *Acrostichum* and mixed *Sonneratia*. However, in the present study, only the most abundant and true mangrove species (i.e. *A. alba*, *N. fruticans* and *S. caseolaris*) (Tomlinson 1994) were considered for mapping. The introgressive species, *Acrostichum*, was considered as a mangrove associate because of its ill affects on the original biodiversity and functionality of the mangrove ecosystems (Dahdouh-Guebas *et al.* 2005a,b,c).

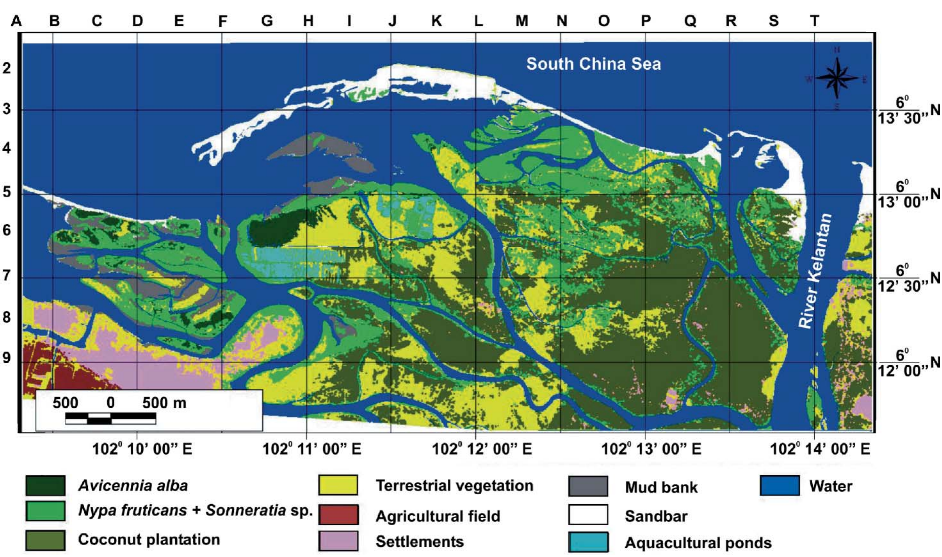

Figure 2. Land-use/cover classification of Kelantan Delta (based on QuickBird imagery dated 29 April 2006).

Mangrove areas are commonly characterized by rapid anthropogenic events (e.g. conversion into aquacultural ponds, agriculture and industry) and the occurrence of certain natural events (e.g. accretion of new land area and erosion along the coast and rivers) (Kovacs *et al.* 2001, Ramasubramanian *et al.* 2006). The area statistics indicate that the mangroves at Tumpat occupied only 339.6 ha in 2006 despite having a large deltaic area (1200 ha). More recently, Mohd-Azhar (2008) estimated area calculations for this region (Kelantan Delta) with the aid of Landsat Thematic Mapper (TM) satellite images and reported that the mangroves occupied nearly 354.1 ha in the year 2000. In this case, the loss of mangrove cover was 14.5 ha in 6 years. Between 1988 and 2000, the depletion of mangroves was 139.3 ha due to aquaculture, sediment accretion and human settlements (Kasawani *et al.* 2006). Figure 3 shows the changes in the mangrove cover between 1988 and 2006.

In Kelantan Delta, coastal erosion is also responsible for the loss of mangrove cover. In particular, mangroves at the border facing the South China Sea (e.g. *A. alba*, *N. fruticans* and *S. caseolaris*) (sites C6, G6 and J5) are submitted to high-impact current/waves and sand deposition, causing the death of several mature trees (figure 4).

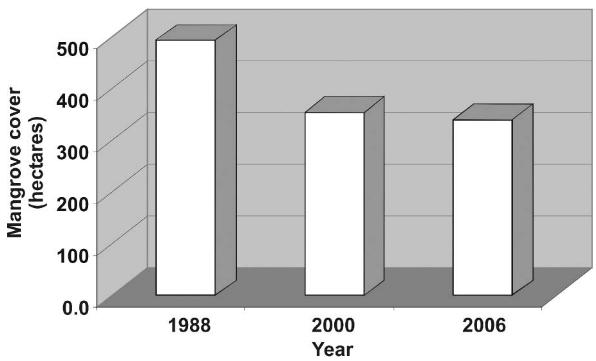

Figure 3. Changes in the extent of mangrove cover at Tumpat, Kelantan Delta.

