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Depletion of the mangroves of Continental Asia

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Abstract

The mangroves located around the Bay of Bengal and along the coast of South China Sea are of special interest for many reasons. This coastline receives three major tropical rivers (Ganges, Irrawaddy, Mekong) and it has the world's largest mangrove stands in a single block (the Sunderbans). The contrasted climatic conditions from sub-arid (southeastern India), to moist (coastal Cambodia), and the extreme diversity of human impacts in one of the world's highest population densities (West Bengal in India and Bangladesh), have created a mosaic of mangrove types that are floristically rich and with different histories, different ecological frameworks and distinct evolutionary trends.

For the first time, we draw together remote sensing data along with essential structural and physiognomic parameters of mangrove forest areas. We have devised a sufficiently accurate coastal mapping methodology providing statistics on the actual areal extent of mangrove types and sub-types, both at local and continental scales. Some results are entirely new, and others provide comparison with existing data. The exact extent of mangroves in Myanmar was previously unknown. Using remote sensing we also demonstrate the magnitude of the ongoing deforestation in this country. The current location and status of mangrove forests in the affected area are described using the methodology which is also being applied in other sites around the world.

Introduction

Covering less than 3% of the world's tropical forests (about 180,000 km^2; Spalding et al., 1997) and containing a limited number of woody species (about 70 species of trees and shrubs throughout the world's tropics; IUCN, 1983; Duke et al., 1998), mangroves play a vital role for many coastal peoples and their countries especially in Asia. They are also under immense threat owing to very strong demographic pressure, large scale timber exploitation and alterations of freshwater inflows by various upstream activities in catchment areas.

Mangrove ecosystems have almost disappeared along the east coast of India, except in Bengal, and they have been depleted in most coastal areas in Thailand, Vietnam, The Philippines and many other Asian countries. With the exception of coastal Myanmar (formerly Burma, Figure 1) where ecological studies are scanty, an important collection of papers and books is now available related to the ecology of the mangroves of Asia at various ecological scales (Rao, 1987; Blasco and Aizpuru, 2000).

The importance of remote sensing technology to coastal ecosystems studies is unquestionable due to the scale of such work (nearly 10,000 km of coastline) and due to the extremely difficult local conditions especially in countries like Myanmar where access by the international scientific community is practically impossible.

The existing strong connections between remote sensing technology and mangrove ecology illustrate the need for a better integration with other biological data of dominant organisms – especially phenological stages of conspicuous woody taxa and the distribution of rare species of trees – for which structural and ecological changes can be observed from space.

This study is an attempt to produce a cartographic assessment of mangrove ecosystems of tropical continental Asia, from West Bengal in India to Ho Chi

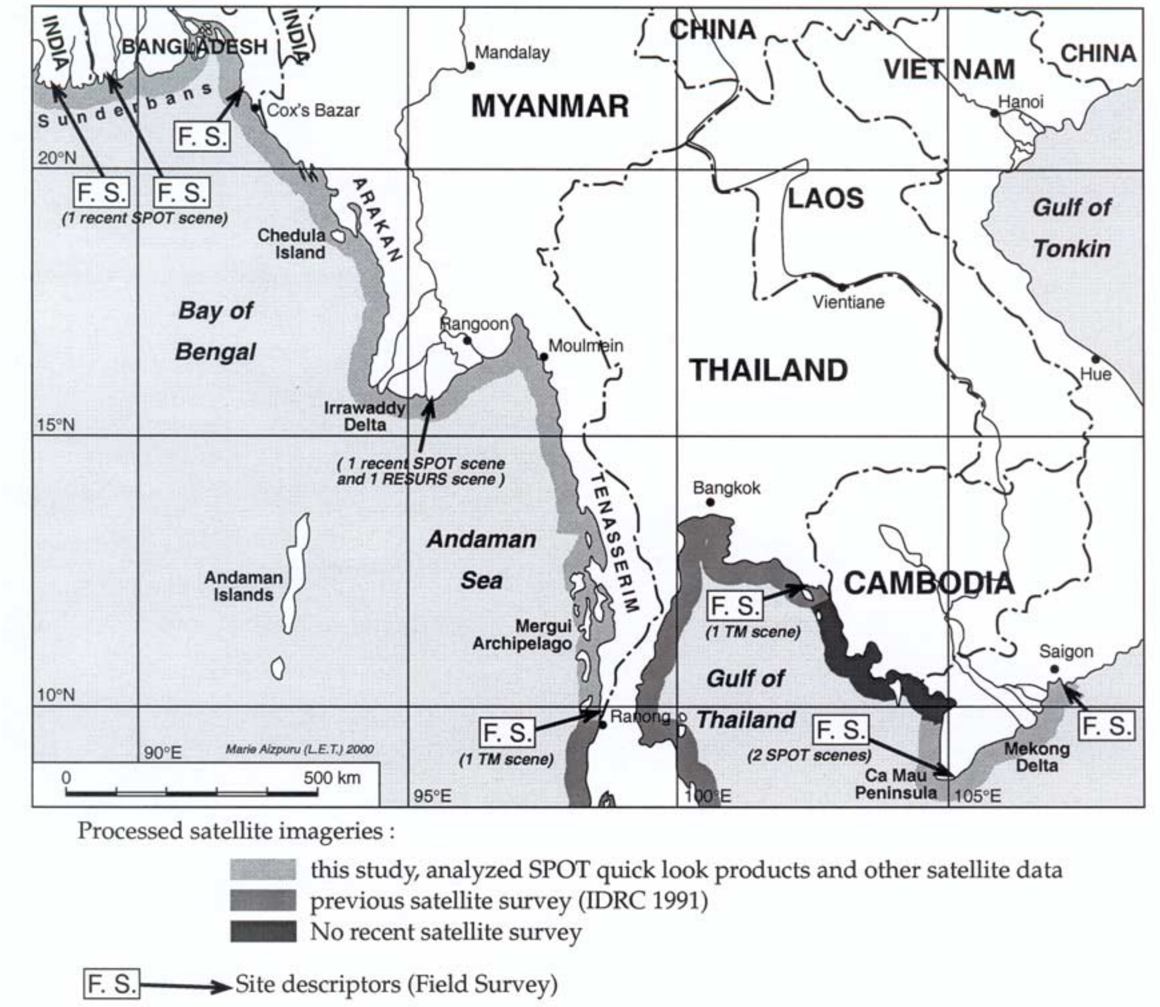

Figure 1. A sketch of the studied locations.

