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Recent advances in mangrove studies using remote sensing data

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Abstract. This paper summarizes present capabilities in studying mangrove vegetation from space. There is no standard image processing method that can be applied for the identification and delineation of coastal ecosystems. From a spectral point of view, it is practically impossible to characterize each of the sixty species of trees and shrubs that constitute the mangroves of the world. Nevertheless, some possibilities exist to map at global and at local scales mangrove areas from satellite products, combining several space data sets, interpretation of aerial photographs and ground surveys.

The monitoring of mangroves can be considered as operational at a local level using remote sensing techniques, whereas monitoring of these ecosystems at global or at regional levels has not yet been achieved.

Introduction

The first 'World Mangrove Atlas' (Spalding *et al.* 1997) provided the opportunity to evaluate the capability to provide a realistic assessment of existing mangroves and their evolutionary trends, both at a global and at a local scale.

A few mangrove forests have been managed for decades, especially for wood production (e.g. Matang forest in Malaysia, the Sunderbans in India and Bangladesh (Imhoff *et al.* 1987; Imhoff and Gesch 1990; Blasco *et al.* 1994), and some mangroves have been mapped and monitored for various reasons with aerial photos or satellite data, as in Florida (Jensen *et al.* 1991; Ramsey and Jensen 1996), Guiana (Sery *et al.* 1995), Kenya (Gang and Agatsiva 1992; Brakel 1984), Senegal, Goa and Cauvery in India, Cilacap in Java, Thailand (Silapathong 1992), Ecuador (Klemas and Bartlett 1975, Terchunian *et al.*, 1986). With the exception of data derived from those, all estimates of the areal extent of mangroves have been wrong for at least three reasons: *(1)* the lack of a universal definition of what is a mangrove and what is not, *(2)* the technical and financial limitations, *(3)* the instability and constant changes which characterize coastal ecosystems.

In this paper, recent attempts to use satellite sensors for analysing and monitoring mangroves and coastal change are reviewed.

Uncertainties concerning the present mangrove extent

The lack of a universally accepted definition of mangrove communities or mangrove habitats leads to an array of estimates concerning their areal extent around the world. It is impossible at present to ascertain that the worldwide extent of mangrove ecosystems is of 100 000 or of 200 000 km^2. The term 'mangrove' is not precise; its meaning differs from one country to another and from one author to another. As a result, the statistics quantifying mangrove areas quantify different things. The term 'mangrove' is being interpreted in the four following major ways.

Mangrove ecosystem

In this case, the concept includes forest communities and open water surfaces such as networks of rivers, canals and creeks, and sandy or muddy sediments without any forest. It is implicitly understood that inter-relationships among plants–animals–fisheries–hydrology cannot be reasonably dissociated. This is why in the Sunderbans, which are the world's largest mangroves (about 6000 km^2 in a single block, at the mouth of the Ganges), the area of mangroves often includes the hydrographical network associated with forest stands of *Heritiera fomes* Buch.-Ham., *Nypa fruticans* Wurmb, *Ceriops tagal* (Per.) C. B. Robinson and *Sonneratia apetala* Buch.-Ham.

Mangrove forest

To foresters, the definition is generally clear, though somewhat restrictive. A mangrove forest is only the intertidal community of trees or the productive areas with marketable, natural or planted tree species. *Nypa fruticans* is usually included in area statistics. The question of successional stages or the dynamic aspects of the vegetation are not taken into account and only natural or semi-natural forest and plantations are considered. Fringing mangroves lining creeks and river banks are usually included in this category, and it is normally studied by means of aerial photographs.

Mangrove land

All woody and grassy halophytic communities included in the intertidal zone are considered as potential mangrove area. Most West African 'tannes' are included in 'mangrove land' although they are almost barren saline soils, occasionally flooded for a few days of the year. In such a case the concept

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of 'ecosystem' is a dynamic one, *sensu* Schimper (1903). It implies that herbaceous halophytes, developed in the intertidal zone, are derived from mangrove forests and all plant communities found in the 'mangrove land' are only serial stages of the same vegetation series. In theory, mangroves can be restored in the so-called 'mangrove land'.

Mangrove area

This concept is still wider than the others and always remains extremely vague. Its definition is not accurate enough for statistical purposes. It includes all mangrove and back-mangrove plant communities including salt flats and an extended array of land-use units resulting from mangrove conversion to other uses (fish-ponds, agriculture, salt pans etc.). Usually, small-scale maps (< 1 : 1000000) showing the location of mangroves give only a rough location of 'mangrove areas'.

