Biogeosciences Discuss., 10, 2591–2615, 2013
www.biogeosciences-discuss.net/10/2591/2013/
doi:10.5194/bgd-10-2591-2013

Biogeosciences
Discussions
Open Access

Spatial heterogeneity in mangroves assessed by GeoEye-1 satellite data: a case-study in Zhanjiang Mangrove National Nature Reserve (ZMNNR), China

K. Leempoel[1,*], C. Bourgeois[1], J. Zhang[2], J. Wang[2], M. Chen[3], B. Satyaranayana[1,4], J. Bogaert[5], and F. Dahdouh-Guebas[1,4,*]

[1]Laboratory of Systems Ecology and Resource Management, Département de Biologie des Organismes, Faculté des Sciences, Université Libre de Bruxelles-ULB, Avenue Franklin D. Roosevelt 50, 1050 Brussels, Belgium
[2]Administration Bureau of Zhanjiang Mangrove National Nature Reserve (ZMNNR), Huguang township, Mazhang District, Zhanjiang City, 524088 Guangdong Province, China
[3]Guangdong Ocean University (GDOU), Xiashan District, Zhanjiang City, 524025 Guangdong Province, China
[4]Laboratory of Plant Biology and Nature Management, Mangrove Management Group, Vrije Universiteit Brussel-VUB, Pleinlaan 2, 1050 Brussels, Belgium
[5]Biodiversity and Landscape Unit, Université de Liège, Gembloux Agro Bio Tech, Passage des Déportés 2, 5030 Gembloux, Belgium

[*] now at: Laboratory of Geographic Information Systems LASIG, Ecole polytechnique fédérale de Lausanne – EPFL, Station 18, Lausanne, 1015, Switzerland

Received: 20 December 2012 – Accepted: 13 January 2013 – Published: 13 February 2013

Correspondence to: K. Leempoel (kleempoe@ulb.ac.be) and F. Dahdouh-Guebas (fdahdouh@ulb.ac.be)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Mangrove forests, which are declining across the globe mainly because of human intervention, require an evaluation of their past and present status (e.g. areal extent, species-level distribution, etc.) to better implement conservation and management strategies. In this paper, mangrove cover dynamics at Gaoqiao (under the jurisdiction of Zhanjiang Mangrove National Nature Reserve – ZMNNR, P. R. China) were assessed through time using 1967 (Corona KH-4B), 2000 (Landsat ETM+), and 2009 (GeoEye-1) satellite imagery. An important decline in mangrove cover (–36 %) was observed between 1967 and 2009 due to dike construction for agriculture (paddy) and aquaculture practices. Moreover, dike construction prevented mangroves from expanding landward. Although a small increase of mangrove area was observed between 2000 and 2009 (+24 %), the ratio mangrove/aquaculture kept decreasing due to increased aquaculture at the expense of rice culture. In the land-use/cover map based on ground-truth data (5 m × 5 m plot-based tree measurements) (August–September, 2009) and spectral reflectance values (obtained from pansharpened GeoEye-1), both *Bruguiera gymnorrhiza* and small *Aegiceras corniculatum* are distinguishable at 73–100 % accuracy, whereas tall *A. corniculatum* is identifiable at only 53 % due to its mixed vegetation stands close to *B. gymnorrhiza* (classification accuracy: 85 %). Sand proportion in the sediment showed significant differences (Kruskal-Wallis/ANOVA, $P < 0.05$) between the three mangrove classes (*B. gymnorrhiza* and small and tall *A. corniculatum*). Distribution of tall *A. corniculatum* on the convex side of creeks and small *A.corniculatum* on the concave side (with sand) show intriguing patterns of watercourse changes. Overall, the advantage of very high resolution satellite images like GeoEye-1 for mangrove spatial heterogeneity assessment and/or species-level discrimination is well demonstrated, along with the complexity to provide a precise classification for non-dominant species (e.g. *Kandelia obovata*) at Gaoqiao. Despite the limitations such as geometric distortion and single band information, the 42-yr old Corona declassified images

are invaluable for land-use/cover change detections when compared to recent satellite data sets.

1 Introduction

Mangroves provide a wide array of ecological and economic benefits (Dahdouh-Guebas and Koedam, 2006a; Dahdouh-Guebas et al., 2006a; Nagelkerken et al., 2008; Walters et al., 2008) but are now considered as one of the most threatened ecosystems in the world (Duke et al., 2007). The mangroves once fringing ∼ 75 % of tropical coasts (Chapman, 1976) are reduced to about 25 % due to human intervention (Rönnbäck, 1999). Recent estimates on global mangrove cover indicate between 137 760 and 152 000 km^2 of forest in 123 countries and territories (Giri et al., 2011; Spalding et al., 2010). In general, mangrove denudation at the rate of 2.1 % annually is much higher than the loss of tropical forests and coral reefs (Valiela et al., 2001).

This persisting pressure on mangrove ecosystems underlines the demand for mangrove biogeographical data and vegetation maps (produced at species level or areal extent) that can ultimately be used by local authorities for better conservation and management practices (Masso i Aleman et al., 2010). With the difficulty of conventional monitoring techniques in mangrove environments, the data obtained from aerial and/or satellite remote sensing sensors became essential, particularly when analyzing vegetation history and dynamics (Dahdouh-Guebas and Koedam, 2008). The coarse resolution of most remote sensors (e.g. Landsat, SPOT, etc.) provides enough information to discriminate at the species level but only for large and homogeneous stands. In mangrove research, both spatial and spectral resolution need to be high to enable delineation of small patch size of certain species. In this context, the modern sensors like IKONOS, QuickBird and GeoEye-1 are providing Very High Resolution (VHR) images that enable the spotting of voluminous single trees on the ground (Dahdouh-Guebas et al., 2004). Overall, remote sensing, combined with ground-truth observations in a GIS environment, remains time-saving as well as cost-effective for qualitative and quantitative assessment of the mangrove vegetation (Dahdouh-Guebas, 2002; Dahdouh-Guebas et al., 2006b; Satyanarayana et al., 2011; Green et al., 2000).