Minh in Vietnam. This part of the world is unique in many ways. It has the world's largest mangroves in a single block, at the top of the Bay of Bengal (about 6,900 km^2), the world's largest coastal afforestation programmes in Bangladesh and Vietnam and a unique case of mass military use of herbicides on a natural ecosystem at the mouths of the Mekong River.

This long stretch of moist tropical coastland receives three major tropical rivers described in Table 1. In theory, these board climatic, geomorphological and hydrological conditions should be extremely favourable for the development of luxuriant mangroves in the deltas as well as in creeks and bays of the region. In practice they are receding at an alarming rate.

In this paper, a new assessment of the mangroves of tropical continental Asia is given, supported by an updated cartographic process. The present status of important mangrove species, including endangered species, is also partly achieved from remote sensing.

Data and methods of estimating the extent and evolution of mangroves

Satellite products

Remote sensing technology becomes operational when two basic conditions are fulfilled: easy access to the data, at a reasonable price. Taking into account the relatively small size of mangrove ecosystems and their narrowness in coastal fringes, only high resolution satellite products can be used (SPOT-HRV,

Table 1. Characteristics of major rivers of the study area.

	Mean tidal amplitude	Average flow (m^3/s)	Annual sediment discharge (tons/years)	Catchment area (km^2)	deltaic area (km^2)
Ganges	5 m	35,000	700 million	1.6 million	100,000
Irrawaddy	3 m	12,000	300 million	320,000	20,000
Mekong	3 m	14,000	90 million	500,000	90,000

SPOT-HRVIR, Landsat TM, IRS etc.). The present work depends on two biophysical assumptions:

1. Mangrove stands, like other humid tropical forest types, can be detected from space using optical sensor imagery with sufficient accuracy concerning their limits and density with high resolution instruments (Blasco et al., 1997; Hill, 1999). This ground resolution (20 to 30 m), even degraded by resampling methods, remains extremely useful even in the form of 'quick look' data obtained in the following channels of SPOT 1, 2 and 3:

XS1 – 0.50–0.59 μm
XS2 – 0.61–0.68 μm
XS3 – 0.79–0.89 μm

The short-wave middle-infra-red is now available on SPOT 4 (XS4 – 1.50–1.75 μm). All 'quick look' data are available on the web site http://www.spotimage.fr. These digital data are produced following 3 steps: (1) raw data, with spatial resolution of 20m, is degraded by extracting 1 pixel out of 6, on each line, and one line out of 6. A 500 by 500 pixels is obtained; (2) then, a 1A level radiometric correction is applied (detectors equalization); (3) a colour composite may be produced in order to locate possible clouds and make sure the quality of the image matches with the scientist's requirements.

2. Degraded stages or conversion to other uses can also be detected, to some extent, with the same 'quick look' data.

However, the use of 'quick look' data through a visual image interpretation (here about 150 scenes obtained almost without delay) may correspond with the relevant ground features if a new classification system compatible with this type of data and with the aim of the study is set up.

As it is almost impossible to rely upon a classification exclusively based on 'quick look' products we compared and cross-validated the results obtained with recent genuine SPOT and RESURS data, especially in critical areas such as the extensive deltas of the Ganges, the Irrawaddy and the Mekong where almost all mangrove types are found.

This material included:

– for the Gangetic deltaic complex, one SPOT HRV image (K234/J306 dated 11 March 1999 – SPOT1).
– for the Irrawaddy delta, one RESURS image and one SPOT HRV image (K251/J318 dated 17 March 1999 – SPOT1).
– for the Mekong delta, two SPOT HRV images (K274/J333 dated 18 Dec. 1997 – SPOT1 – and K274/J332 dated 22 Jan. 1998 – SPOT2).

SPOT HRV reflectance data are generally 'bimodal' in spectral character, with useful and often sufficient information provided by wavebands XS2 (red) and XS3 (near infra-red) for vegetation analysis. Best classification results were obtained using a visual interpretation (delineation of conspicuous homogeneous units) complemented by a supervised digital classification previously tested and validated in various mangrove types (Rasolofoharinoro et al., 1998).

Field survey has been conducted in twenty five check plots (Figure 1) mainly in the Sunderbans and in the Mekong delta, were the maximum of structural and floristic diversities are found. Each ecosystem has been primarily characterized according to its density, size of trees and dominant species composition which determine the spectral responses in visible and near-infrared wavebands.

A new classification system

Taking into account the relatively modest technical performance of 'quick look' data the proposed classification system has to be very simple. Nevertheless it has to fulfil the purpose of giving a clear and indisputable status of the mangroves of the coastline. As it is the case with natural or degraded ecosystems, exact boundaries are often difficult to define and their limits can only be approximated.

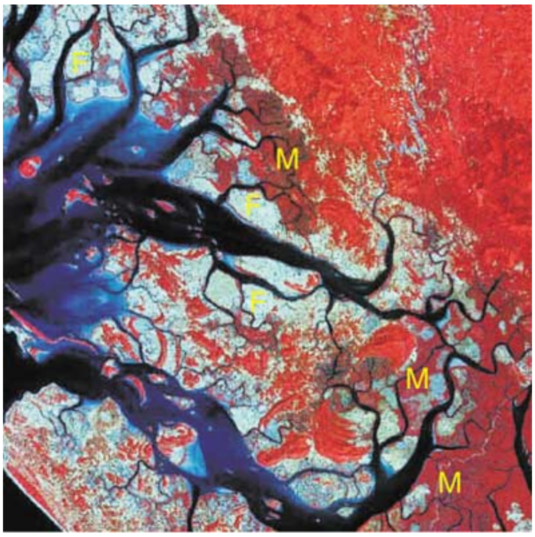

Figure 2. SPOT 2 'quick look' (KJ 246/311) dated 13/01/99 Large scale deforestation is in progress in Myanmar (near Ramree Island, see Figure 4). Almost all white-greenish patches correspond to clear-felled mangroves (F). Remaining mangrove forests are in dark-red (M).