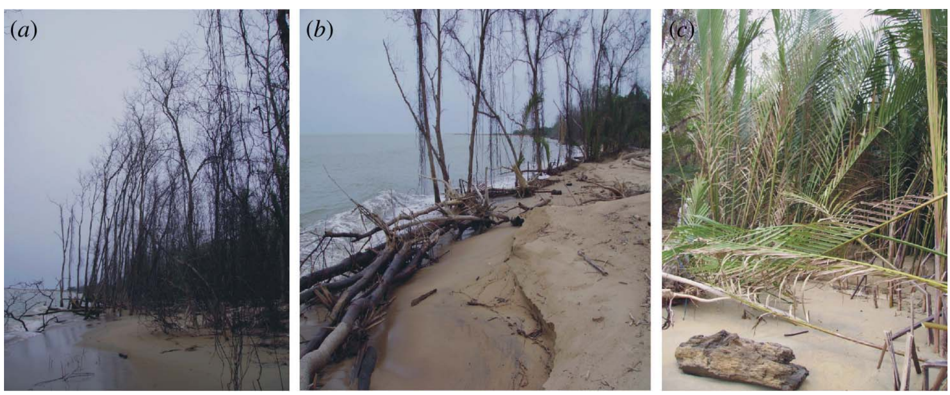

Figure 4. Photographs showing the impact of strong current/waves from the South China Sea on the bordering mangrove vegetation in Kelantan Delta. (*a*) Death of *Sonneratia caseolaris* trees (height 10–15 m) due to sand deposition over muddy substratum and above their pneumatophores. (*b*) Coastal erosion and uprooted *S. caseolaris*. (*c*) Sand deposition at the patch of *Nypa fruticans* adjacent to *S. caseolaris*.

Table 3. Confusion matrix based on supervised classification and ground-truth data.

	Supervised classification										
Ground truth	Agricultural field	Aquacultural ponds	Terrestrial vegetation	Coconut plantation	Mangrove vegetation	Settlement area	Mud bank	Sandbar	Water	Total	Accuracy (%)
Agricultural field	–	–	–	–	–	–	–	–	–	0	N/A
Aquacultural ponds	–	–	–	–	–	–	–	–	–	0	N/A
Terrestrial vegetation	–	–	45	8	–	–	–	–	–	53	85
Coconut plantation	–	–	12	50	–	8	–	–	–	70	71
Mangrove vegetation	–	–	–	–	54	–	–	–	–	54	100
Settlement area	–	–	–	–	–	45	–	–	–	45	100
Mud bank	–	–	–	–	–	–	–	–	–	0	N/A
Sandbar	–	–	–	–	–	–	–	–	–	0	N/A
Water	–	–	–	–	–	–	–	–	–	0	N/A
Total	0	0	57	58	54	53	0	0	0	214	
Accuracy (%)	N/A	N/A	79	86	100	85	N/A	N/A	N/A		

Similar erosion effects have also been observed in the deforested mangrove sites in Kenya (Dahdouh-Guebas *et al.* 2004). Terrados *et al.* (1997) reported adverse effects of increased sediment accretion on the growth and survival of mangroves with reference to *R. apiculata.* The local Forestry Department of Kelantan (in association with other governmental and non-governmental organizations) is, however, carrying out mangrove afforestation works with some promising results (personal observation).

Among the other land-use/cover classes, coconut vegetation ranked first with 715.2 ha, followed by settlements (621.6 ha), sandbar (148.4 ha), other terrestrial vegetation (99.7 ha), agriculture (89 ha), aquaculture (42.7 ha), and mud bank (23.3 ha). The confusion matrix (table 3) indicates that the 'mangrove' category (i.e. *A. alba*, and *N. fruticans* + *S. caseolaris*) was well classified, with an estimated accuracy of 100%. In addition, terrestrial vegetation including coconut and settlement areas could be distinguished with 79–86% accuracy. The overall accuracy of the supervised classification was 88.3%.

