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

F. DAHDOUH-GUEBAS[1,*], T. ZETTERSTRÖM[1,2], P. RÖNNBÄCK[2], M. TROELL[2,3], A. WICKRAMASINGHE[4] and N. KOEDAM[1]

[1]*Laboratory of General Botany and Nature Management, Mangrove Management Group, Vrije Universiteit Brussel, Pleinlaan 2, B-1050 Brussels, Belgium*

[2]*Department of Systems Ecology, Stockholm University, Frescati Backe, SE-106 91 Stockholm, Sweden (pat@system.ecology.su.se)*

[3]*The Beijer International Institute of Ecological Economics, The Royal Swedish Academy of Sciences, Box 50005, SE-104 05 Stockholm, Sweden*

[4]*Small Fishers Federation of Lanka (SFFL), Pambala-Kakkapalliya, PO Box 1, Chilaw, Sri Lanka*

*(*author for correspondence, e-mail: fdahdouh@vub.ac.be, nikoedam@vub.ac.be; fax: +32 2 629 34 13; tel.: +32 2 629 39 22)*

(Received 7 June 2001; accepted 10 October 2001)

Abstract. Shrimp aquaculture is currently one of the major threats to mangroves, their destruction causing both environmental and social problems. This study investigated the mangrove area in the Pambala–Chilaw Lagoon complex (07°30′ N, 079°49′ E) in Sri Lanka. Using air-borne remote sensing, a land-use map was constructed in a geographical information system of the study area and pond managers were interviewed about the functioning of their shrimp farms. Based on fieldwork during the four years after taking the aerial photographs, an updated GIS-based land-use map was constructed and compared the original situation. This revealed that shrimp farms had expanded with by 25 ha in four years, mainly at the expense of mangrove forest (approx. 13 ha) and coconut plantations (approx. 11 ha). Official documents from the World Conservation Union advise conservation of the undisturbed habitats in Pambala, but this study's observations do not corroborate an eventuation of this. Other authors reported political patronage as the main cause of this adverse situation. Since the shrimp industry depends on various ecological services provided by the mangrove ecosystem in order to maintain production (cf. ecological footprint concept) the mangrove destruction is counter-productive and these observations are therefore alarming for the aquaculturists as well. The low ratio (2.6 : 1) of remaining mangrove to shrimp pond area suggests that the industry may experience severe problems, particularly as mangrove areas continue to be reclaimed for aquaculture or other land uses, unless drastic measures are taken.

Key words: mangrove, aquaculture, aerial photography, Sri Lanka

1. Introduction

1.1. MONITORING CHANGES IN MANGROVES

Since the dawn of civilisation, the oceans and coastal areas have played a key role in the development of human societies and communities. Mangroves and associated ecosystems are among the biologically most productive, socio-economically important, aesthetically attractive and ecologically indispensable ecosystems in the tropics (IUCN, 1996), characteristics that should place mangroves high on the conservation agenda. These values have been recognised and are well established among both scientists and local people, and a will to protect and manage these invaluable ecosystems can be discerned (e.g. Charter for Mangroves, Field, 1995). However, for a long time mangroves have been regarded as wastelands, and destroyed accordingly (Hamilton et al., 1989). The mangrove areas of Sri Lanka have also been reduced and impoverished in quality under an increasing human pressure (De Silva and Balasubramaniam, 1984–85; Jayewardene, 1986). In recent years, shrimp farming has emerged as a major threat to mangrove ecosystems in Sri Lanka (Jayasinghe and De Silva, 1993).

Apart from a clear understanding of the nature and dynamics of local mangrove ecosystems (Field, 1996), accurate information for managers and policy makers is crucial for rational management of mangroves. However, for many countries such data are not available. To address the primary, direct conservation threats, there is a need for a programme of detection and quantification of mangrove forest loss. Remote sensing has been used successfully to quantify mangrove losses in, for example, India (Nayak et al., 1997), Ecuador (Farnsworth and Ellison, 1997), Thailand (Aschbacher et al., 1995) and Sri Lanka (Dahdouh-Guebas et al., 2000; Dahdouh-Guebas 2001). The use of aerial photography and other remote sensing technology on mangroves in combination with geographical information systems (GIS) offers a useful tool for monitoring the coastal environment (e.g. Zainal et al., 1993; Blasco et al., 1998; Dahdouh-Guebas et al., 1999). However, in many countries legislative impediments and military bans on aerial and space-borne data gathering have been obstacles to this process (Farnsworth and Ellison, 1997). For Sri Lanka, the use of aerial photography has been found to be particularly appropriate for monitoring mangrove vegetation (Dahdouh-Guebas et al., 2000; Verheyden et al., 2002), and complemented with other information in a GIS it may act as a tool for enforcing conservation.