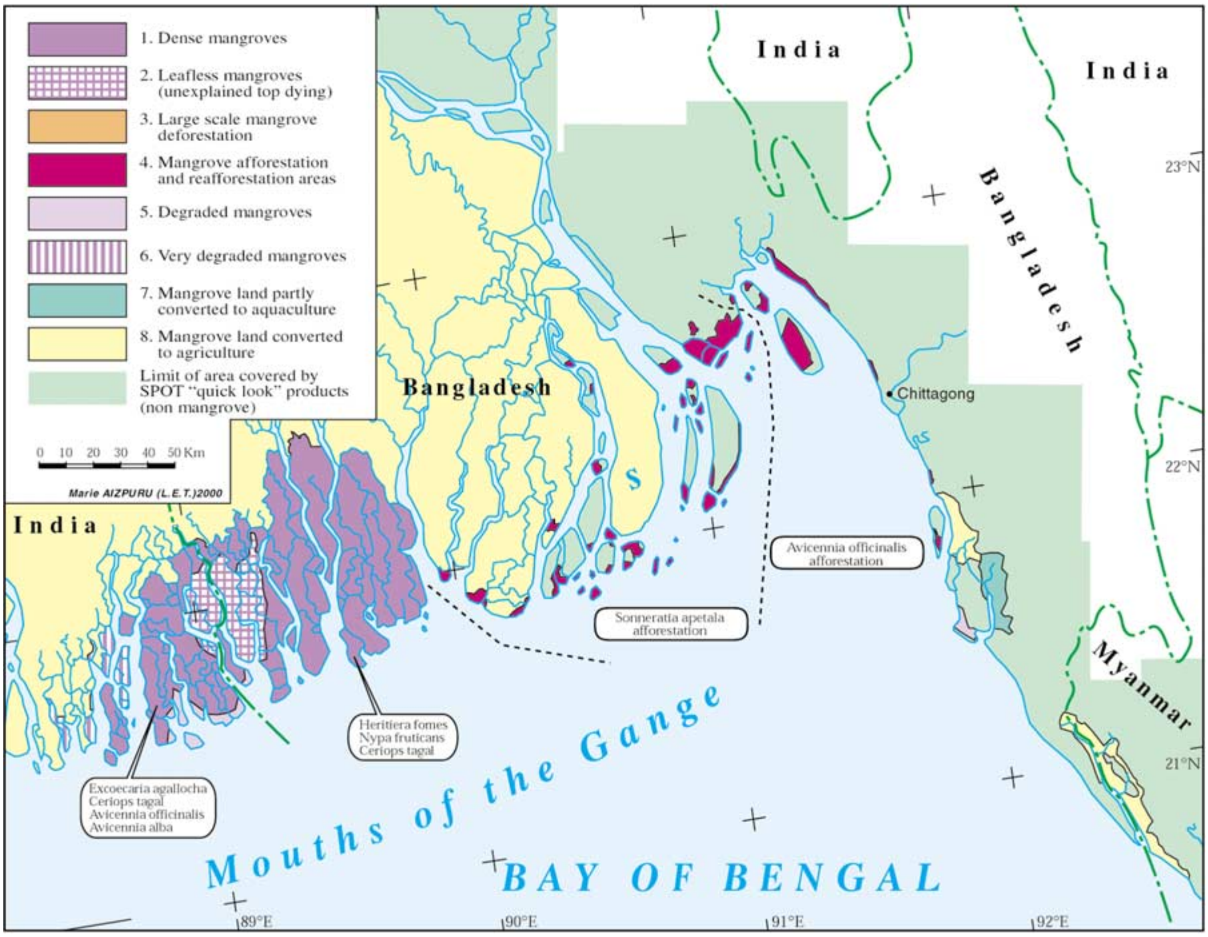

Figure 3. The current status of mangroves in the Sunderbans.