3.3 *The NDVI and its relationship with dendrometric parameters*

Figure 5 shows the NDVI map of Kelantan Delta. Within the vegetation cover, a portion of dark green indicates higher NDVI (0.5–0.8), bright green indicates moderate NDVI (0.2–0.5) and light green lower NDVI (0.1–0.2). The mean NDVI values at the seven mangrove sites sampled ranged between 0.38 and 0.68 (table 2 and figure 5). The simple linear regression analysis between (mean) NDVI and density and between NDVI and basal area suggests that the relationship, although relatively weak, was particularly significant and meaningful between NDVI and density ($R^2 = 0.2096$, $p = 1.3 \times 10^{-8}$) (figure 6). Density-wise mapping of mangroves based on NDVI has previously been carried out by Giri *et al.* (2007) and Thu and Populus (2007). The sites having young/growing and also mature trees with lush green cover (e.g. sites G9, K4 and N6 and O4) reflected greater NDVI (0.40–0.68) (implying healthy vegetation), while matured forest (sites C6, G6 and J5) under the environmental stress due to sand deposition and/or poor tidal inundation indicated lower NDVI (0.38–0.47) (unhealthy vegetation). Similarly, Nayak *et al.* (2001), Kovacs *et al.* (2005), and Lee and Yeh (2009) used NDVI to represent the health of mangroves

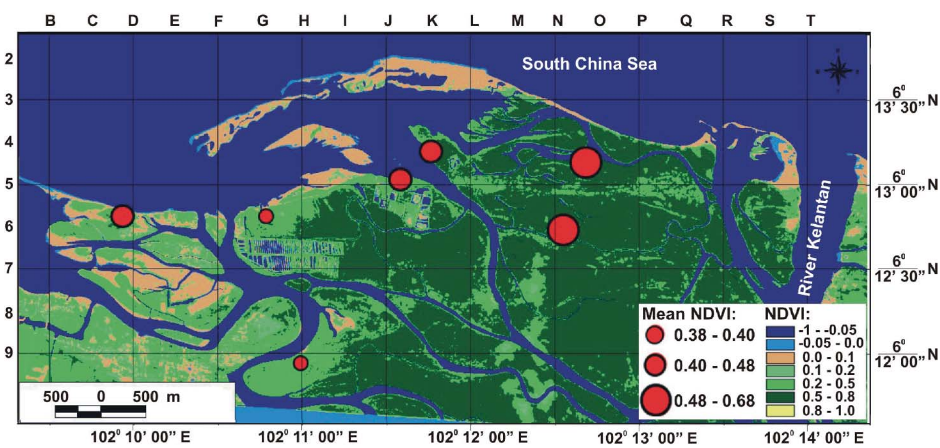

Figure 5. Pseudocolour image of NDVI (QuickBird 2006), and its mean value distribution at the mangrove sites in Tumpat, Kelantan Delta.

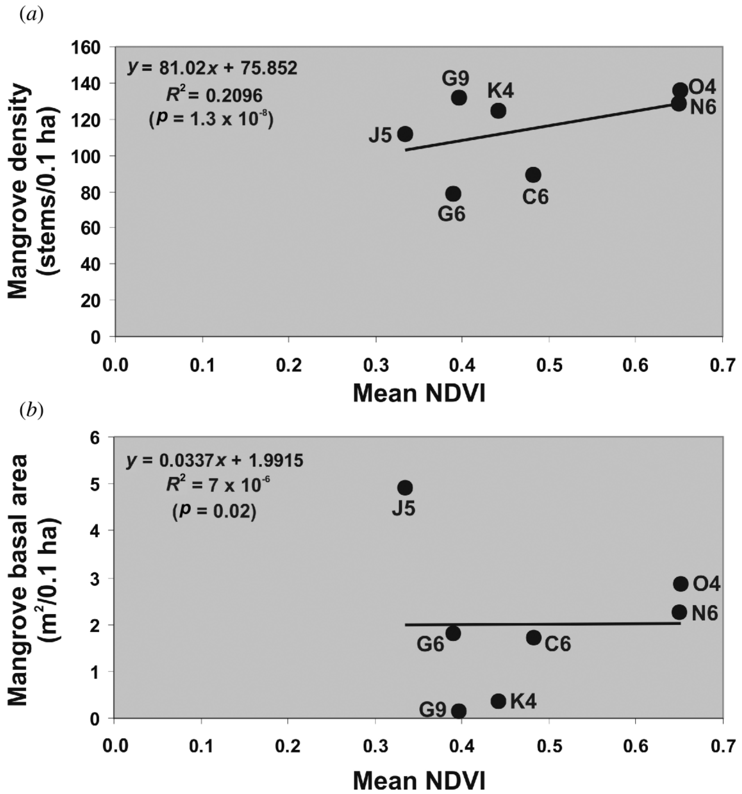

Figure 6. Illustration of simple linear regression between (*a*) mean NDVI and density and (*b*) mean NDVI and basal area.

in their studies. Another notable observation is that mature trees (usually with large stem diameter and height) may not necessarily show greater biomass in the remote sensing analysis, unless they are found to be growing in the most suitable and distress-free environments in terms of hydrological, anthropogenic and natural climate change scenarios (Townsend *et al.* 1991, Simard *et al.* 2008).