For all these reasons, it is still extremely difficult to assess the area of mangroves for different countries and continents from available maps and data bases (Table 1).

Table 1. Estimates of mangrove areas

Region	Mangrove area (km^2)		
	Spalding *et al.* (1997)	Saenger *et al.* (1983)	Fisher and Spalding (1993)
South and South-east Asia	75688	51766	76226
Australasia	18789	16980	15145
The Americas	49 485	67446	51286
West Africa	27995	27110	49500
East Africa and the Middle East	10348	5508	6661
Total area	182305	168810	196825

Towards a spectral discrimination of mangroves

Another approach for the computation of mangrove areas could be the delineation and quantification of areas occupied by mangrove species. About 60 species of trees and shrubs belonging to about twenty genera in over fifteen families are recognized throughout the world as being mangroves (Tomlinson 1986). Most of these species occur in the Indo–Pacific region, and there are about 10 species in the Western Hemisphere (Hutchings and Saenger 1987; Blasco *et al.* 1996).

From a spectral point of view, it is almost impossible at present to characterize each individual mangrove species. However, at the generic level, *Rhizophora* and *Avicennia* are dominant throughout the world, with each genus having several closely related species in both the east and the west (Macnae 1968; Tomlinson 1986; Ellison 1991; Saenger and Bellan 1995).

Attempts to measure the radiometric behaviour of most noteworthy mangrove plant communities (Loubersac 1991) have concerned discrimination of *Rhizophora* community, *Avicennia* community, *Bruguiera* community, open stands with *Salicornia*, barren soils with algal deposits, and almost completely barren soils.

The equipment included two radiometers. CIMEL measures the radiometries on the ground with the same wavelengths as SPOT (XS1 0.50–0.59 µm; XS2 0.61–0.68 µm; XS3 0.79–0.89 µm); the mean area of the target was 1600 cm^2. HRS (High Spectral Resolution) is a spectro-radiometer that, from a helicopter, measures reflectances from blue (470 nm) to the near infrared (920 nm) at 95 and 1140 m elevation respectively; the mean area of the target was 400 m^2).

Although the experiment seemed to provide some possibilities for a spectral distinction of these important coastal communities (Fig. 1), these ground and aerial experiments have had several important limitations, primarily because the spectral signal of these plant communities is strongly influenced by tidal effects on the soils. It is also determined by the physiological status of plants and most likely also by the morphological properties of each species. In other words, the spectral behaviour of *Avicennia marina* (Forsk.) Vierh. and that of *Avicennia officinalis* L., thriving side by side in some mangroves of Asia (as in Southern India), may not be similar. In the above experiments, the thickness of the atmosphere was not taken into account. Satellite data (average altitude 705 km for Landsat TM, 830 km for SPOT) are altered by atmospheric properties, especially in coastal areas where air humidity is usually extremely high.

These assumptions have been confirmed in south-western Florida (Ramsey and Jensen 1996) and in Brazil (Herz 1991). In Brazil the reflectance of each mangrove plant community is strongly influenced by the physical properties of the soil (Fig. 2). Leaf reflectance alone, for *Rhizophora*, *Laguncularia* and *Avicennia*, does not permit precise

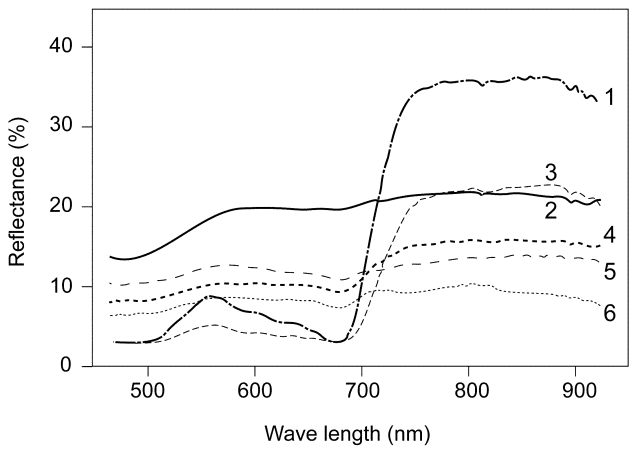

Fig. 1. Spectral responses of main plant commmunities recorded with HRS spectroradiometer (Loubersac 1991). 1, *Bruguiera*; 2, barren soils; 3, *Rhizophora*; 4, *Avicennia*; 5, swamp with *Salicornia*; 6, barren soils with algal deposits.

discrimination. These measurements (Herz 1991) were obtained from field experiments and radiometric values collected from a helicopter platform, between the violet (400 nm) and the near-infrared (1050 nm). The radiometric values have been compared with those provided by Landsat, especially TM4 and TM5, in order to evaluate the impacts of mangrove soils and tidal penetration on mean reflectances of mangrove communities. As statistical details regarding the number of samples taken for the experiment are not given, it is impossible to assess these spectral signatures.