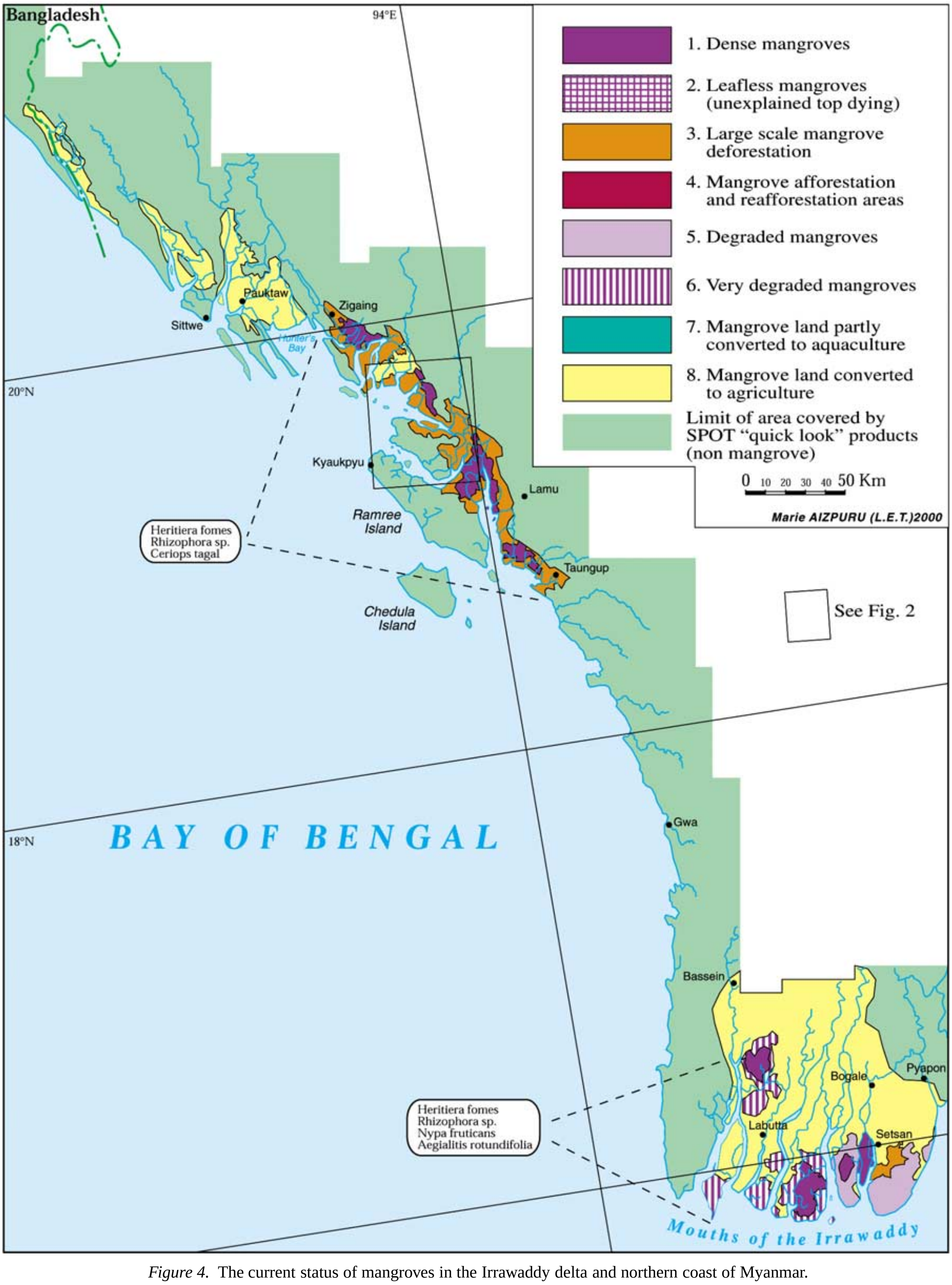

Figure 4. The current status of mangroves in the Irrawaddy delta and northern coast of Myanmar.

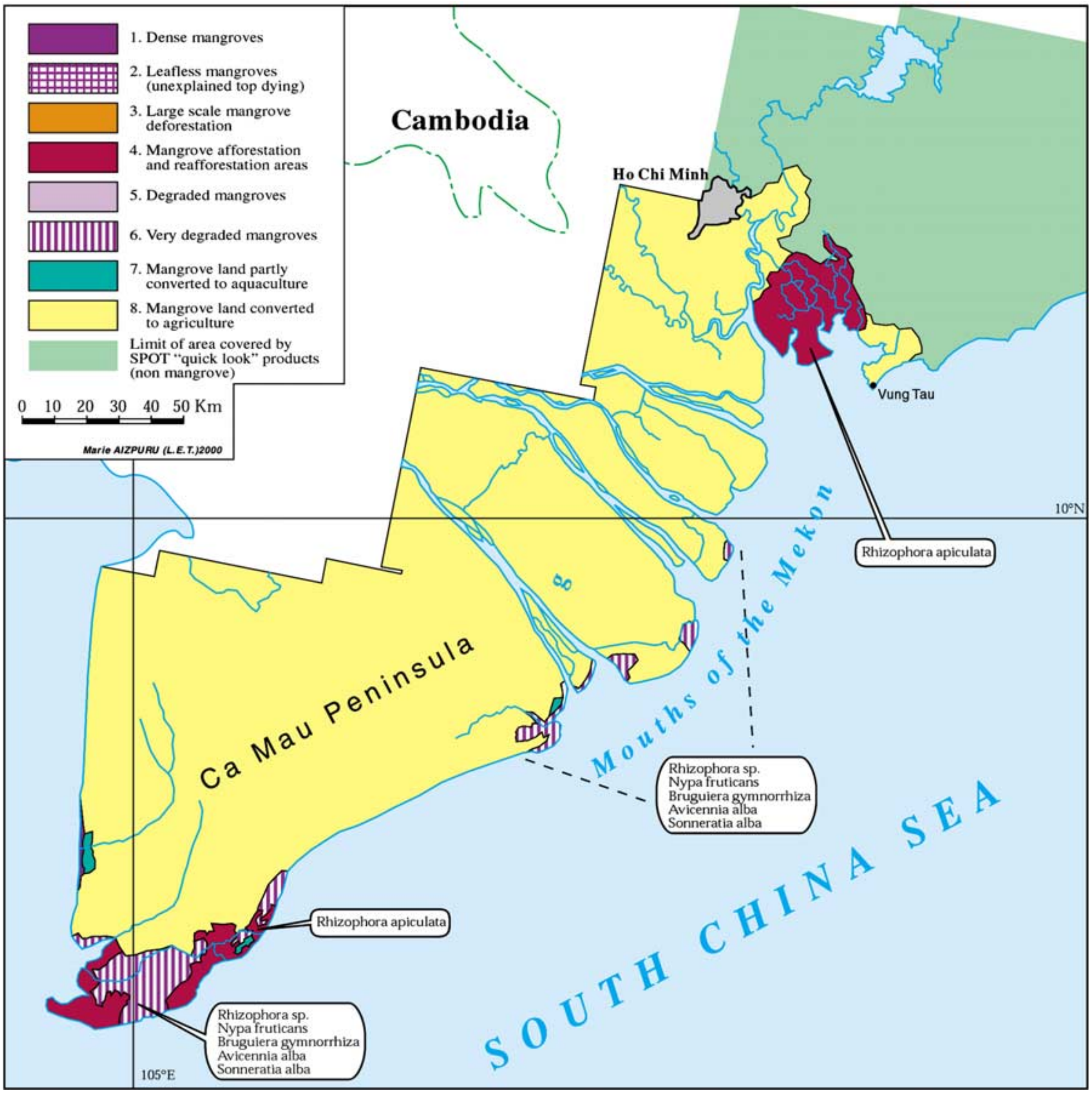

Figure 5. The current status of mangroves in southern Vietnam.

The guiding considerations in developing a mangrove classification system have been to utilize the criteria of density (estimated crown cover density), physiognomy (height and number of strata) and phenology (some trees are deciduous: *Excoecaria agallocha*) which could be easily detected by different methods of remote sensing imagery. These criteria portray the real-world entities and successional stages presently found in the mangroves of continental Asia (Blasco and Aizpuru, 1997, 2000). In this classification and in figures or tables, 'deforestation' refers to the loss of mangrove forest cover or the clearance of these ecosystems mainly for agriculture; 'degradation' is the deterioration of the density and structure of a natural mangrove cover, and the loss of its species diversity.

Eight major mangrove classes have been defined on the ground and can be extracted from 'quick look' products.

Dense (tall or low) mangroves (class 1), ground coverage $>80\%$

Normally, a natural mature mangrove has a dense evergreen canopy. It can be either a forest or a thicket. In this class, the spectral response is high in the near infra-red (0.79–0.89 μm), low in the red band (0.61–0.68 μm) and the values of any vegetation index is permanently high.

In this part of the world were fresh water swamp forest does not exist anymore, there is a clear-cut limit between mangroves, inland croplands (generally rice fields), sandy bars or open brackish waters seaward. The spectral response of all these communities being extremely contrasted, mangrove communities can be routinely extracted from space data.