The main objective of this study is to analyze the spatial heterogeneity of different mangrove species in Gaoqiao (Leizhou Peninsula, China) using ground-truth and GeoEye-1 data. In addition, a diachronic observation of three satellite images (obtained from Corona, Landsat ETM+ and GeoEye-1) enabled the assessment of land cover change within and outside the mangrove over a 42 yr period (1967–2000–2009). In addition, the role of abiotic and biotic factors influencing local mangrove distribution was analyzed.

2 Materials and methods

2.1 Study area

The present study was conducted near Gaoqiao (facing the Gulf of Tongking on Leizhou Peninsula) in Southern China (Fig. 1), where the mangroves are managed by the Zhanjiang Mangrove National Nature Reserve (ZMNNR). The conservation area in Leizhou Peninsula is estimated to be 20 000 ha of which 12 375 ha consist of the actual mangrove vegetation, while the remaining area (7625 ha) consists of mudflats suitable for mangrove propagation (Chen et al., 2009; ZMNNR, 2010). The historic extent of mangroves was estimated at 14 027 ha in 1957 (Gao et al., 2009) and is discontinuous along the coast, mostly because of aquaculture activities. Being the largest mangrove wetland in China (Li and Lee, 1997; Chen and Li, 2007; Chen et al., 2009), its rich biodiversity was indicated by 22 mangrove species (Gao et al., 2009), 82 bird species, 48 gastropods and shellfish species, and 11 fin fish species (Ramsar, 2009). The study zone considered for the present investigation (Gaoqiao) comprises 2000 ha (21°33′55″ N and 109°45′17″ E), represented by seven mangrove species including *Aegiceras corniculatum* (L.) Blanco, *Avicennia marina* (Forssk.) Vierh., *Bruguiera gymnorrhiza* (L.) Lamk., *Excoecaria agallocha* L., *Kandelia obovata* (Sheue), *Rhizophora* *stylosa* Griff., and *Sonneratia apetala* (Buch-Ham). A Ramsar status (no. 1157) was conferred to the whole ZMNNR in January 2002. Plantations in open areas are mostly constituted of *B. gymnorrhiza*.

A northern tropical climate, a mean annual temperature of 23 °C, and a coldest and hottest day in January and July, respectively, characterize the site. The rainfall, with uneven rates of precipitation, lasts from May to September with a mean annual of 1500 mm (Gao et al., 2009). Local diurnal tides have an average depth of 2.53 m and a maximal range of 6.25 m. The mean annual temperature of the seawater is 23.5 °C, the salt content ranges between 20 ‰ and 23 ‰, and the pH is 7.6–7.8 (Liang and Dong, 2004).

2.2 Fieldwork

Data on mangrove vegetation, salinity and sediment characteristics were collected along 9 transects (running perpendicular to the coast/creek line) (Fig. 1) in 5 m × 5 m area plots at 50 m intervals. A total number of 70 plots, located in the main stands of the high tide area, were studied between 6 August and 8 September 2009. In each plot, the vegetation data consisted of tree identification, height (m) and girth G_{130} (the girth at 130 cm height along the stem which was subsequently converted into the diameter – D_{130}) measurements. In the case of trees smaller than 130 cm, girth was measured at 10 cm height (G_{010}). This may introduce a bias but it was encountered mostly for small *A. corniculatum* which forms pure stands and thus is not problematic for the class assignment method used. Based on these measurements, different tree structural parameters such as density (stems m^{-2}), basal area (m^2), relative density (%), dominance (%) (i.e. relative basal area), relative frequency (%), were estimated using standard formulae (Cottam and Curtis, 1956; Cintron and Schaeffer Novelli, 1984; Dahdouh-Guebas and Koedam, 2006b).

The pore-water salinity (from a 20 cm deep hole dug into the ground) was measured at three different (randomly chosen) areas within each plot using a hand refractometer (Atago®, MASTER-S/Millα, Japan). A soil sample (~ 250 g) was collected from each plot and analyzed for its textural content through hydrometer method (Bouyoucos, 1962). Soils were analyzed in the soil laboratory of the Agriculture College in Guangdong Ocean University. The geographical coordinates of all plots were obtained using a handheld global positioning system (Garmin, GPS 60$^{\text{TM}}$, USA).

2.3 Remote sensing

Three satellite images, namely from Corona KH-4B, a recently declassified US military program (dated 17 December 1967) (spatial resolution: 1.8 m), Landsat ETM+ (30 October 2000) (spatial resolution: 14.25 m), and the pansharpened GeoEye-1 (16 October 2009) (spatial resolution: 0.5 m) sensors, were used to identify changes in mangrove and adjacent land-use/cover (e.g. aquaculture) patterns. The panchromatic Corona image was obtained from the United States Geological Survey (USGS) and georeferenced (using ground control points – GCPs against GeoEye-1) in ArcMap v. 9.3.1, whereas others are procured duly after their image rectification.