It may be concluded that, because the interface between land and oceans is an extremely dynamic area, the properties of its main components, such as soils and plant communities, vary on both short (diurnal and seasonal) and long time

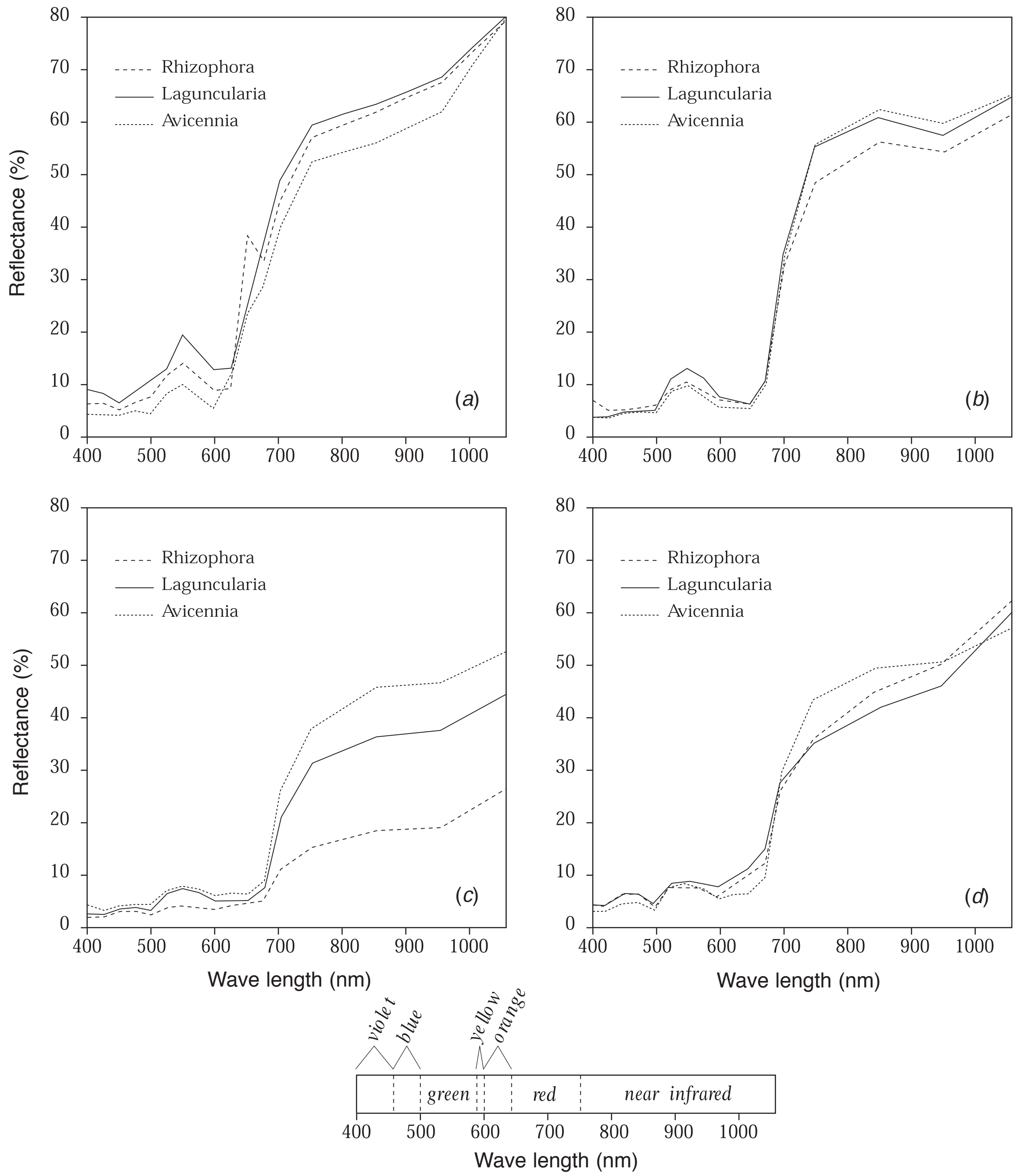

Fig. 2. Reflectance of mangrove trees in Brazil (Herz 1991): *(a)* leaf reflectance; *(b)* substratum with litter fall; *(c)* loamy substratum; *(d)* sandy substratum.

scales (yearly, century etc.). These variations, in particular daily changes, are major obstacles to a rigorous radiometric characterization of each component of the intertidal zone.