At this level however it is impossible to try to go deeper into the analysis trying to discriminate mangrove stands according to their floristic composition, the size of trees or shrubs, or their standing biomass.

Leafless mangroves ‘Top dying trees’ (class 2)

In the case of a mangrove in which an abnormal rate of absorption in the near infra-red band (0.79–0.89 μm) is noticed, it may be assumed that the absorption through the canopy is due to tidal waters. This could mean that the mangrove trees of whatever species, are shedding their leaves due to an unknown stress and could be dying . This class is delineated and mapped in the Gangetic delta were an unexplained mortality of mangrove trees (*Heritiera fomes*) has been recorded (Siddiqi, 1998; Figure 3).

Large scale mangrove deforestation (class 3)

Tropical deforestation using remote sensing data has been studied by several authors (Achard et al., 1998; Malingreau et al., 1995; Lambin and Ehrlich, 1997). In the case of mangroves any opening in the woody canopy can be immediately detected either because corresponding pixels are replaced by water at high tides, like in the case of fish-ponds (class 7), or when the same pixels show a high reflectance in all wavelengths, at low tides, in which case crusts of sodium chloride deposits cover barren soils. Here, for the first time, we have been able to clearly ascertain that deforestation is proceeding in mangrove ecosystems in Myanmar (Burma), between Zigaing and Taungup (Arakan coast). To the North, all mangroves have already disappeared.

In these ‘hot spots’, active deforestation activity (Figure 2 and 4) in fragile coastal ecosystems, far exceeds the regrowth capability especially in *Heritiera fomes* communities, an endemic Sterculiaceae recorded only from these coastal areas extending from Orissa and West Bengal in India to Myanmar.

Mangrove afforestation areas (class 4)

Two countries are involved in huge coastal afforestation programmes, Bangladesh and Vietnam (Saenger and Siddiqi, 1993; Choudhuri, 1985 and 1990; Islam et al., 1990; Field, 1996). In Bangladesh, two main species are used: *Sonneratia apetala* Buch.-Ham (80% of mangrove plantation, especially in islands where the salinity is lower (about 20‰), and *Avicennia officinalis* L. which is planted in the eastern coastal belt where the salinity of the water is higher (about 25‰). According to our satellite observations, the rate of survival and growth seem to be different from one place to another. Today, some afforested island are covered by dense monospecific plantations whereas on other islands, planted mangroves have been washed away by cyclones or destroyed by outbreaks of two major insect pest species (Saenger and Siddiqi, 1993). If the afforestation programme in Bangladesh which began in 1966 has involved about 1,600 km^2, the global apparent rate of success is about 50% (800 km^2).

In the Mekong delta, an extensive reafforestation programme with *Rhizophora apiculata* Bl. began fifteen years ago and covers about 1,300 km^2 today.

Dense, young, monospecific replanted mangroves, have a characteristic spectral response as they are in an active growing phase. High photosynthetic activity causes high absorption of photons, leading to low response in the 0.61–0.68 μm wavelength. This phase is therefore expressed by a very strong reflectance in the 0.79–0.89 μm wavelength.

Four additional classes are also mapped, because they illustrate the magnitude of human impacts on these coastal areas i.e.:

Degraded mangroves (class 5), ground coverage 50 to 80%

Very degraded mangroves (class 6), ground coverage 20 to 50%

Mangrove land partly converted to fish ponds (class 7)

Mangrove land converted to agriculture (class 8), mainly paddy

All these basic coastal features being obtained from ‘quick look’ data any further ecological investigation requires the access to genuine high resolution data for deeper ecological and land use analysis. This type of image processing is now sufficiently mastered and number of software programs for digital analysis are available (Imhoff et al., 1987; Klemas and Bartlett, 1975; Ramsey and Jensen, 1996; Blasco et al., 1997).

Biological reorganization, floristic changes and distribution patterns

Interesting synoptic ecological data at large and at local scales may be extracted from measurements of reflected and emitted radiations by various coastal ecosystems. It is, however, extremely difficult or even impossible to extract straightforward taxonomic and ecophysiological data (Ball, 1988; Ball et al., 1988) from present remote sensing data.

Ground surveys have shown that the coastal study area is certainly one of the richest at the specific level, with at least 28 species of mangrove trees and shrubs recorded (20 genera; 15 families), most of these in the Sunderbans. The spatial distribution of mangrove trees and shrubs, often occurring randomly intermingled, remains almost totally unexplained. One of the major reasons is certainly due to human interferences especially in the Sunderbans were silvicultural practices have almost completely disturbed the original distribution of plants along ecological gradients, such as tidal amplitudes and soil salinities. Some species became abnormally abundant due to their economic importance. Good examples are *Heritiera fomes* for its timber, *Excoecaria agallocha* L. which produces paper pulp, *Nypa fruticans* from which thatching material is extracted, *Ceriops tagal* C.B. Robinson and *Avicennia officinalis* L. which are cropped as fire wood products.

As a result, the relationships between abundance and distribution of woody species in the Sunderbans which are the world's largest mangroves in a single block (about 6,000 km^2) do not properly reflect the response of individual species or populations to local ecological conditions.

Some species like the monotypic *Kandelia candel* (L.) Druce are uncommon in the study area presumably because it is at the western edge of its geographic range (Lee, 1989). Its abundance declines westwards leaving large areas uninhabited especially along the East Coast of India. The same explanation is perhaps valid for *Aegialitis rotundifolia* Roxb.; but this Plumbaginaceae is locally extremely abundant in the Irrawaddy delta and then disappears abruptly westwards, after the Ganges or the Mahanadi delta in Orissa (India). Strangely, it is unknown in Thailand and Eastwards (Prakash and Lim, 1995).

Another interesting mangrove species of this coastal zone is *Sonneratia griffithii* Kurz, a rare apetalous tree, apparently endemic (from Chittagong to north western peninsular Malaysia), which can be considered as 'Allied to, but distinctly different from*S. ovata* Backer' and endangered (Backer and van Steenis, 1951). This species is not recorded in recent botanical surveys carried out in the West Coast of Thailand (UNDP-UNESCO, 1991).