Both GeoEye-1 and Landsat ETM+ images were subjected to contrast-enhancement (applying Brovey Transformation in ERDAS IMAGINE® v. 8.5) for clear identification of the features. The mangrove and aquaculture areas were delineated from all three satellite images through on-screen digitization and compared. Since no aquaculture ponds were easily recognizable in 1967, the mangrove/aquaculture ratio was calculated only for 2000 and 2009. In the case of recent (2009) data, the pansharpened NDVI (Normalized Difference Vegetation Index) map of GeoEye-1 was added to the pansharpened multispectral image of GeoEye-1 as a band, and supervised classification was carried out using maximum likelihood classification to achieve better accuracy (Green et al., 2000). All aforementioned species were sampled during fieldwork, however only *B. gymnorrhiza* and *A. corniculatum* formed large pure stands. Within mangroves, three different classes, namely *B. gymnorrhiza*, tall *A. corniculatum* and small *A. corniculatum*, were assigned (through the training sets of the signature editor) with five mangrove plots (Table 1) based on dominance (Neukermans et al., 2008; Satyanarayana et al., 2011), and tree height variations. Other classes in the supervised classification included water, sand, open area (i.e. grassland), and aquaculture ponds (in total seven classes including mangroves). Finally, the accuracy assessment of the land-use/cover map was carried out using 113 GCPs scattered across mangrove and non-mangrove areas.

2.4 Correlation between dominant vegetation and abiotic factors

Information on soil texture and pore-water salinity for each plot were regrouped according to the mangrove class of the plot. One-way analysis of variance (ANOVA) was applied to test whether the means of the groups were equal, while Student's *t*-tests (with Bonferroni correction) were used to compare two groups. For some datasets, however, the conditions for using ANOVA were not observed. In such cases, the Kruskal-Wallis test substituted the ANOVA and the Wilcoxon rank sum test replaced the Student's *t*-test. Statistic tests were computed using R (R Development Core Team, 2010).

3 Results

3.1 Mangrove cover dynamics

Between 1967 and 2009, mangrove degradation occurred mainly along the landward sides of Gaoqiao (Fig. 2). The most perceptible change was observed on its south-east corner where a large mangrove stand has been converted into an agricultural (paddy) area and aquaculture ponds, delimited by a new dike. Similarly, mangroves on the north, adjacent to main water channels, where cleared for rice and aquaculture practices. Changes in the river course pattern were also evidenced at some places on the north (Fig. 2). Time-series data revealed that certain paddy fields were replaced by aquaculture ponds between 2000 and 2009. In this context, the dike limits remained the same with only those aquaculture developments on its landward side (Fig. 2). At the same time (i.e. between 2000 and 2009), the mangrove/aquaculture ratio at Gaoqiao decreased despite a small increase of the mangrove cover (192 ha) (Table 2).

3.2 In situ plant and animal diversity

In transects, *A. corniculatum* was the most present species (63/66 plots) followed by *B. gymnorrhiza* (44/66) and *K. obovata* (29/66). The relative density of *A. corniculatum* was also important in most plots (90 % on average) when compared to *B. gymnorrhiza* (7 %) or *K. obovata* (3 %). However, canopy cover is better estimated using dominance (69 % on average for *A. corniculatum*, 22 % for *B. gymnorrhiza*, and 6 % for *K. obovata*) than with relative density, making dominance, in this case, more appropriate for a supervised classification of remote sensing imagery. No understory was observed, except for seedlings. *E. agallocha* was rarely found and clear of vegetation for a 2–3 m circle. Three crab species were identified (*Sesarma bidens* De Haan 1835, *Parasesarma affinis* De Man 1895 and *Uca arcuata* De Haan 1833) which may have a role in nutrient dynamics in soil. Barnacles were observed in high quantity on leaves of *A. corniculatum* and *A. marina* in the vicinity of large watercourses.

3.3 Land-use/cover classification

Spectral reflectance values of the seven land-use/cover classes were separable (Fig. 3). Aquaculture and water classes were distinguished primarily by the blue and NDVI bands. In contrast, differences between open areas and sand classes were found small. For the mangrove classes, although values were similar for the blue and green bands, their differentiation in the red, near infrared (NIR), and NDVI bands was considerably high. The highest value for NDVI was found for *B. gymnorrhiza*, followed by tall *A. corniculatum* and small *A. corniculatum*.

3.4 Mangrove distribution

In agreement with the aforementioned spectral characteristics, the supervised classification (Fig. 4) provided satisfactory results. The interior position of *B. gymnorrhiza* could be noticed as a single patch with few smaller ones close by. Tall *A. corniculatum* were present in the northern part of the study zone and along the major water channels, whereas small *A. corniculatum* were mostly distributed in the peripheral margins and close to open areas. While aquaculture, open area and small *A. corniculatum* classes are fully accurate, others such as water and dike/sand, including two mangrove classes (i.e. tall *A. corniculatum* and *B. gymnorrhiza*), were less well delineated. Tall *A.corniculatum* had a low accuracy owing to the fact that nearly seven plots were misclassified from *B. gymnorrhiza* to tall *A. corniculatum* (Table 3).

The sediments at Gaoqiao were predominantly of clayey-silt in nature (Table 4). Sand content was found higher in small *A. corniculatum* sites. In contrast, clay and silt content as well as salinity varied less and remained insignificant among classes.

4 Discussion

4.1 Mangrove cover changes

Mangrove degradation has been reported substantially since increasing pressure of paddy cultivation is exercised. Mangroves lost two thirds of their original cover during the last 50 yr, especially between 1960 and 1970s, due to deforestation, land reclamation for aquaculture or tourist resorts and urbanization activities (Li and Lee, 1997; Chen et al., 2009; Chen and Ye, 2011; Spalding et al., 2010; Ren et al., 2008). At Gaoqiao, the loss of mangroves in a 42-yr period (by 35.9 % between 1967 and 2009) is due to both agriculture (paddy) and aquaculture practices for shrimps and crabs (Fig. 2). After acquiring the Ramsar site of international importance, the dike which was constructed previously did not change but the type of land-use inside the dike area was shifted from agriculture fields to aquaculture ponds. Nevertheless, the negative impacts of aquaculture on mangrove vegetation and the booming of this industry during the 1980–1990s for economic reasons are well known (Rönnbäck, 1999; Dahdouh-Guebas et al., 2002; Primavera, 1998; Hamilton et al., 1989). In fact, in order to filter the nitrogen and phosphorus loads within mangrove ecosystem, the minimum sustainable ratio for mangrove and aquaculture areas was proposed at 2–22 ha of forest per ha of aquaculture (Costa-Pierce, 2002; Primavera et al., 2007; Robertson and Phillips, 1995). In the case of Gaoqiao, the mangrove/aquaculture ratio is below 1 and decreasing (Table 2) due to aquaculture extension. In addition, the actual mangrove cover (i.e. 775 ha) we estimated using 2009 GeoEye-1 satellite imagery was found to be less than the area (i.e. 2000 ha) projected by (Ramsar, 2009).