Mapping mangrove ecosystems

In spite of the limitations stressed above, the use of high resolution satellite data for coastal studies is now a common feature. Major recent advances are primarily related to new, more or less complex and specific algorithms, applied to satellite data processing. Ultimately, the combination of channels, the computation of various indices and the application of classic methods such as the maximum-likelihood or the minimum-distance classifications have provided the capability to discriminate mangrove vegetation from neighbouring ecosystems and, to some extent, to obtain useful data on the density as well as on changes due to human activities or to natural hazards such as cyclones, surges and floods (Blasco *et al.* 1994).

Paradoxically, although there is no standard image-processing method (or set of methods) that could be applied for the identification and delineation of any kind of coastal ecosystem, it appears that mangroves can be mapped, from satellite data, at least in specialized laboratories. Some technical 'groping' is always necessary before the most appropriate digital processing method, compatible with local features, is found.

Several algorithms for mangrove studies in Madagascar have recently been tested (Rasolofoharinoro *et al.* 1998) at Mahajamba Bay (Fig. 3), this being the first attempt of a study from space of mangroves on this island (Fig. 4). The conclusions of the experiment, based on SPOT data from 1986 and 1993, were as follows. Five mangrove classes can usually be extracted and mapped with the computation of the Vegetation Index after a classical stretching (Fig. 3 and Table 2):

$$[\mathrm{VI}] = \frac{\mathrm{XS3} - \mathrm{XS2}}{\mathrm{XS3} + \mathrm{XS2}}$$

These classes are: *(1)* Dense mature mangrove (*Rhizophora mucronata* Lamk., *Xylocarpus granatum* Koenig, *Avicennia marina* (Forsk.) Vierh.); *(2)* Open mangrove stands, e.g. humid and dry tannes, pioneering mangrove (*Salvadora angustifolia* L., *Salicornia*, *Sporobolus* etc); *(3)* Swampy meadows (*Cyperus laevigatus*, *Typha angustifolia*, *Phragmites* sp.); *(4)* Water (including aquaculture); and *(5)* Barren soils (including sandy deposits, muds etc.)

Neither mangrove species zonation (Snedaker 1982) nor such quantitative data as standing biomass, volume classes etc. can be obtained from space data in the region of Madagascar.

During the past few years, the mapping of mangroves has been extensively developed on all continents, either on paper maps or in digital formats, mainly derived from SPOT and Landsat TM data. One of the most impressive works recently published is the atlas of the mangroves of Brazil (Herz 1991). Interestingly, it shows that the total extent of the mangroves of that country has been significantly over-estimated for many years. It was believed that Brazil had the largest mangrove areas in the world, with a total estimated extent of about 25 000 km^2 (Saenger *et al.* 1983), whereas in reality (Fig. 5) Brazil, with a total of 10 124 km^2 of