1.2. Shrimp farming in Sri Lanka

There is no traditional aquaculture in Sri Lanka, as there is in China and India (Jayasekara, 1993). Shrimp farming did not start until the mid-1980s in the western coastal belt between Kalpitiya and Negombo, but there has been a rapid expansion in shrimp cultivation in recent years (Jayasinghe and De Silva, 1993; Foell et al., 1999). In 1996, Sri Lanka produced 4000 metric tons of shrimp (*Penaeus monodon* Fabricius) at a value of US$ 540,000 (FAO, 1998), and during the period 1985–1992 it contributed between 53% and 73% of the total foreign exchange earnings from the fisheries sector (Jayasinghe and Macintosh, 1993). As recently as 1997, the Director of the Aquaculture Development Division, Ministry of Fisheries and Aquatic Resources in Sri Lanka stated that more areas were to be brought under shrimp farming (Jayasekara, 1997).

In the beginning of commercial shrimp culture in Sri Lanka, most of the large-scale shrimp farms adopted intensive culture practices, which depend on hatchery-bred post larvae, high stocking density, use of formulated feeds, application of aeration and intensive water management. However, in the late 1980s outbreaks of diseases made the majority of farmers change to semi-intensive systems, in which the stocking density is 15–20 post larvae per square meter (Dayaratne et al., 1997). According to Jayasinghe and De Silva (1993) shrimp farming in Sri Lanka can today be categorised broadly into three levels of operation (Table I). The first is comprised of companies involved in large-scale operations with large investment costs. These companies usually have some form of joint collaboration with foreign personnel or companies and have satisfactory technologies. The second group consists of farms that primarily depend on local technology and have moderate investment costs. The third group consists of farmers who operate small-scale farms, usually not larger than 1 ha, that are often constructed on private land (De Silva and Jayasinghe, 1993).

To set up a shrimp farm one must have the approval of the Inter-Ministerial Scoping Committee, which is a multidisciplinary body representing all government agencies involved in the management of the coastal area. Farms of less than 1 ha are usually exempted from this procedure as well as those set up on private land (Jayasinghe and De Silva, 1993). The government policy of Sri Lanka has been based for a long time on the promotion of small-scale business through projects such as the poverty alleviation programme and encouraging small enterprises (De Silva and Jayasinghe, 1993). In addition there is the problem of political patronage in acquiring the respective lands for aquaculture (Foell et al., 1999). This has resulted

TABLE I. Comparison of the three shrimp farming levels in Sri Lanka (De Silva and Jayasinghe, 1993).

	Large scale	Medium scale	Small scale
Stocking density (post larvae m^{-2})	>10	5–12	5–10
Average farm area (ha)	>15	2–15	0.5–0.7
Average pond size (ha)	1.2	1.2	0.6
Aeration	With aeration	With or without aeration	No aeration
Feed	Formulated	Formulated	Formulated and supplementary
Land ownership	State-owned	State-owned	Private or state-owned
Number of culture cycles per year	2.5	2–2.5	2
Average production (kg ha^{-1} per year)	2000–3500	1500–2500	1200–1700
Investment	Local + foreign collaboration	Local	Local

in an increased number of small farms, which have been designed and brought into operation in an *ad hoc* manner. As a result, the operating procedures are not well defined and this invariably leads to problems (De Silva and Jayasinghe, 1993). As mentioned before, most farms of this category have been constructed on private land, and proper site selection has usually not taken place (De Silva and Jayasinghe, 1993), a counter-productive approach when it comes to reducing the environmental impacts of pond aquaculture (Boyd, 2000). No conditions are made due to the small farm size, and environmental impact assessments are only required for farms larger than 4 ha (Dayaratne et al., 1995). It is unfortunate that Sri Lanka, being the first tropical country with a centrally managed integrated coastal zone management (ICZM) programme (Clarke, 1996), featured a situation that is rather contrary to the spirit of ICZM.