4. Conclusion

In summary, the delineation of mangrove and non-mangrove areas and even species-level classification is best achieved with high-resolution multispectral satellite imageries such as QuickBird. Although higher resolution may complicate the process of image classification (Mironga 2004, Dahdouh-Guebas *et al.* 2005c), it is still advantageous for species identification/mapping (Wang *et al.* 2004, Saleh 2007, Neukermans *et al.* 2008). The land-use/cover map thus produced for Tumpat should be able to assist in better monitoring and management practices in the delta. The relationship between the spectral indices and dendrometric parameters indicated that lush green mangroves with high green leaf density (both young and mature trees) represent healthy vegetation (high NDVI), while mature forest under environmental stress show an unhealthy situation (low NDVI). It should be noted that the empirical relationship could have been very strong if the number of mangrove sites (i.e. sample size) was comparatively high. A combination of ground-survey and remote sensing data was very useful for the assessment of mangrove vegetation types (i.e. young/growing or mature forest) as well as their health at Tumpat, Kelantan Delta.

Acknowledgements

The present study was undertaken as a part of our E-Science project (no. 04-01-12-SF0049) on 'Vegetation health and stress evaluations based on remote sensing and ground survey techniques in Kelantan Delta, East Peninsular Malaysia', awarded by the Ministry of Science, Technology and Innovation (MOSTI), Government of Malaysia. B.S. is supported by the Belgian National Science Foundation (FNRS). We are grateful to the financial and administrative authorities at MOSTI, UMT and FNRS. We also thank the Forestry Department of Tumpat for their kind support in providing a boat and men for our fieldwork. Finally, we thank the unknown referee for his objective criticism and invaluable suggestions.

References

Abeysinghe, P.D., Triest, L., Greef, B.D., Koedam, N. and Hettiarachi, S., 2000, Genetic and geographic variation of the mangrove tree *Bruguiera* in Sri Lanka. *Aquatic Botany*, **67**, pp. 131–141.

Alongi, D.M., 2002, Present state and future of the world's mangrove forests. *Environmental Conservation*, **29**, pp. 331–349.

Alongi, D.M., 2008, Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. *Estuarine, Coastal and Shelf Science*, **76**, pp. 1–13.

Anaya, J.A., Chuvieco, E. and Palacios-Orueta, A., 2009, Aboveground biomass assessment in Colombia: a remote sensing approach. *Forest Ecology and Management*, **257**, pp. 1237–1246.

Bahuguna, A., Nayak, S. and Roy, D., 2008, Impact of the tsunami and earthquake of 26th December 2004 on the vital coastal ecosystems of the Andaman and Nicobar Islands assessed using RESOURCESAT AWiFS data. *International Journal of Applied Earth Observation and Geoinformation*, **10**, pp. 229–237.

Bartholy, J. and Pongracz, R., 2005, Extremes of ground based and satellite measurements in the vegetation period for the Carpathian Basin. *Physics and Chemistry of the Earth*, **30**, pp. 81–89.

Blasco, F., Aizpuru, M. and Gers, C., 2001, Depletion of the mangroves of Continental Asia. *Wetlands Ecology and Management*, **9**, pp. 245–256.

Brokaw, N. and Thompson, J., 2000, The H for DBH. *Forest Ecology and Management*, **129**, pp. 89–91.

Chauhan, H.B. and Dwivedi, R.M., 2008, Inter sensor comparison between RESOURCESAT LISS III, LISS IV and AWiFS with reference to coastal landuse/landcover studies. *International Journal of Applied Earth Observation and Geoinformation*, **10**, pp. 181–185.

Cintron, G. and Schaeffer-Novelli, Y., 1984, Methods for studying mangrove structure. In *The Mangrove Ecosystem: Research Methods*, C.S. Samuel and G.S. Jane (Eds), pp. 91–113 (Paris: UNESCO).

Congalton, R.G., 1991, A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sensing of Environment*, **37**, pp. 35–46.

Cottam, G. and Curtis, J.T., 1956, The use of distance measures in phytosociological sampling. *Ecology*, **37**, pp. 451–460.