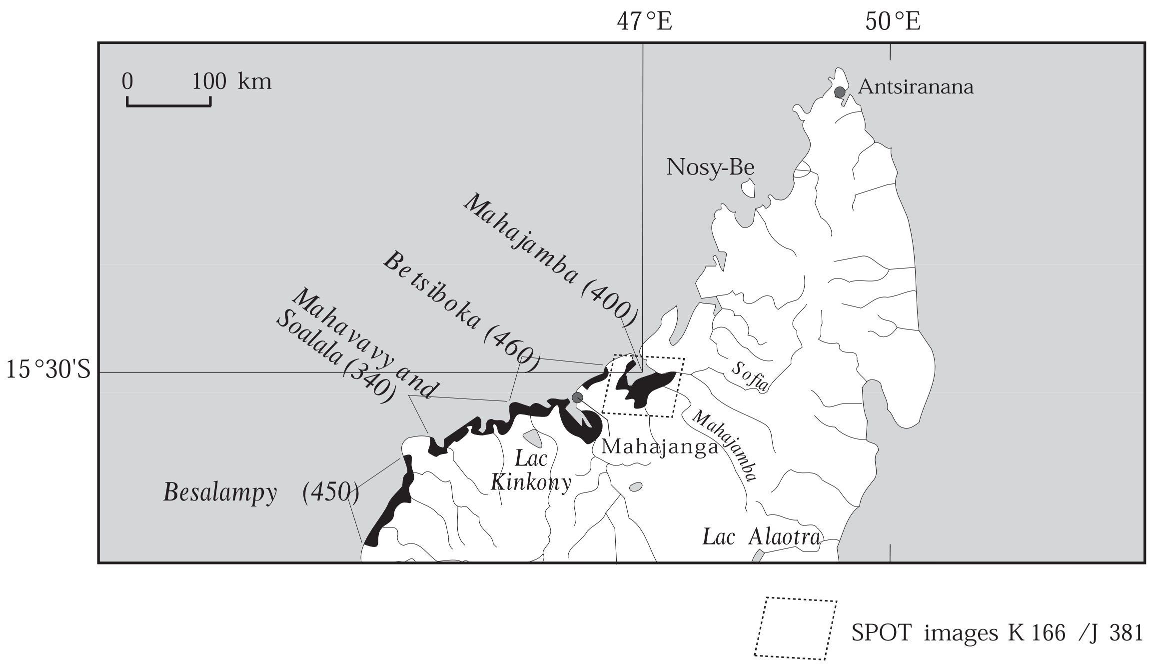

Fig. 3. Location of Mahajamba Bay and main mangrove stands in northern Madagascar (adapted from Kiener 1972; km^2).