Pond preparation is similar for all operational levels and the species of shrimp cultured is the tiger prawn *Penaeus monodon* (Corea et al., 1995). The farms use post-larvae shrimp, depending upon commercial hatcheries for stocking, but the hatcheries still depend upon wild caught gravid female broodstock. Private enterprises supply imported aquatic feeds (De Silva and Jayasinghe, 1993), the use of which has recently been reported to introduce an element of inefficiency in the production of aquatic species, because of its disproportionate formula cost (Suresh, 2000). However, this must be regarded from the point of view of protein conversion and not from an economic perspective.

At the initial stages of the cultivation cycle, water is pumped into the ponds mainly to replace water lost through seepage and evaporation. Extensive seepage and other technical problems caused by improper design may result in increased fuel costs, which together with the cost of feed are the most important variable costs (loc. cit.). These are also the inputs that cause the greatest environmental impacts. Therefore, a reduction in feed and fuel consumption would not only benefit the environment, but also result in greater profitability.

1.3. Reduced yield from fisheries

Fishing is the most important economic activity in the coastal regions of Sri Lanka, and many communities depend upon it for their livelihood. Fish also constitutes approximately 65% of the animal protein consumption and 13% of the total protein intake for the population of Sri Lanka (Rajasuriya et al., 1995). Mangrove areas provide food and shelter for many commercially important species, and a positive correlation has been observed between near shore coastal shrimp and fish catches and mangrove area cover (Singh et al., 1994; Baran and Hambrey, 1998; de Graaf and Xuan, 1998; Baran, 1999; Rönnbäck, 1999; Naylor et al., 2000). Analysis of the data available from the Pambala–Chilaw Lagoon complex shows that the fish catch from the lagoon per unit effort has dropped on average from 4 to 1.5 kg between 1994 and 1997 (Wickramasinghe, 1997). Similar situations prevail in a majority of the lagoons in Sri Lanka, and the deterioration of mangrove vegetation is considered to be one of the main causes for this reduction in fish harvest (Wickramasinghe, 1997). A reduced yield in fisheries may seriously affect the nutrition of local communities. Mangrove degradation may also reduce the availability of wild shrimp, caught as broodstock, thus shrimp farmers that reclaim mangrove areas create a negative loop for themselves.

2. Objective of the study and area description

This study aims to quantify, by the aid of aerial photography and GIS, the extent of mangroves and shrimp farms in Pambala and their recent (1994–1999) changes, and to document the ecological support from mangroves to shrimp farming (in part reviewed in the introduction), as a first step in investigating the sustainability of the shrimp industry in the Pambala–Chilaw Lagoon complex.

The study site was Pambala (07°30′ N, 079°49′ E), also called the Pambala–Chilaw Lagoon complex, the southern part of Chilaw Lagoon on the west coast of Sri Lanka (Figure 1), located in the island's intermediate climate zone (Mueller-Dombois, 1968). The mangroves here are of the fringe or riverine type (Lugo and Snedaker, 1974), and have a rather irregular distribution along a complex of creeks (Marambettiya Ela, Bate Ela, Pol Ela and Dutch Channel). There are, however, no rivers streaming directly into the lagoon. Most freshwater influx stems from the Karambalan Oya catchment and rainwater runoff channels from inland to the lagoon form at regular intervals. In- and outflow from and to the sea is possible at Chilaw (07°35′48″ N, 079°47′25″ E) and Toduwawa (07°29′30″ N, 079°48′16″ E). With 16 mangrove species, excl. an introduced *Nypa fruticans* (Thunb.) Wurmb. and an as yet unidentified specimen of the genus *Rhizophora* (Jayatissa, Abeysinghe, Dahdouh-Guebas, Duke, Hettiarachchi, Triest and Koedam, unpublished results), they constitute the most species-diverse mangrove along the south-western coast of Sri Lanka (Jayatissa et al., 2002). The nearest important mangrove forests (both in terms of area and ecological functioning) to Chilaw Lagoon are located in Negombo Lagoon and Puttalam Lagoon, about 40 km away along either side of the coastline. There are some mangroves around Mundel Lake, but this area has been severely degraded due to wood extraction and the explosive expansion of shrimp farm activities (Wetland Conservation Project, 1992).