Another endemic mangrove species which could be endangered is *Heritiera fomes* Buch.-Ham. It has a patchy distribution from the western India (Orissa and Ganges) to the Irrawaddy delta. This could be a vicariant species (or an ecotype?) of *H. littoralis* Aiton, commonly found in freshwater riparian communities from East Africa to Australia. The exact biological status of *H. fomes* (local names are 'sundri' in the Bengal and 'Pinlé Kanazo' in Myanmar) is unknown. From an ecological point of view the 'sundri' is a mangrove buttressed tree (10 to 25 m high) with dense, robust pneumatophores about 50 cm high. It requires low soil and water salinities (5 to 15þ). When the salinity increases, the species becomes stunted, rare and ultimately disappears. In the highly populated Bengal (India and Bangladesh) the dry season demand for freshwater has increased dramatically; major rivers have been dammed and the downstream effects are becoming apparent with increasing soil salinities and unexplained 'top dying ' in local populations of *Heritiera fomes* (class 2 in Figure 3).

The fate of *Heritiera fomes* in the mangroves of Myanmar is practically unknown although several papers and academic books, in local language, are probably available but not easily accessible to the international research community. In the mid-1950s (Kostermans, 1959), the tidal or delta forests of the Bassein Division (Irrawaddy delta) contained large areas of *Heritiera*; today according to the latest satellite data (RESURS, April 1998) these forest have almost disappeared. Between the mouth of the Mayu (Sittwe or Akyab city) and Lamu city where most important stands of this species were found 50 years ago, recent SPOT data indicate that they have been already almost completely depleted especially in the North (Paktaw, Hunter's Bay etc.), whereas further south, a large scale deforestation activity is in progress (SPOT data 1998; Figure 2).

For all these reasons the total extinction of most or all populations of the poorly known species *Her-*

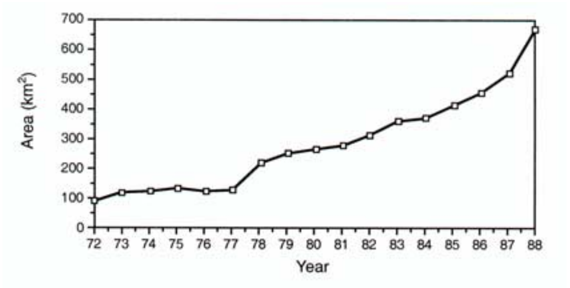

Figure 6. Changes in land area used for aquaculture in Thailand (1972–1988) (Silapathong, 1992).

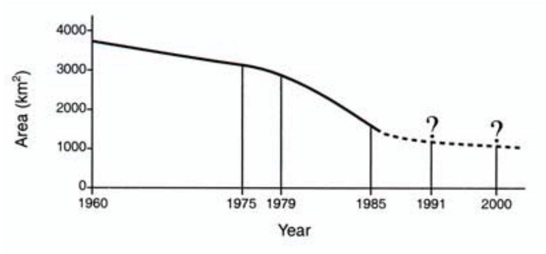

Figure 7. Mangrove forest depletion in Thailand and extrapolated trends (IDRC, 1991).

itiera fomes is to be feared. Along the coastline of Thailand (Andaman Sea and Gulf of Thailand), the floristic composition of mangrove is not as rich as at the top of the Bay of Bengal (India-Bangladesh-Myanmar). However 24 species of trees, shrubs and climbers are recorded in natural mangroves of Ranong Province (Andaman Sea) and the floristic composition is similar to that of Chantaburi (East Thailand), even if soils and bioclimatic patterns differ substantially (UNDP-UNESCO, 1991).

In the depletion of mangroves in Thailand there is no clear indication of any phanerogam species particularly threatened, although the regressive evolution of mangrove communities is extremely rapid, closely correlated with the increase of shrimp ponds (Figures 6 and 7). The depletion is almost complete

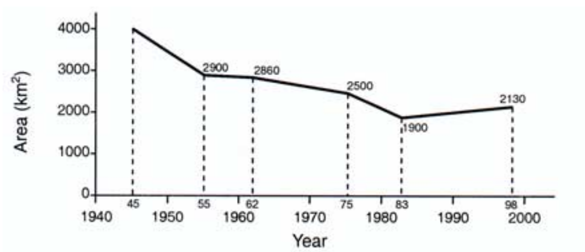

Figure 8. Total mangrove area in Vietnam (1945–1998) (Tri et al., 1998 in LOICZ, 1998; Hong and San, 1993; and this study).

especially in Khlung (Gulf of Thailand) where mangroves classified as 'National Reserved Forests' have also disappeared (Silapathong and Blasco, 1992).

A remote sensing and cartographic study on the mangroves of Thailand has shown (IDRC, 1991) that the average annual forest depletion between 1979 and 1990 has been about 130 km^2. The main cause of mangrove forest clearance is the extension of shrimp farming especially in the Gulf of Thailand (Silapathong, 1992). During the last decade the rate of mangrove change to other uses has been slowing down, whereas some mangrove plantings have been undertaken, near Pattani for instance (about 5 km^2). In this work we have not revised the present status of the mangroves of Thailand. We assume that the present mangrove forest area in Thailand as shown in Table 2 is about 1,900 km^2, 75% being located along the Andaman sea coast. But these figures have to be checked.

The coastal part of southern Vietnam, from Vung Tau Cape to Ha Tien, is occupied by the Mekong delta, where mangrove habitats have been largely converted to irrigated crop fields during historical times.

The history of mangrove ecosystems in Vietnam is certainly unique. Since the mid-1950's some interesting figures concerning the depletion of the remaining mangroves are available (Hong and San, 1993; Tri et al., 1998). During the French colonial period, until 1943, these mangroves covered about 4,000 km^2 (Moquillon, 1950). During the last war the mangroves of Cape Ca Mau became one of the major targets of herbicides and defoliants especially between 1965 and 1969 (NAS, 1974; Ross, 1975; Teas and Kelly, 1975). In addition to these direct human impacts, the post-war period was marked by an increased destruction of the remaining mangroves due to massive construction of shrimp ponds. This caused major changes in drainage patterns, in tidal flooding frequency and in soil toxicity wherever acid sulphate soils have developed (Figure 8).

In 1983, the mangroves of south Vietnam comprised about 1,900 km^2 including 1,360 km^2 of rather dense, mainly secondary forests, 140 km^2 of shrubby types and 430 km^2 of plantations, mainly with *Rhizophora apiculata*.

Here we produce for the first time since the end of the war in this country (1971), a satellite survey showing the areal extent of these mangroves:

Table 2. Assessment of mangrove depletion in six countries of tropical Continental Asia.