4.2 Land-use/cover classification

On one hand, the single (panchromatic) band information in Corona image did not support both unsupervised and supervised classifications. On the other hand in the GeoEye-1 image, in addition to *B. gymnorrhiza* and both tall and small *A. corniculatum* stands, we tried to provide supervised classes for *S. apetala*, *K. obovata* and the mixed mangrove stands of *A. corniculatum*-*A. marina* sampled in the southern transect. However, due to their lower dominance and limited coverage, the accuracy of these classes in the confusion matrices was poor and their distribution in the classified maps unrealistic, their where thus suppressed. Overall, the importance of NIR and NDVI bands for (dominant) mangrove species discrimination at Gaoqiao is shown (Fig. 3). Despite of the same species, a clear-cut difference in the NDVI and blue reflectance between tall and small sites of *A. corniculatum* is observed. This could be due to both variation in their greenness/biomass and to the difference in dominance of *B. gymnorrhiza* in tall *A. corniculatum* class (18 %) compared to small *A. corniculatum* class (3 %). This latter hypothesis may also explain the misclassified plots of tall *A. corniculatum* in the *B. gymnorrhiza* class (Table 3).

4.3 Current mangrove distribution

In addition to previous observations made (Tam et al., 1997; Ye et al., 2005; He et al., 2007; Ren et al., 2008; Gao et al., 2009; Ramsar, 2009) (from the mangrove sites close to Hong Kong, Yingluo Bay and Leizhou Bay), the present study highlights the dominance of *A. corniculatum*, along with *B. gymnorrhiza*, in the vicinity. This could be due to the fact that different patches/areas (even in the same region) support different species in relation to their geographic location (sea or landward), freshwater runoff and the extent of inundation.

Species like *B. gymnorrhiza* are usually characteristic of interior sites away from main flooding channels (Ye et al., 2003; Satyanarayana et al., 2010), and this might be the reason for its abundance inside the forest (Fig. 4). *K. obovata* is more tolerant to water logging than *B. gymnorrhiza* (Ye et al., 2003), and here was found along small permanent watercourses and waterlogged areas. In fact, water channels in the study zone (vectors added in Fig. 4) are often boarded by the tall *A. corniculatum* class and it is exactly in these areas that most *K. obovata* individuals were found. Open areas are the last areas to be inundated, as was observed in situ and this might be related tot the very low density of propagules observed in these areas, indicating their limited transport by water.

The intriguing pattern of distribution by tall *A. corniculatum* and small *A. corniculatum* observed along the convex and concave creek sides respectively (Fig. 4) is likely to correspond to accretion and erosion zones (Fig. 2), suggesting an important role of currents on the dynamics of habitats and vegetation regeneration The low salinity (8.5 ‰) in the high tide area of Gaoqiao could be due to sampling during the rainy season but also to constant freshwater input from Ximi and Qaoqiao rivers flowing into Yingluo Bay. Therefore, pioneer mangrove species like *A. marina*, which occupies the frontier edge of the tidal flat (= low tidal flats) in China (Ye et al., 2005; Ren et al., 2011), was found essentially in the most southern transect. However, salinity in Mangroves close to Gaoqiao has been measured by (Liang and Dong, 2004) at 23 ‰. This important difference of measurement could explain why no significant correlation was found with salinity. An important point is the observation of old *A. marina* sites in the northern part of the study area, which may reflect an ancient disjunct zonation of this species restrained by parasitism (such as barnacles) or by man.

Although mangrove associate species (e.g. *Heritiera littoralis*, *Cerbera manghas*, etc.) were also reported, they are poorly represented in the forest itself. In the mangroves, they occupy only the raised areas (*Ipomoea pescapreae*), where the rate of flooding is likely very small, and the side of the dikes, where they are dominant. They also colonize, mixed with some mangrove species (*Aegiceras*, *Acrostichum*, *Excoecaria*), the banks of rivers and small streams inland that supply the rice fields. This abrupt transition in zonation along the land-sea gradient inside the mangroves and the presence of landward mangroves species both testify to a restriction of mangrove habitats after construction of this artificial barrier.

5 Conclusions

The applicability of very high resolution imagery such as GeoEye-1 for mangrove spatial heterogeneity assessment and species-level discrimination, along with its difficulty to provide a precise classification for non-dominant species, is demonstrated in the present study. If the mangrove stand size is considerable, it is possible to identify the same species (e.g. *A. corniculatum*) using GeoEye-1 NIR imagery even when present with different tree heights. In addition, the use of 42-yr old Corona satellite imagery, compared to newly derived satellite data (e.g. GeoEye-1), allowed studying mangrove and other land-use/cover dynamics. While mangrove destruction between 1967 and 2000 was associated with the land reclamation for agriculture and aquaculture practices, conversion of agricultural zones into aquaculture ponds, between 2000 and 2009, was also responsible for mangrove/aquaculture ratio decrease. The mangrove species distribution spreading over 775 ha at Gaoqiao appeared to be determined largely by its geographic (sea or landward) location. The overwhelming dominance of *A. corniculatum* (which is known as “river mangrove”) coincides with strong freshwater input in the vicinity. However, no environmental factors measured were able to discriminate *B. gymnorrhiza* and Tall *A. corniculatum* stands.