Pambala is a relatively unaffected mangrove site that has been proposed for conservation (IUCN, 1996). The mangrove areas of Chilaw Lagoon have for a long time sustained the subsistence economies of the surrounding human communities, especially through provision of firewood, poles, posts, tanbark and also crabs, shrimps, molluscs and a variety of finfish for consumption (Liyanage, 1997). An important feature in (Pambala-) Kakkapalliya is the recent establishment of the Small Fishers Federation of Lanka (SFFL), a non-governmental organisation (NGO) concerned with the well-being of the local fishing community, including their wives and children, and with eco-friendly projects and mangrove conservation (Liyanage, 1997; Wickramasinghe, 1997; Wickramasinghe and Dahdouh-Guebas, 2000).

3. Material and methods

The study was based on an aerial photograph of the study site of scale 1 : 20,000, that was photographically magnified to 1 : 10,000 (N. Koedam, Ilford 100 Delta). The photographic copy (Figure 1) was scanned and imported in a GIS-environment

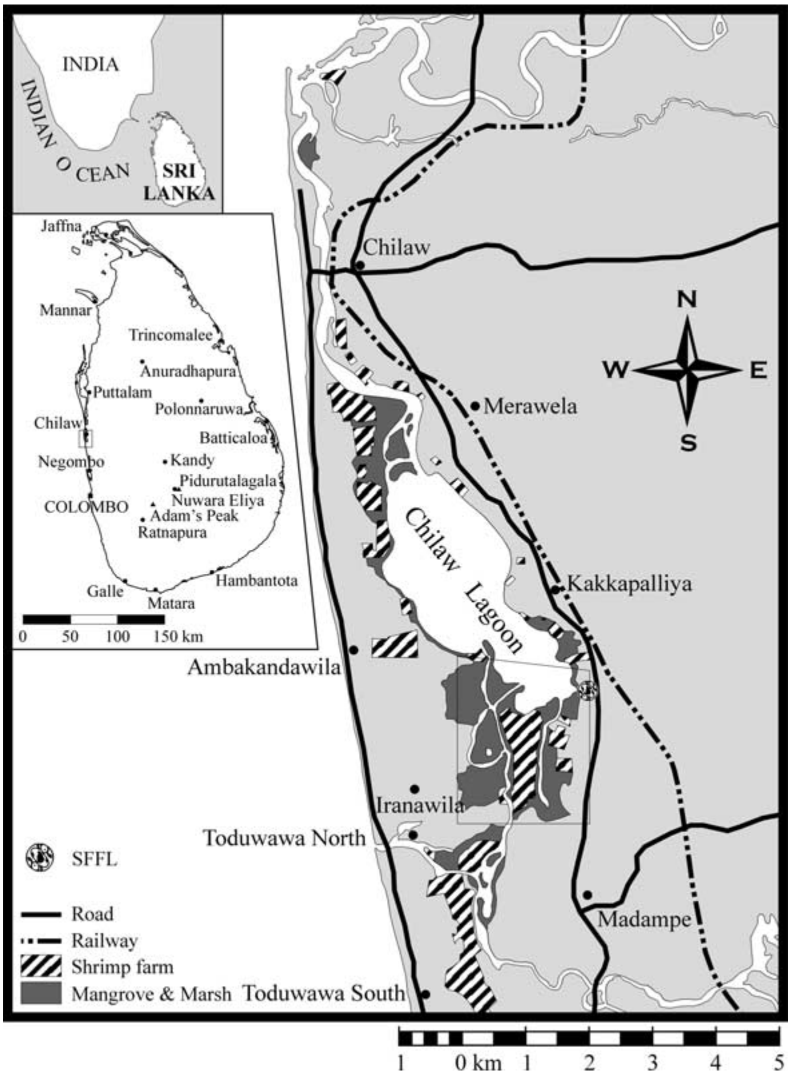

Figure 1. Map showing the location of Sri Lanka in the Indian Ocean and some of the major cities on the island. Chilaw Lagoon has been shown in close-up and the exact location of our study site in the complex of creeks in Pambala (= coverage of aerial photograph) is indicated by the trapezium shaped frame (cf. Figures 2–4).