	Total Mangrove Area (Km^2)					
	IUCN (1983)	World Mangrove Atlas (1977)	This study (±10%)			
		(Spalding, Blasco, Field)	Dense	Degraded	Reafforested	Total
India	2,000 (Sunderbans)	4,050 (Sunderbans)	1,550 (Sunderbans)	400 (Sunderbans)	– (Sunderbans)	1,950 (Sunderbans)
Bangladesh	4,050	6,340	4,100	50	800	4,950
Myanmar	5,170	3,790	2,300	4,600	–	6,900
Thailand	1,634	1,960	1,000	900	Negligible (<50)	1,900
Cambodia	100	850	200	150	–	350
Vietnam	2,500	2,200	Negligible (<30) (Mekong delta)	800 (Mekong delta)	1,300 (Mekong delta)	2,100 (Mekong delta)
Total	15,454	19,190	9,150	6,900	2,100	18,150

Dense natural mangrove forests .... negligible
Degraded mangroves .... 800 km^2
Mangrove reafforestated areas .... 1,300 km^2

Results and conclusion

There is a continuing doubt and controversy over the exact mangrove areal extent. The primary reason is that we are unable to produce a sufficiently accurate classification and mapping method of these ecosystems over large areas. Unfortunately, the knowledge acquired on the use of NOAA-AVHRR for tropical forest monitoring at a global scale does not provide appropriate response of coastal ecosystems which are generally narrow strips, less than one kilometer wide in the intertidal zone.

The density and phenology (which are essential characteristics of every natural woody ecosystem), and land use changes, all are key variables directly observable with high resolution optical sensor. Regarding coastal studies we need to discern each individual ecological system, including shrimp ponds, reafforested saltmarshes, dense and open mangroves, logging activities etc.. Such studies can be carried out only if we have access to frequent satellite observations, at very low cost. For the first time we have demonstrated that accurate mangrove ecosystem studies are possible at a regional scale.

Two main kinds of results can be extracted from this study (Table 2).

From a qualitative and botanical point of view the coastal part of Asia located between West Bengal in India and Peninsular Malaysia is quite enigmatic. Three important mangrove species at least, are endemic and have a vicarious distribution:

Endemic species:	**closely allied to:**
Heritiera fomes Buch.-Ham.	*H. littoralis* Aiton
Sonneratia griffithii Kurtz	*S. ovata* Backer
Aegialitis rotundifolia Roxb.	*A. annulata* R. Br.

However, these allied or sibling species, are often wrongly diagnosed, since their morphological and genetic characters are so close and poorly documented throughout the region (Duke, 1995; Duke et al., 1998). An important question is whether these related taxa are the result of environmentally induced phenotypic variation or the result of genetic divergence.

Extensive physical and biological changes have occurred during the last 50 years in this coastal stretch. They have led to an artificial assemblage of species in which the exceptional abundance of some of them (*Heritiera fomes* and *Sonneratia apetala* in the Ganges, *Rhizophora apiculata* in the Mekong etc.) is the result of economic needs and environmental change. They are not the result of natural successional processes or of local natural selection of species (Snedaker, 1982). Ultimately these coastal systems are changing in various ways, in each individual country. They constitute interesting examples of how the concept of ‘integrated conservation and management’ is variously implemented in coastal environments of continental Asia. This concept promises to approach the sustainable management of mangrove ecosystems in such a way that their environmental, economic and social values are ensured for the benefit of present and future generations (Bruenig, 1996; UNESCO/UNDP, 1986; ISME, 1993). This study has shown that nearly

40% of the remaining mangroves of tropical Continental Asia are degraded.

From a quantitative point of view a clear idea of the location and areal extent of each mangrove type and subtype in tropical continental Asia is now available (Table 2). As shown in this table, dense natural mangroves have almost totally disappeared in the Mekong delta where 62% of present mangroves are replanted. In Myanmar, the estimation of dense mangroves was 5,170 km^2 in 1983; 6,900 km^2 are recorded today out of which nearly 70% are already either degraded or very degraded. In the world's largest mangrove area found at the mouths of the Ganges, at least 90% are totally artificial (silviculture) or replanted.

The area presently covered by mangroves is mapped (Figures 3, 4, 5) without using fixed thresholds. This result is obtained by a simple analysis of available SPOT 'quick look' data, based upon classical thresholding in bands XS2 and XS3 which are usually for XS2 (0.61–0.68 μm) between 20 for lower levels and 120 for higher levels and for XS3 (0.79–0.89 μm) between 30 and 100.

A mangrove depletion algorithm based upon the NDVI and empirical thresholds may improve the spectral separability of mangroves and the quality of the classification accuracy of coastal ecosystems about 10%. However, such approaches are demanding on resources (costly data acquisition, digital image processing facilities, times consuming etc.). The immediate explanation for this unexpected spectral separability of mangroves and meaningful results obtained from coarse space data is presumably related to the very contrasted spectral behaviour of mangroves and their derived coastal ecosystems. These plant communities are dense evergreen coastal forests, twice daily flooded, whereas neighbouring pixels of coastal and deltaic land covers, in tropical continental Asia, correspond either to free waters or to irrigated crops both having very distinct sensitivities in the concerned wavelengths. Further work is required to investigate the actual capabilities of 'quick look' products for mangrove degradation stages survey and classification.

References

Achard, F., Eva, H., Glinni, A., Mayaux, P. 1998. Identification of Deforestation not SPOT Areas in the Humid Tropics. TREES project. Joint Research Center, Ispra.

Backer, C.A. and Van Steenis, C.G.G.J. 1951. Sonneratiaceae. Flora Malesiana Ser. I. 4: 280–289.

Ball, M.C. 1988. Ecophysiology of Mangroves. Trees 89: 129–142.

Ball, M.C., Cowan, J.R., Farquaar, G.D. 1988. Maintainance of leaf temperature and the optimum of carbon gain in relation to water loss in a tropical mangrove forest. Aust. J. Plant Physiol. 15: 263–276.

Blasco, F., Gauquelin, T., Rasolofoharinoro, M., Denis, J., Aizpuru, M. and Calderou, V. 1997. Recent advances in mangrove studies using remote sensing data. Aust. J. Marine & Fresh Water Res. 49: 287–296.

Blasco, F. and Aizpuru, M. 1997. Classification and evolution of the mangroves of India. Tropical Ecol. 38: 357–374.

Blasco, F. and Aizpuru, M. 2000. Recent data on the mangroves of the Bay of Bengal. Indian J. Marine Sci. (submitted).