Knowing the current mangrove distribution at Gaoqiao, we suggest that further studies (involving both remote sensing and ground-truth assessments) should be focused on other mangrove patches in south of our study zone (Yingluo Bay) and other mangrove areas in ZMNNR (i.e. Beitan, Techeng, Taiping, Yucheng, Qishui, He' an and Tuli) for a complete monitoring and more efficient management.

Acknowledgements. We wish to express our sincere gratitude to the authorities at F.R.S.-F.N.R.S. Fonds de la Recherche Scientifique, Brussels, Belgium, for funding this project. BS is supported by the Belgian National Science Foundation (# F6/15 – MCF/OL Convention no 2.4532.09). Special thanks are due to all people who have helped us during the fieldwork, especially the students from the Guangdong Ocean University.

References

Bouyoucos, G. J.: Hydrometer method improved for making particle size analysis of soils, Agron. J., 54, 464–465, 1962.

Chapman, V. J.: Mangrove Vegetation, Strauss and Cramer, Vaduz, 499 pp., 1976.

Chen, G. C. and Ye, Y.: Restoration of *Aegiceras corniculatum* mangroves in Jiulongjiang Estuary changed macro-benthic faunal community, Ecol. Eng., 37, 224–228, doi:10.1016/j.ecoleng.2010.10.003, 2011.

Chen, L. Z., Wang, W. Q., Zhang, Y. H., and Lin, G. H.: Recent progresses in mangrove conservation, restoration and research in China, J. Plant. Ecol.-UK, 2, 45–54, doi:10.1093/Jpe/Rtp009, 2009.

Chen, R. and Li, X.: DEM compression based on integer wavelet transform, P. Soc. Photo.-Opt. Ins., 10, 133–136, doi:10.1007/s11806-007-0038-8, 2007.

Cintron, G. and Schaeffer Novelli, Y.: Methods for Studying Mangrove Structure, UNESCO, Paris, International, 1984.

Costa-Pierce, B. A.: Ecological aquaculture: the evolution of the blue revolution, in: Blackwell Science Ltd, 163–164, 2002.

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

Dahdouh-Guebas, F.: The use of remote sensing and GIS in the sustainable management of tropical coastal ecosystems, Environ. Dev. Sust., 4, 93–112, doi:10.1023/a:1020887204285, 2002.

Dahdouh-Guebas, F. and Koedam, N.: Coastal vegetation and the Asian tsunami, Science, 311, 37–37, 2006a.

Dahdouh-Guebas, F. and Koedam, N.: 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 plus protocol, Forest Ecol. Manag., 228, 1–18, doi:10.1016/j.foreco.2005.10.076, 2006b.

Dahdouh-Guebas, F. and Koedam, N.: Long-term retrospection on mangrove development using transdisciplinary approaches: a review, Aquat. Bot., 89, 80–92, doi:10.1016/j.aquabot.2008.03.012, 2008.

Dahdouh-Guebas, F., Van Hiel, E., Chan, J., Jayatissa, L., and Koedam, N.: Qualitative distinction of congeneric and introgressive mangrove species in mixed patchy forest assemblages using high spatial resolution remotely sensed imagery (IKONOS), Syst. Biodivers., 2, 113–119, 2004.

Dahdouh-Guebas, F., Zetterstrom, T., Ronnback, P., Troell, M., Wickramasinghe, A., and Koedam, N.: Recent changes in land-use in the Pambala-Chilaw Lagoon Complex (Sri Lanka) investigated using remote sensing and GIS: conservation of mangroves vs. development of shrimp farming, Environ. Dev. Sust., 4, 185–200, 2002.

Dahdouh-Guebas, F., Verheyden, A., Kairo, J. G., Jayatissa, L. P., and Koedam, N.: Capacity building in tropical coastal resource monitoring in developing countries: a re-appreciation of the oldest remote sensing method, Int. J. Sust. Dev. World, 13, 62–76, 2006.

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.: A world without mangroves?, Science, 317, 41–42, 2007.

Gao, X.-M., Han, W.-D., and Liu, S.-Q.: The mangrove and its conservation in Leizhou Peninsula, China, J. Forest. Res., 20, 174–178, doi:10.1007/s11676-009-0032-0, 2009.

Giri, C., Ochieng, E., Tieszen, L. L., Zhu, Z., Singh, A., Loveland, T., Masek, J., and Duke, N.: Status and distribution of mangrove forests of the world using earth observation satellite data, Global Ecol. Biogeogr., 20, 154–159, doi:10.1111/j.1466-8238.2010.00584.x, 2011.

Green, E. P., Mumby, P. J., Edwards, A. J., and Clark, C. D.: Remote Sensing Handbook for tropical Coastal management, Coastal Management Sourcebooks 3, 316, 2000.

Hamilton, L., Dixon, J., and Miller, G.: Mangroves: an undervalued resource of the land and the sea, Ocean Yearbook, 8, 254–288, 1989.

He, B. Y., Lai, T. H., Fan, H. Q., Wang, W. Q., and Zheng, H. L.: Comparison of flooding-tolerance in four mangrove species in a diurnal tidal zone in the Beibu Gulf, Estuar. Coast. Shelf S., 74, 254–262, doi:10.1016/j.ecss.2007.04.018, 2007.

Li, M. S. and Lee, S. Y.: Mangroves of China: a brief review, Forest Ecol. Manag., 96, 241–259, 1997.

Liang, S. C. and Dong, M.: Spatial heterogeneity of population structure of the mangrove Bruguiera gymnorrhiza at Yingluo Bay, South-China Coast, Acta Bot. Sin., 46, 1015–1024, 2004.