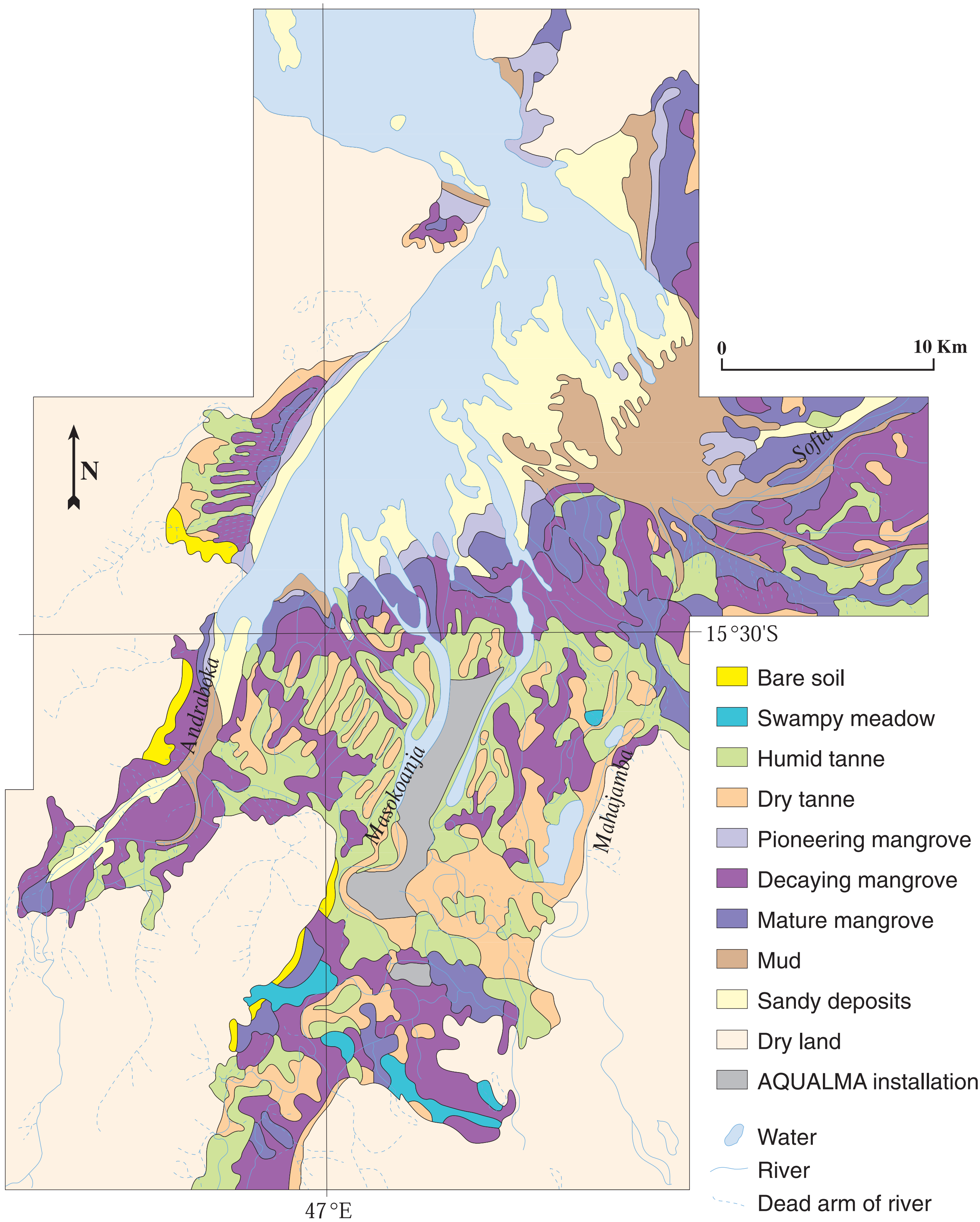

Fig. 4. Dynamics of mangrove in Mahajamba Bay, 1995. Sources: base map 1953; digital processing of SPOT images August 1986 and April 1993; field survey 1995 (reprinted from Rasolofoharinoro *et al*. 1998).

Table 2. Summary of knowledge of the mangroves of Mahajamba Bay (Madagascar Island) (Rasolofoharinoro *et al*. 1998)

Field survey only	SPOT data, validated with aerial photos and field survey
Mean annual rainfall 1420 mm year^{-1}	Water
Dry season 8 consecutive dry months (April–November)	Barren soils including sandy deposits, muds etc
Frequent risk of cyclonic storms	Swampy meadows
Large catchment area	Open mangrove stands
Mean water salinity 25–30	Dense mature mangrove
Dominant soil type clayey–loamy (surface)	
pH of topsoil 5 to 6.5	
Average tidal amplitude 1 to 3 m	
Average population density < 5 inhab. km^{-2}	
Dominant mangrove types: tall dense mature mangroves and senescent sub-types	
Area ~400 km^2 (total for Madagascar ~3000 km^2)	
Main mangrove species: 7 tree species only: *Avicennia marina, Ceriops tagal, Rhizophora mucronata, Sonneratia alba, Xylocarpus granatum, Salvadora angustifolia, Bruguiera gymnorhiza*	

mangroves, ranks third, after Indonesia (presumably more than 15 000 km^2) and Australia (11600 km^2).

The main issue for decision makers, managers and foresters is a clear evaluation of the various mangrove sub-classes included in the class 'mangrove'. Ideally, the following sub-classes should be discriminated and duly characterized from their ecological and floristic properties, and ultimately mapped: tall dense mangrove; low dense mangrove; open mangrove stands; mixed grassy and woody halophytes; and almost-barren saltish soils. These levels of discrimination can be reached only when mapping procedures are carried out at large scales, i.e. 1 / 25 000 to 1 / 50 000; however, the height of the vegetation cannot be directly determined from space.

In summary, there is no standard method or predetermined recipe for satellite data processing that could be applied to any mangrove type in the world. The monitoring of mangroves is operational at a local level, whereas permanent monitoring of the ecosystems both at local and at regional levels is premature. The accuracy of cartographic products is closely related to the season of satellite data acquisition and to the adapted image processing method. The image analysis of SPOT or Landsat TM data is usually very useful, at least for the discrimination of five main mangrove physiognomic sub-classes.

World mangrove resources

Some of the above conclusions have been illustrated in the 'World Mangrove Atlas' (Spalding *et al.* 1997). The idea of writing a book related to the distribution, mapping and