Dahdouh-Guebas, F., Hettiarachchi, S., Lo Seen, D., Batelaan, O., Sooriyarachchi, S., Jayatissa, L.P. and Koedam, N., 2005a, Transitions in ancient inland freshwater resource management in Sri Lanka affect biota and human populations in and around coastal lagoons. *Current Biology*, **15**, pp. 579–586.

DAHDOUH-GUEBAS, F., JAYATISSA, L.P., DI NITTO, D., BOSIRE, J.O., LO SEEN, D. and KOEDAM, N., 2005b, How effective were mangroves as a defence against the recent tsunami? *Current Biology*, **15**, pp. R443–R447.

DAHDOUH-GUEBAS, F. and KOEDAM, N., 2006, Empirical estimate of the reliability of the use of the Point-Centred Quarter Method (PCQM): solutions to ambiguous field situations and description of the PCQM+ protocol. *Forest Ecology and Management*, **228**, pp. 1–18.

DAHDOUH-GUEBAS, F., VAN HIEL, E., CHAN, J.C.-W., JAYATISSA, L.P. and KOEDAM, N., 2005c, Qualitative distinction of congeneric and introgressive mangrove species in mixed patchy forest assemblages using high spatial resolution remotely sensed imagery (IKONOS). *Systematics and Biodiversity*, **2**, pp. 113–119.

DAHDOUH-GUEBAS, F., VAN POTTELBERGH, I., KAIRO, J.G., CANNICCI, S. and KOEDAM, N., 2004, Human-impacted mangroves in Gazi (Kenya): predicting future vegetation based on retrospective remote sensing, social surveys, and distribution of trees. *Marine Ecology Progress Series*, **272**, pp. 77–92.

DAHDOUH-GUEBAS, F., VERHEYDEN, A., DE GENST, W., HETTIARACHCHI, S. and KOEDAM, N., 2000, Four decade vegetation dynamics in Sri Lankan mangroves as detected from sequential aerial photography: a case study in Galle. *Bulletin of Marine Science*, **67**, pp. 741–759.

DUKE, N.C., MEYNECKE, J.-O., DITTMANN, S., ELLISON, A.M., ANGER, K., BERGER, U., CANNICCI, S., DIELE, K., EWEL, K.C., FIELD, C.D., KOEDAM, N., LEE, S.Y., MARCHAND, C., NORDHAUS, I. and DAHDOUH-GUEBAS, F., 2007, A world without mangroves? *Science*, **317**, pp. 41–42.

EVERITT, J.H., ESCOBAR, D.E. and JUDD, F.W., 1991, Evaluation of airborne video imagery for distinguishing black mangrove (*Avicennia germinans*) on the lower Texas Gulf coast. *Journal of Coastal Research*, **7**, pp. 1169–1173.

FAO, 2007, *Mangrove Guidebook for Southeast Asia* (RAP/2006/07) (Bangkok, Thailand: Dharmasarn Co., Ltd).

FROMARD, F., VEGA, C. and PROISY, C., 2004, Half a century of dynamic coastal change affecting mangrove shorelines of French Guiana. A case study based on remote sensing data analyses and field surveys. *Marine Geology*, **208**, pp. 265–280.

GILMAN, E., ELLISON, J., DUKE, N.C. and FIELD, C., 2008, Threats to mangroves from climate change and adaptation options: a review. *Aquatic Botany*, **89**, pp. 237–250.

GIRI, C., PENGRA, B., ZHU, Z., SINGH, A. and TIESZEN, L.-L., 2007, Monitoring mangrove forest dynamics of the Sundarbans in Bangladesh and India using multi-temporal satellite data from 1973 to 2000. *Estuarine, Coastal and Shelf Science*, **73**, pp. 91–100.

GREEN, E.P., CLARK, C.D. and EDWARDS, A.J., 2000, Image classification and habitat mapping. In *Remote Sensing Handbook for Tropical Coastal Management*, A.J. Edwards (Ed.), pp. 141–154 (Paris: UNESCO).

GREEN, E.P., MUMBY, P.J., EDWARDS, A.J. and CLARK, C.D., 1996, A review of remote sensing for tropical coastal resources assessment and management. *Coastal Management*, **24**, pp. 1–40.

GREEN, E.P., MUMBY, P.J., EDWARDS, A.J., CLARK, C.D. and ELLIS, A.C., 1997, Estimating leaf area index of mangroves from satellite data. *Aquatic Botany*, **58**, pp. 11–19.