Masso i Aleman, S., Bourgeois, C., Appeltans, W., Vanhoorne, B., De Hauwere, N., Stoffelen, P., Heughebaert, A., and Dahdouh-Guebas, F.: The "Mangrove Reference Database and Herbarium", Plant Ecol. Evol., 143, 225–232, doi:10.5091/plecevo.2010.439, 2010.

Nagelkerken, I., Blaber, S. J. M., Bouillon, S., Green, P., Haywood, M., Kirton, L. G., Meynecke, J. O., Pawlik, J., Penrose, H. M., Sasekumar, A., and Somerfield, P. J.: The habitat function of mangroves for terrestrial and marine fauna: a review, Aquat. Bot., 89, 155–185, doi:10.1016/j.aquabot.2007.12.007, 2008.

Neukermans, G., Dahdouh-Guebas, F., Kairo, J. G., and Koedam, N.: Mangrove species and stand mapping in GAzi bay (Kenya) using Quickbird satellite imagery, J. Spat. Sci., 53, 75–86, 2008.

Primavera, J. H.: Tropical shrimp farming and its sustainability, in: Tropical Mariculture, edited by: Diego, A. P. S., 257–289, 1998.

Primavera, J. H., Altamirano, J. P., Lebata, M. J. H. L., delos Reyes, A. A., and Pitogo, C. L.: Mangroves and shrimp pond culture effluents in Aklan, Panay Is., Central Philippines, B. Mar. Sci., 80, 795–804, 2007.

Ramsar Sites information Service: available at: www.wetlands.org/rsis/, last access: 3 February 2010, 2009.

Ren, H., Jian, S. G., Lu, H. F., Zhang, Q. M., Shen, W. J., Han, W. D., Yin, Z. Y., and Guo, Q. F.: Restoration of mangrove plantations and colonisation by native species in Leizhou bay, South China, Ecol. Res., 23, 401–407, doi:10.1007/s11284-007-0393-9, 2008.

Ren, H., Wu, X. M., Ning, T. Z., Huang, G., Wang, J., Jian, S. G., and Lu, H. F.: Wetland changes and mangrove restoration planning in Shenzhen Bay, Southern China, Landsc. Ecol. Eng., 7, 241–250, doi:10.1007/s11355-010-0126-z, 2011.

Robertson, A. I. and Phillips, M. J.: Mangroves as filters of shrimp pond effluent: predictions and biochemical research needs, Hydrobiologia, 295, 649–666, 1995.

Rönnbäck, P.: The ecological basis for economic value of seafood production supported by mangrove ecosystems, Ecol. Econ., 29, 235–252, doi:10.1016/s0921-8009(99)00016-6, 1999.

Satyanarayana, B., Idris, I. F., Mohamad, K. A., Husain, M. L., Shazili, N. A. M., and Dahdouh-Guebas, F.: Mangrove species distribution and abundance in relation to local environmental settings: a case-study at Tumpat, Kelantan Delta, east coast of peninsular Malaysia, Bot. Mar., 53, 79–88, doi:10.1515/Bot.2010.006, 2010.

Satyanarayana, B., Koedam, N., De Smet, K., Di Nitto, D., Bauwens, M., Jayatissa, L. P., Cannicci, S., and Dahdouh-Guebas, F.: Long-term mangrove forest development in Sri Lanka: early predictions evaluated against outcomes using VHR remote sensing and VHR ground-truth data, Mar. Ecol. Progr. S., 443, 51–63, doi:10.3354/meps09397, 2011.

Spalding, M., Kainuma, M., and Collins, L.: World Atlas of Mangroves, Earthscan Publications Ltd., UK, 319 pp., 2010.

Tam, N. F. Y., Wong, Y. S., Lu, C. Y., and Berry, R.: Mapping and characterization of mangrove plant communities in Hong Kong, Hydrobiologia, 352, 25–37, 1997.

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

Walters, B. B., Rönnbäck, P., Kovacs, J. M., Crona, B., Hussain, S. A., Badola, R., Primavera, J. H., Barbier, E., and Dahdouh-Guebas, F.: Ethnobiology, socio-economics and management of mangrove forests: a review, Aquat. Bot., 89, 220–236, doi:10.1016/j.aquabot.2008.02.009, 2008.

Ye, Y., Tam, N. F. Y., Wong, Y. S., and Lu, C. Y.: Growth and physiological responses of two mangrove species (*Bruguiera gymnorrhiza* and *Kandelia candel*) to waterlogging, Environ. Exp. Bot., 49, 209–221, 2003.

Ye, Y., Tam, N. F. Y., Lu, C. Y., and Wong, Y. S.: Effects of salinity on germination, seedling growth and physiology of three salt-secreting mangrove species, Aquat. Bot., 83, 193–205, doi:10.1016/j.aquabot.2005.06.006, 2005.

Zhanjiang Mangrove National Nature Reserve: available at: http://www.zjmangrove.org/en/about.asp, last access: 1. August 2010, 2010.

Table 1. Relative dominance and average height of *A. corniculatum* and *B. gymnorrhiza* in sample plots used to define mangrove classes for supervised classification (maximum likelihood classification) in ZMNNR, Gaoqiao, China.

		Relative dominance (%)		
	Plot ID	*Aegiceras corniculatum*	*Bruguiera gymnorrhiza*	Tree height (cm)
Bruguiera gymnorrhiza	A07	0.00	0.96	304
	B02	0.04	0.96	244
	B06	0.01	0.95	234
	D01	0.04	0.92	332
	A05	0.06	0.89	302
Aegiceras corniculatum (tall)	C05	0.80	0.20	313
	C03	0.62	0.38	311
	D08	1.00	0.00	308
	C04	0.68	0.29	292
	B07	0.68	0.32	265
Aegiceras corniculatum (small)	F04	0.80	0.06	89
	B08	1.00	0.00	83
	D06	1.00	0.00	74
	AE04	1.00	0.00	66
	F05	1.00	0.00	61

Table 2. Extent, difference and mangrove/aquaculture ratio of mangrove and aquaculture areas (1967–2000–2009) in ZMNNR, Gaoqiao, China.