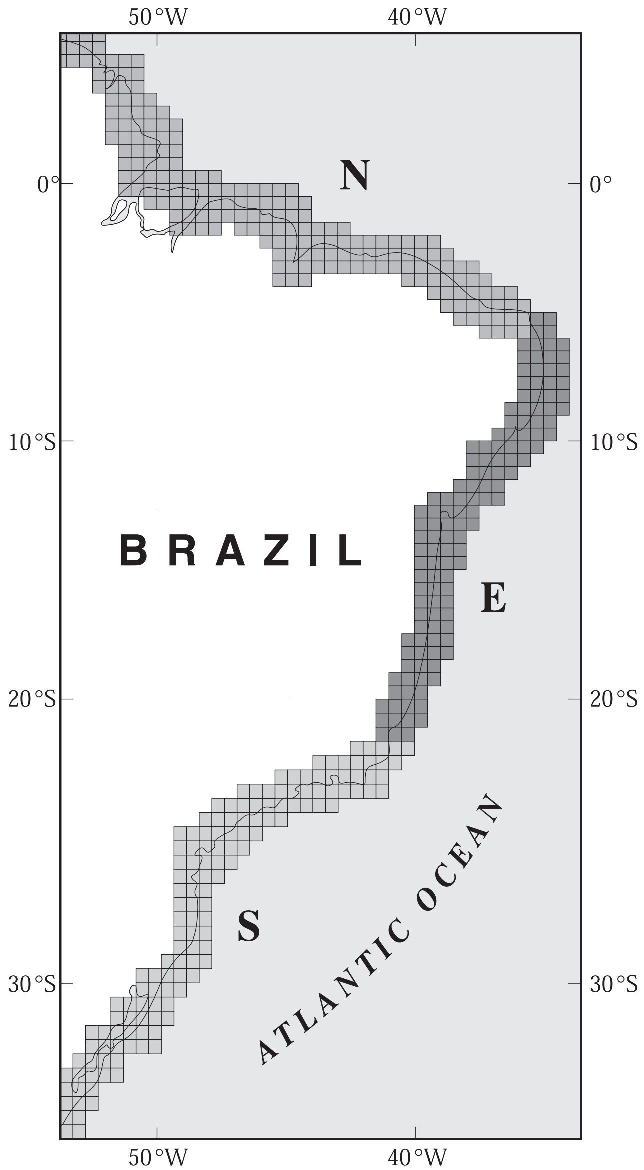

Fig. 5. Mangroves of Brazil (adapted from Herz 1991). N, northern coast, 8605 km^2 of mangroves; E, eastern coast, 998 km^2 of mangroves; S, southern coast, 521 km^2 of mangroves. Each square refers to a coastal map derived from radar images (Xband).

current known status of mangroves ecosystem emerged from the International Society of Mangrove Ecosystems (ISME, Okinawa, Japan) and the International Tropical Timber Organization (ITTO). The authors were aware of potential risks of omissions, of misinterpretation and of errors. However, it was considered that in this specific field of research, dealing with very vulnerable ecosystems that are threatened on at least 50% of tropical coasts, an approximate assessment and a provisional account would be preferable to a complete absence of updated information.

Among important goals, the 'Mangrove Atlas' was viewed as a baseline from which major changes related to human activities, to natural disasters or to global climatic changes could in future be measured. The second main goal was more technical; on the basis of a set of case studies, present capabilities and limitations of satellites have been demonstrated, especially in quantifying the global presence of mangroves and their changing status.

For the preparation of the atlas most data were transferred to Geographical Information Systems or other software systems for ease of processing, especially to correct geometric distortions, to convert them to a given scale or to undertake data analysis.

The global distribution of mangrove areas has been mapped in the atlas at very small scale. The 25 small-scale maps result from a synthesis of all available information for every country in the tropical and sub-tropical worlds (112 countries including many small island nations). As exemplified by Fig. 6, the mapped 'Mangrove area' is merely an indication of the location of mangroves recorded in each coastal zone. For the sake of clarity, the boundaries of each small site have been enlarged and hence should not be considered as indicative of actual mangrove area at that site. Basic socio-economic and ecological data for each country help in understanding the present status of their mangroves (Table 3).

A compilation of all available area statistics led to the conclusion that the present areal extent of mangroves is probably of the order of 180 000 km^2, of which at least 50% can be considered as dense (low or tall) woody types (Table 1).

Conclusion

The main technical and practical conclusions that have been reached so far are summarized in Table 4.

As the number of mangrove studies by remote sensing continues to grow, so does the problem of integration of multiple data sets and how to analyse them. Perhaps the most rigorous practical treatment is the result of the superimposition of visible data sets with microwave data for the delineation and areal quantification of a limited number of mangrove sub-classes (about five). Combining data sets generated from ground survey, aerial photographs and high resolution satellite data leads to more accurate estimation of all mangrove resources and the ecological conditions that influence them than does the analysis of SPOT or Landsat TM data alone.

Although the validity of the results presented in the voluminous literature on mangroves is not in question for those countries where detailed studies have been conducted recently, some mangrove data in poorly known coastal areas are merely indicative (Spalding *et al.* 1997).