Bruenig, E.F. 1996. Conservation and Management of Tropical Rainforests. University Press, Cambridge.

Choudhuri, P.K. Roy. 1985. Silvo-pisciculture prospects and problems in Sundarban West-Bengal, India. Some studies. National Symposium of mangroves, Shivaji University, Kolhapur, Maharastra: 330–334.

Choudhuri, P.K. Roy. 1990. Artificial regeneration of Sonneratia apetala (BUCH-HAM in Sundarbans, West Bengal). The Indian Forester 116: 773–779.

Duke, N.C. 1995. Genetic diversity, distributional barriers and rafting continents; more thoughts on the evolution of mangroves. Hydrobiologia 295: 167–181.

Duke, N.C., Ball, M.C., Ellison, J.C. 1998. Factors influencing biodiversity and distributional gradients in mangroves. Global Ecol. Bio. Lett. 7: 27–47.

Field, C. 1996. Restoration of Mangrove Ecosystems. ISME, Okinawa.

Hill, R.A. 1999. Image segmentation for humid tropical forest classification in Landsat TM data. Int. J. Remote Sens. 20: 1039–1044.

Hong, P.N. and San, H.T. 1993. Mangroves of Vietnam. The IUCN Wetlands Programme. IUCN, AIT, Bangkok.

IDRC/NRCT/RFD 1991. Remote Sensing and Mangroves Project (Thailand). National Research Council of Thailand, Bangkok.

Imhoff, M.I., Vermillion, C., Story, M.H. 1987. Monsoon flood boundary delineation and damage assessment using space borne imaging radar and landsat data. Photogram. Engin. Remote Sens. 53: 405–413.

Islam, M.R., Khan, M.A.S., Siddiqi, N.A., Saenger, P. 1990. Optimal planting season for Keora (*Sonneratia apetala*) in Bangladesh. Bangladesh J. Forest Sci. 19: 54–65.

ISME 1993. The economic and Environmental Values of Mangrove Forests and Their Present State of Conservation in the South East Asia/Pacific Region, Okinawa.

IUCN 1983. Global Status of Mangrove Ecosystems. Commission on Ecology Papers n°3. IUCN, Commission on Ecology, Gland.

Klemas, V. and Bartlett, D.S. 1975. Coastal zone classification from satellite imagery. Photogram. Engin. Remote Sens. 41: 499–513.

Kostermans, A.J.G.H. 1959. The genus *Heritiera*. Reinwardtia 4: 465–583.

Lambin, E.F. and Ehrlich, D. 1997. The identification of tropical deforestation fronts at broad spatial scales. Int. J. Remote Sens. 18: 3551–3568.

Lee, S.Y. 1989. Litter production and turnover of the mangrove *Kandelia* in a Hong Kong tidal shrimp pond. Estuarine, Coast. Shelf Sci. 29: 75–87.

LOICZ 1998. Towards Integrated Modelling and Analysis in Coastal Zones: Principles and Practices. LOICZ (Land-Ocean Interactions in the Coastal Zone) reports and studies n° 11, Den Burg – Texel.

Malingreau, J.P., Achard, F., D'Souza, G., Stibig, H.J., D'Souza, J., Estréguil, C., Eva, H. 1995. AVHRR for global tropical forest monitoring: the lessons of the TREES project. Remote Sens. Rev. 12: 29–40.

Moquillon, C. 1950. La forêt de palétuviers de la pointe de Ca Mau. Archives Services Forestiers, Saigon.

NAS (National Academy of Science). 1974. The Effects of Herbicides in South Vietnam. Part A: Summary and Conclusion. Committee on the Effects of Herbicides in Vietnam. Wash. IV, pp. 92–125.

Prakash, N. and Lim, A.L. 1995. The systematic position of *Aegialitis*, the enigmatic mangrove. Wallaceana 74: 11–15.

Rao, A.N. 1987. Mangrove Ecosystems of Asia and the Pacific. Mangroves of Asia and the Pacific, status and management. UNDP/UNESCO, RAS/79/002, pp. 1–48.

Ramsey, E.W. and Jensen, J.R. 1996. Remote sensing of mangrove wetlands; relating canopy spectra to site-specific data. Photogram. Engin. Remote Sens. 62: 939–48.

Rasolofoharinoro, M, Blasco, F., Bellan, M.F., Aizpuru, M. and Gauquelin, T. 1998. A remote sensing based method for mangrove studies in Madagascar. Int. J. Remote Sens. 19: 1873–1886.

Ross, P. 1975. The mangrove of South Vietnam: the impact of Military use of herbicides. Proceedings of International Symposium of Biology and Management of mangroves. Hawaii: 695–709.

Saenger, P. and Siddiqi, N.A. 1993. Land from the sea: the mangrove afforestation program of Bangladesh. Ocean & Coast. Manag. 20: 23–39.

Siddiqi, N.A. 1998. Enrichment planting in the mangrove of Sunderbans – Arcview. Bangladesh J. Forest Sci. 27: 103—113.

Silapathong, C. 1992. Utilisation combinée d'un S.I.G. et de la télédétection pour le suivi des mangroves en Thaïlande. Thèse, Université Paul Sabatier, Toulouse.

Silapathong, C. and Blasco, F. 1992. The application of geographic information system to mangrove forest management: Khlung, Thailand. Asian Pacific Remote Sens. J. 5: 97–104.

Snedaker, S.C. 1982. Mangrove species zonation: why? Tasks for Vegetation Science Vol. 2. *In:* Sen, D.N. and Rajpurobit, K.J. (eds.). pp. 111–125. Dr. W. Junk Publishers.

Spalding, M., Blasco, F. and Field, C. 1997. Word Mangrove Atlas. ISME, Okinawa.

Teas, H.J. and Kelly, J. 1975. Effect of herbicides on mangroves of South Vietnam and Florida. Proceedings of International Symposium on Biology and Management of Mangroves. Hawaii: 719–728.

Tri, W.H., Adger, W.N. and Kelly, P.M. 1998. Natural resources management in mitigating climate impacts: mangrove restoration in Vietnam. Global Env. Change 8: 49–61.

UNESCO-UNDP 1986. Mangroves of Asia and the Pacific: Status and Management. Quezon City.

UNDP-UNESCO 1991. The integrated multidisciplinary survey and research programme of the Ranong mangrove ecosystem. RAS/86/120. National Research Council of Thailand, Bangkok.