Year	Aquaculture area (ha)	Difference with 2000	Mangrove area (ha)	Difference with 1967	Mangrove/Aquaculture ratio
1967	–	–	1209	–	–
2000	707.2	–	583	−51.8 %	0.82
2009	994.1	28.9 %	775	−35.9 %	0.78

Table 3. Accuracy assessment of the classified land-use/cover map of Gaoqiao, China.

Class	Aquaculture	Water	Sand	Open area	Small *A. corniculatum*	Tall *A. corniculatum*	*B. gymnorrhiza*	Row total	Producer's accuracy (%)
Aquaculture	**24**	0	0	0	0	0	0	24	100
Water	1	**20**	0	0	0	0	0	21	95
Sand	0	0	**33**	2	0	0	0	23	91
Open area	0	0	0	**8**	0	0	0	8	100
Small *A. corniculatum*	0	0	0	0	**11**	0	0	11	100
Tall *A. corniculatum*	0	0	0	0	2	**10**	7	19	53
B. gymnorrhiza	0	0	0	0	0	4	**11**	15	73
Column total	25	20	33	10	13	14	18	**133**	
User's accuracy (%)	96	100	100	80	85	71	61		85
						$\kappa = 0.86$		$\tau = 0.86$	

Table 4. Average value and standard deviation of soil variables for the three mangrove classes at ZMNNR, Gaoqiao, China. Statistical analysis indic[illegible]g significance (P value) levels (α = 0.05 with Bonferroni correction for multiple test = 0.017). Significant results are highlighted in bold face.

	Sand (%)		Silt (%)		Clay (%)		Average salinity (‰)	
B. gymnorrhiza	0.22 ± 0.15		0.31 ± 0.13		0.47 ± 0.18		6.2 ± 4.5	
Tall *A. corniculatum*	0.23 ± 0.15		0.35 ± 0.13		0.42 ± 0.14		8.3 ± 5.1	
Small *A. corniculatum*	0.38 ± 0.16		0.31 ± 0.15		0.32 ± 0.14		9.4 ± 5.7	
Analysis of variance	Kruskal-Wallis	df	Kruskal-Wallis	df	Kruskal-Wallis	df	Kruskal-Wallis	df
	0.009	55	0.2791	55	**0.0405**	55	0.1861	53
Average of the difference	Wilcoxon		Wilcoxon		Wilcoxon		Wilcoxon	
B. gymnorrhiza = Tall *A. corniculatum*	0.5823		–		0.3025		–	
B. gymnorrhiza = Small *A. corniculatum*	0.0184		–		0.0343		–	
Tall *A. corniculatum* = Small *A. corniculatum*	**0.0046**		–		0.0381		–	

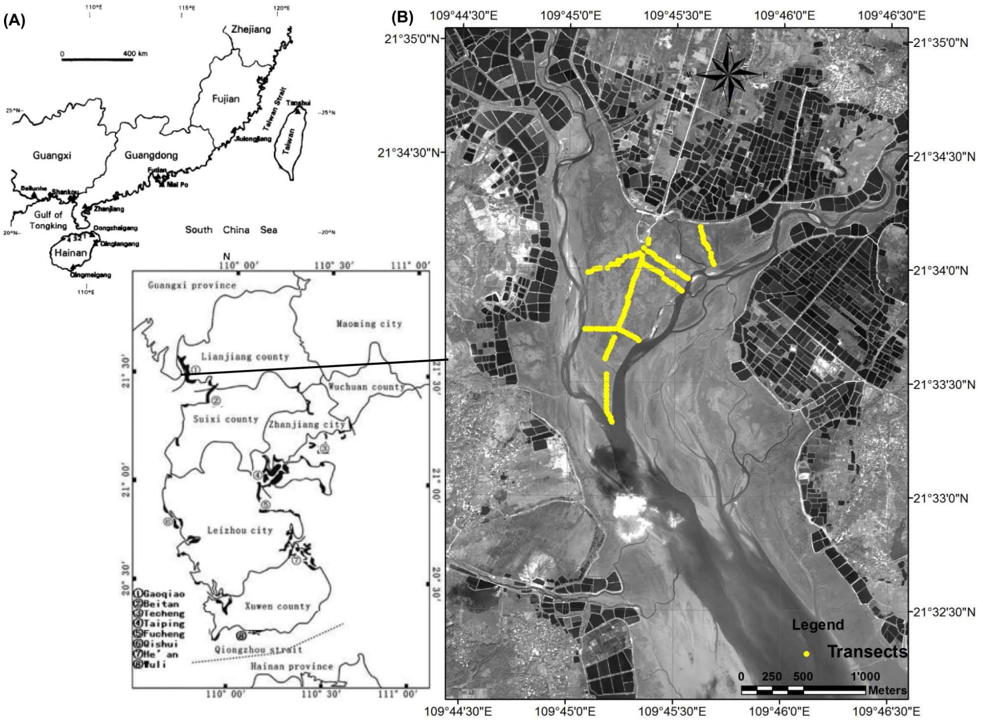

Fig. 1. (A) The eight mangrove areas found in Leizhou Peninsula of southern China, and **(B)** pansharpened multispectral GeoEye-1 satellite (2009) imagery showing Gaoqiao mangrove cover facing the Gulf of Tongking. The ground inventory has been carried out in transects (yellow lines) running perpendicular to the coast/creek line.