This review of the present capabilities of remote sensing tools for mangrove studies has resulted in the identification of several urgent research needs, the most noteworthy being as follows.

Synergy between visible and microwave wavelengths especially for sub-equatorial coastal areas, where data acquisition is a major practical problem, such as Guiana, Cameroon, Gabon and Papua New Guinea (Gastellu-Etchegorry 1987; Nezri *et al.* 1993; Dale *et al.* 1996).

To test the new generation of instruments providing data with very high ground resolution (5–10 m), especially for the discrimination and classification of mangrove sub-types and coastal degradation processes.

Table 3. Examples of synthetized data provided (Spalding *et al.* 1997) for two countries having mangroves

Singapore	
Land area	620 km^2
Total forest extent (1990)	40 km^2
Population (1995)	2 853 000
Gross National Product (1992)	$US15 790 per capita
Mean monthly temperature range	26–27°C
Mean annual rainfall	2358 mm
Spring tidal amplitude	3.5 m
Alternative estimate of mangrove area (Chou 1990)	6 km^2
Area of mangrove on the map	no data
No. protected areas with mangrove	2

Sri Lanka	
Land area	65 610 km^2
Total forest extent (1990)	17 460 km^2
Population (1995)	18 346 000
Gross National Product (1992)	$US540 per capita
Mean monthly temperature range (Colombo)	27–28°C
Mean monthly temperature range (Trincomalee)	26–30°C
Mean annual rainfall (Colombo)	2424 mm
Mean annual rainfall (Trincomalee)	1580 mm
Spring tidal amplitude	< 1 m
Alternative estimate of mangrove area (Jayewardene 1986)	63 km^2
Area of mangrove on the map	89 km^2
Number of protected areas with mangrove	8

To determine the reliability of phenological studies with remote sensing data.

To implement the practical applications of remote sensing data to mangrove inventories and monitoring in various parts of the world, where their conversion to other uses is extremely rapid, as it is in Thailand (aquaculture), in West Africa (agriculture) and in East Africa or in southern Brazil (industrialization).

Fig. 6. One of the regional maps representing the distribution of mangroves at a global level in the World Mangrove Atlas (Spalding *et al.* 1997).

Table 4. Remote sensing technology applied to mangrove studies

Instrument Spectral band Resolution	Area coverage and repetition rate	Criteria of discrimination	Suitable mapping scale	Detected data	Applications
NOAA-AVHRR ch. 1: 0.58–0.68 µm ch. 2: 0.72–1.1 µm 1.1 × 1.1 km	Width 2700 km daily	Radiometric, geographic	1/1 000 000	Broad approximate distribution of large mangrove	Extremely rare (Sunderbans)
LANDSAT MSS ch. 5: 0.61–0.69 µm ch. 7: 0.8–1.1 µm 60 × 80 m (see also Mos: MESSR)	185 × 185 km 18 days	Broad physiognomy	1/250 000	One or two dominant sub-classes – dense mangrove – open intertidal ecosystems	Few – global distribution – regional studies (Gulf of Guinea)
LANDSAT TM ch. 3: 0.63–0.69 µm ch. 4: 0.76–0.90 µm 30 × 30 m or SPOT HRV XS.2: 0.61–0.68 µm XS.3: 0.76–0.89 µm 20 × 20 m or 10 m	185 × 185 km 16 days 60 × 60 km 26 days to 3 days	Density, phenology, hydrological status, human impacts	1/25 000 to 1/50 000	– dense mangrove – open mangroves – mixed grassy and woody halophytes – almost barren dry saltish soils – mudflats – degraded stages – agriculture and aquaculture	Numerous – cartographic inventories – conversion of mangroves – conservation
AERIAL PHOTOS Infrared or panchromatic	Average frequency 10 to 20 years	As above + height + floristics	1/5 000 to 1/25 000	As above tall dense *Rhizophora* stand > 15 m	Mainly unpublished forest working plans
FROM THE GROUND	Seasonal access	Biological data, ecological data	Test sites, experiments	As above + standing stock. Biovolumes, productivity, salinity, pH, tidal regime, biodiversity etc.	Academic research and conversion or management
ERS 1, ERS 2, JERS 1 Band C: 5–7 cm 30 × 30 m	100 × 100 km daily	Broad physiognomy geomorphology	1/50 000?	Still at a research level (Guiana, Thailand, West Africa etc.)	Complementary to Landsat TM and SPOT research level

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