JENNERJAHN, T.C. and ITTEKKOT, V., 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. *Naturwissenschaften*, **89**, pp. 23–30.

JENSEN, J.R., 1996, *Introductory Digital Image Processing – A Remote Sensing Perspective* (Upper Saddle River, NJ: Prentice-Hall, Inc.).

JENSEN, J.R., 2000, *Remote Sensing of the Environment – An Earth Resource Perspective* (Upper Saddle River, NJ: Prentice-Hall, Inc.).

Jensen, J.R., Lin, H., Yang, X., Ramsey, E., Davis, B.A. and Thoemke, C.W., 1991, The measurement of mangrove characteristics in southwest Florida using SPOT multi-spectral data. *Geocarto International*, **2**, pp. 13–21.

Jiang, Z., Huete, A.R., Chen, J., Chen, Y., Li, J., Yan, G. and Zhang, X., 2006, Analysis of NDVI and scaled difference vegetation index retrievals of vegetation fraction. *Remote Sensing of Environment*, **101**, pp. 366–378.

Karthigeyan, V., 2008, Short term and long term shoreline changes in Kelantan Delta. MSc dissertation, University Malaysia Terengganu, Malaysia.

Kasawani, I., 2003, Mapping and distribution of the Kelantan Delta mangroves using remote sensing and ground data. MSc dissertation, University College of Science and Technology Malaysia (KUSTEM), Malaysia.

Kasawani, I., Sulong, I., Mohd-Suffian, I. and Khairani, A., 2006, Mangrove forest classes, distribution and changes using remote sensing techniques and ground truth data in Kelantan Delta, Kelantan. In *Proceedings of the KUSTEM 5th Annual Seminar on Sustainability Science and Management*, N.A.M. Shazili and A.B. Abol-Munafi (Eds.) (Kuala Terengganu, Malaysia: College University of Science and Technology Malaysia), pp. 115–118.

Kathiresan, K. and Rajendran, N., 2006, Coastal mangrove forests mitigated tsunami. *Estuarine, Coastal and Shelf Science*, **65**, pp. 601–606.

Kovacs, J.M., Flores-Verdugo, F., Wang, J. and Aspden, L.P., 2004, Estimating leaf area index of a degraded mangrove forest using high spatial resolution satellite data. *Aquatic Botany*, **80**, pp. 13–22.

Kovacs, J.M., Wang, J. and Blanco-Correa, M., 2001, Mapping disturbances in a mangrove forest using multi-date Landsat TM imagery. *Environmental Management*, **27**, pp. 763–776.

Kovacs, J.M., Wang, J. and Flores-Verdugo, F., 2005, Mapping mangrove leaf area index at the species level using IKONOS and LAI-2000 sensors for the Agua Brava Lagoon, Mexican Pacific. *Estuarine, Coastal and Shelf Science*, **62**, pp. 377–384.

Lee, T.-M. and Yeh, H.-C., 2009, Applying remote sensing techniques to monitor shifting wetland vegetation: a case study of Danshui River estuary mangrove communities, Taiwan. *Ecological Engineering*, **35**, pp. 487–496.

LeMarie, M., van der Zaag, P., Menting, G., Baquete, E. and Schotanus, D., 2006, The use of remote sensing for monitoring environmental indicators: the case of the Incomati estuary, Mozambique. *Physics and Chemistry of the Earth*, **31**, pp. 857–863.

Lucas, R.M., Ellison, J.C., Mitchell, A., Donnelly, B., Finlayson, M. and Milne, A.K., 2002, Use of stereo aerial photography for quantifying changes in the extent and height of mangroves in tropical Australia. *Wetlands Ecology and Management*, **10**, pp. 161–175.

Mironga, J.M., 2004, Geographic Information Systems (GIS) and remote sensing in the management of shallow tropical lakes. *Applied Ecology and Environmental Research*, **2**, pp. 83–103.

Mohd-Azhar, M.Z., 2008, Relationship between vegetation indices and dendrometric parameters in Kelantan Delta mangrove ecosystem. BSc dissertation, University Malaysia Terengganu, Malaysia.

Mohd-Suffian, I., Nor Antonina, A., Sulong, I., Mohd-Lokman, H. and Suhaila, S.I., 2004, Monitoring the short-term changes of the Kelantan Delta using remote sensing and GIS applications. In *Proceedings of the KUSTEM 3rd Annual Seminar on Sustainability Science and Management*, M.T. Norhayati, M.A. Nakisah, Y. Kamaruzzaman, A.W.M. Effendy, A.H. Nor, S.A. Ahmad, M.S. Jamilah and A.A. Siti (Eds.), pp. 391–394 (Kuala Terengganu, Malaysia: College University of Science and Technology Malaysia).