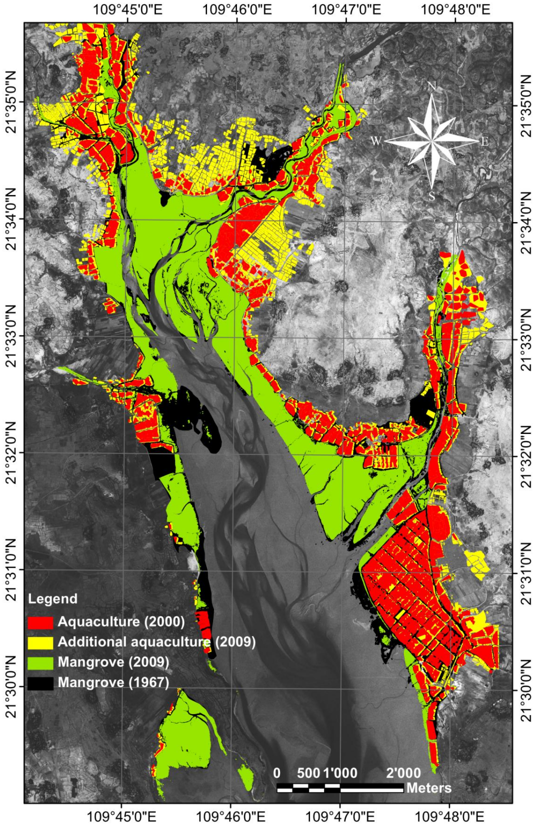

Fig. 2. Changes in the extent of Gaoqiao mangrove cover observed from 1967 (Corona) and 2009 (GeoEye-1) satellite data and expansion of aquaculture ponds observed from 2000 (Landsat) and 2009 (GeoEye-1) satellite data (background: 1967 Corona imagery).

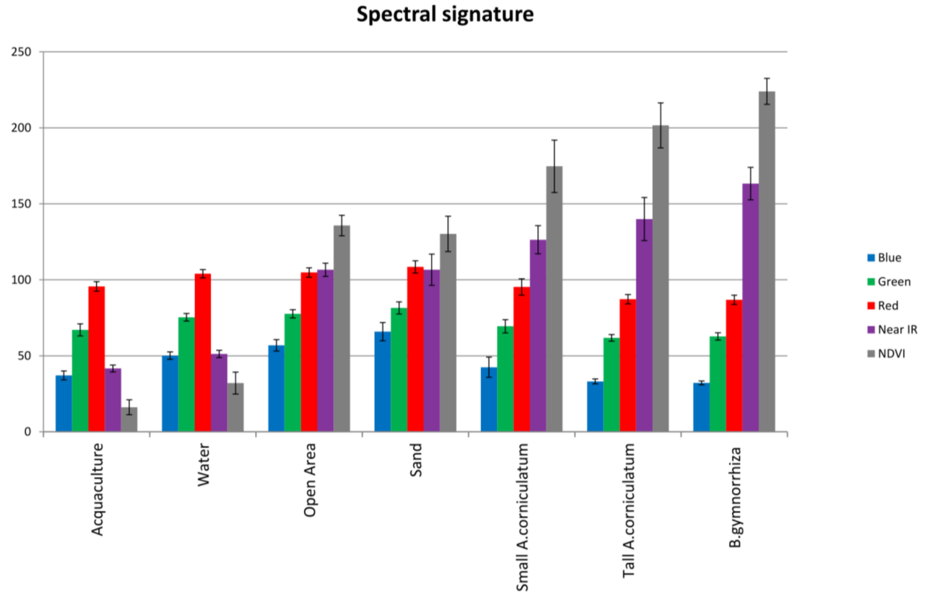

Fig. 3. Spectral reflectance of the land-use/cover classes used for supervised classification of Gaoqiao mangrove and adjacent areas.

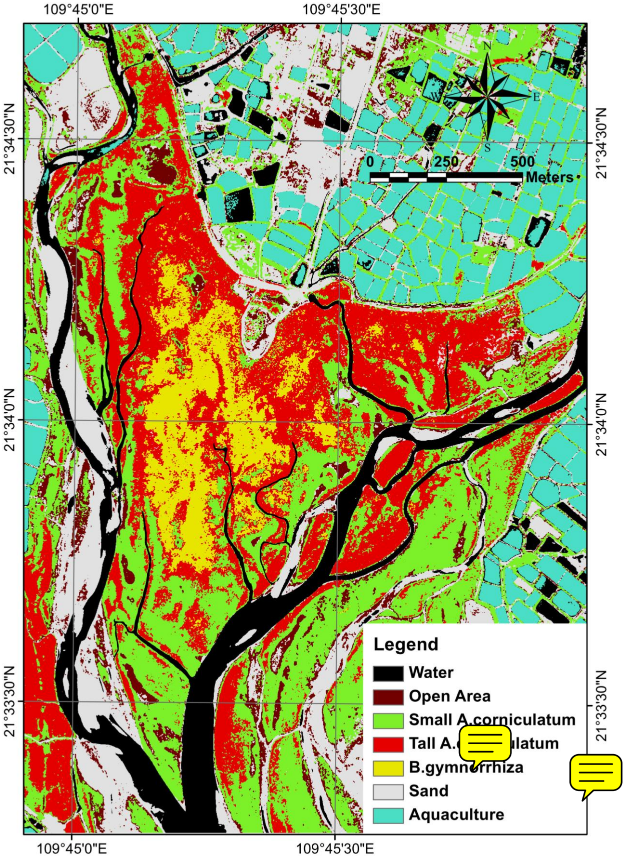

Fig. 4. Land-use/cover supervised classification of Gaoqiao based on the pansharpened multispectral GeoEye-1 (2009) image, and on the fieldwork transects shown in Fig. 1.