Mumby, P.J., Green, E.P., Edwards, A.J. and Clark, C.D., 1999, The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. *Journal of Environmental Management*, **55**, pp. 157–166.

Nayak, S.R., Sarangi, R.K. and Rajawat, A.S., 2001, Application of IRS-P4 OCM data to study the impact of cyclone on coastal environment of Orissa. *Current Science*, **80**, pp. 1208–1213.

Neukermans, G., Dahdouh-Guebas, F., Kairo, J.G. and Koedam, N., 2008, Mangrove species and stand mapping in Gazi Bay (Kenya) using Quickbird satellite imagery. *Journal of Spatial Science*, **52**, pp. 75–86.

Ozesmi, S.L. and Bauer, M.E., 2002, Satellite remote sensing of wetlands. *Wetlands Ecology and Management*, **10**, pp. 381–402.

Proisy, C., Mougin, E., Fromard, F. and Karam, M.A., 2000, Interpretation of polarimetric signatures of mangrove forest. *Remote Sensing of Environment*, **71**, pp. 56–66.

Ramasubramanian, R., Gnanappazham, L., Ravishankar, T. and Navamuniyammal, M., 2006, Mangroves of Godavari: analysis through remote sensing approach. *Wetlands Ecology and Management*, **14**, pp. 29–37.

Ramsey, E.W. and Jensen, J.R., 1996, Remote sensing of mangrove wetlands: relating canopy spectra to site-specific data. *Photogrammetric Engineering and Remote Sensing*, **62**, pp. 939–948.

Saenger, P., 2002, *Mangrove Ecology, Silviculture and Conservation* (Dordrecht, The Netherlands: Kluwer Academic).

Saleh, M.A., 2007, Assessment of mangrove vegetation on Abu Minqar Island of the Red Sea. *Journal of Arid Environments*, **68**, pp. 331–336.

Satyanarayana, B., 2005, Ecobiology and remote sensing based study of Coringa mangroves in the Godavari Delta, East coast of India. PhD dissertation, Andhra University, India.

Satyanarayana, B., 2007, *Application of Remote Sensing: An Approach for Distinguishing Vegetation Structure and Decadal Changes in Mangroves* (Kuala Terengganu, Malaysia: University Malaysia Terengganu).

Satyanarayana, B., Raman, A.V., Dehairs, F., Kalavati, C. and Chnadramohan, P., 2002, Mangrove floristic and zonation patterns of Coringa, Kakinada Bay, East coast of India. *Wetlands Ecology and Management*, **10**, pp. 25–39.

Satyanarayana, B., Thierry, B., Lo Seen, D., Raman, A.V. and Muthusankar, G., 2001, Remote sensing in mangrove research – relationship between vegetation indices and dendrometric parameters: a case for Coringa, East coast of India. In *Proceedings of the 22nd Asian Conference on Remote Sensing*, S.C. Liew (Ed.), pp. 567–572 (Singapore: National University of Singapore).

Seto, K.C., Fleishman, E., Fay, J.P. and Betrus, C.J., 2004, Linking spatial patterns of bird and butterfly species richness with Landsat TM derived NDVI. *International Journal of Remote Sensing*, **25**, pp. 4309–4324.

Seto, K.C. and Fragkias, M., 2007, Mangrove conversion and aquaculture development in Vietnam: a remote sensing-based approach for evaluating the Ramsar Convention on Wetlands. *Global Environmental Change*, **17**, pp. 486–500.

Shamsudin, I. and Nasir, M.H., 2005, Future research and development of mangroves in Malaysia. In *Sustainable Management of Matang Mangroves: 100 Years and Beyond*, M.I. Shaharuddin, A. Muda, R. Ujang, A.B. Kamaruzaman, K.L. Lim, S. Rosli, J.M. Som and A. Latiff (Eds), pp. 153–161, Forestry Biodiversity Series (Kuala Lumpur, Malaysia: Forestry Department Peninsular Malaysia).

Simard, M., Rivera-Monroy, V.H., Mancera-Pineda, J.E., Castañeda-Moya, E. and Twilley, R.R., 2008, A systematic method for 3D mapping of mangrove forests based on Shuttle Radar Topography Mission elevation data, ICEsat/GLAS waveforms and field data: application to Ciénaga Grande de Santa Marta, Colombia. *Remote Sensing of Environment*, **112**, pp. 2131–2144.

Souza Filho, P.W.M., Farias Martins, E.D.S. and da Costa, F.R., 2006, Using mangroves as a geological indicator of coastal changes in the Bragança macrotidal flat, Brazilian Amazon: a remote sensing data approach. *Ocean and Coastal Management*, **49**, pp. 462–475.

Souza Filho, P.W.M. and Paradella, W.R., 2002, Recognition of the main geobotanical features along the Bragança mangrove coast (Brazilian Amazon Region) from Landsat TM and RADARSAT-1 data. *Wetlands Ecology and Management*, **10**, pp. 123–132.

Souza Filho, P.W.M., Tozzi, H.A.M. and El-Robrini, M., 2003, Geomorphology, land use and environmental hazard in Ajuruteua macrotidal sandy beach, northeastern, Pará, Brazil. *Journal of Coastal Research*, **35**, pp. 580–589.

Sulong, I., Mohd-Lokman, H., Kamaruzzaman, Y., Vijendra, P.R.J. and Chong, Y.S., 2001, Aerial photo-interpretation of mangroves in Tumpat Delta. *The Malaysian Forester*, **64**, pp. 55–65.

Sulong, I., Mohd-Yunus, I., Kasawani, I., Amirudin, A., Mohd-Nazri, M.J. and Izarenah, M.R., 2005, *Avicennia* and *Sonneratia* forest types in Kelantan Delta. In *Proceedings of the KUSTEM 4th Annual Seminar on Sustainability Science and Management*, A. Buhri (Ed.), (Kuala Terengganu, Malaysia: College University of Science and Technology Malaysia).

Terrados, J., Thampanya, U., Srichai, N., Kheowvongsri, P., Geertz-Hansen, O., Boromthanarath, S., Panapitukkul, N. and Duarte, C.M., 1997, The effect of increased sediment accretion on the survival and growth of *Rhizophora apiculata* seedlings. *Estuarine, Coastal and Shelf Science*, **45**, pp. 697–701.

Thu, P.M. and Populus, J., 2007, Status and changes of mangrove forest in Mekong Delta: case study in Tra Vinh, Vietnam. *Estuarine, Coastal and Shelf Science*, **71**, pp. 98–109.

Tomlinson, P.B., 1994, *The Botany of Mangroves* (New York: Cambridge University Press).

Townsend, J., Justice, C., Li, W., Gurney, C. and McManus, J., 1991, Global land cover classification by remote sensing: present capabilities and future possibilities. *Remote Sensing of Environment*, **35**, pp. 243–255.

Twilley, R.R. and Rivera-Monroy, V.H., 2005, Developing performance measures of mangrove wetlands using simulation models of hydrology, nutrient biogeochemistry and community dynamics. *Journal of Coastal Research*, **40**, pp. 79–93.

UNEP-WCMC, 2006, *In the Front Line: Shoreline Protection and other Ecosystem Services from Mangroves and Coral Reefs* (Cambridge, UK: UNEP-WCMC).

Valiela, I., Bowen, J.L. and York, J.K., 2001, Mangrove forests: one of the world's threatened major tropical environments. *Bioscience*, **51**, pp. 807–815.

Walters, B.B., Rönnbäck, P., Kovacs, J., Crona, B., Hussain, S., Badola, R., Primavera, J.H., Barbier, E.B. and Dahdouh-Guebas, F., 2008, Ethnobiology, socio-economics and adaptive management of mangroves: a review. *Aquatic Botany*, **89**, pp. 220–236.

Wang, L., Sousa, W.P., Gong, P. and Biging, G.S., 2004, Comparison of IKONOS and QuickBird images for mapping mangrove species on the Caribbean coast of Panama. *Remote Sensing of Environment*, **91**, pp. 432–440.

Zhang, Y., Wang, W., Wu, Q., Fang, B. and Lin, P., 2006, The growth of *Kandelia candel* seedlings in mangrove habitats of the Zhangjiang estuary in Fujian, China. *Acta Ecologica Sinica*, **26**, pp. 1648–1656.

Zomer, R.J., Trabucco, A. and Ustin, S.L., 2009, Building spectral libraries for wetlands land cover classification and hyperspectral remote sensing. *Journal of Environmental Management*, **90**, pp. 2170–2177.