using the computer applications MapClass and MapGrafix on a Macintosh computer platform. Different land-use patterns were digitalised and identified on the aerial photograph, and a colour map for 1994 was constructed. Using ground-truth and field observations from the main fieldwork expedition in April 1998 (some observations were made in February 1997 and some aspects reconfirmed during a fieldwork expedition in November 1999 in the framework of another study), the 1994 map was modified, correcting for the changes in land use, to produce a new map. Global Positioning System points (GPS-points) were recorded in the field, but due to access restrictions in the shrimp farm areas, this ground-truth activity was unable to penetrate to all areas (e.g. all corners of shrimp pond areas), the depth (away from the observer) of which therefore had to be estimated visually in the field using landmarks such as constructions and roads or tracks. In two cases where landmarks were less obvious the area depth was presumably underestimated. The area of mangroves, shrimp farms and coconut plantations in the GIS were quantified in both maps, which constituted different GIS layers, to show the loss of mangroves and coconut plantations, and the expansion of shrimp farms in more detail. The three areas in the Pambala–Chilaw Lagoon complex where shrimp farming occurs were visited in May 1998 and some pond managers were interviewed. Visual observations and interviews with local people were also carried out whenever possible, during the field work missions, in order to gather additional information on the Pambala–Chilaw Lagoon complex and the mangrove area (e.g. past conditions).

4. Results

4.1. Remote sensing of land-use patterns

A broad classification of different types of vegetation and land-use patterns was done, and nine different classes were identified from the aerial photographs: water, mangrove, mangrove regeneration plots, terrestrial vegetation, coconut plantations, shrimp farms (incl. one fish farm), open space, infrastructure and inhabited area (Figures 2 and 3). The area of the fenced broadcasting facility of the Voice of America (recently referred to as the International Broadcasting Bureau), has been highlighted differently (Figure 3b). The major land-use in this area is by coconut plantations and more recently shrimp farming, both of these have reclaimed mangrove areas. The area in the middle of the maps shows a large shrimp farm facility built in 1964 (Figures 2 and 3), that was previously composed of mangrove forest (Daglas Thisera, Coordinator Mangrove Conservation and Education, SFFL, pers. comm.).

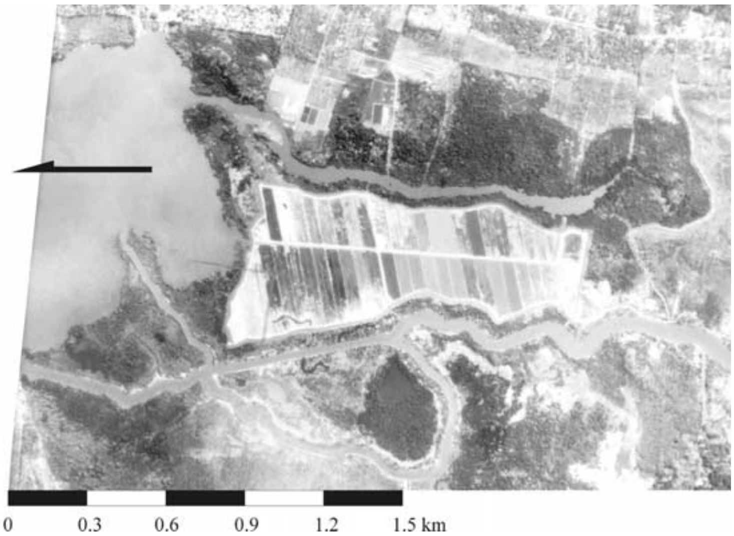

Figure 2. Aerial photograph (1994) of the study area in Pambala (Chilaw Lagoon, Sri Lanka), showing the complex of creeks. The arrow indicates the North.

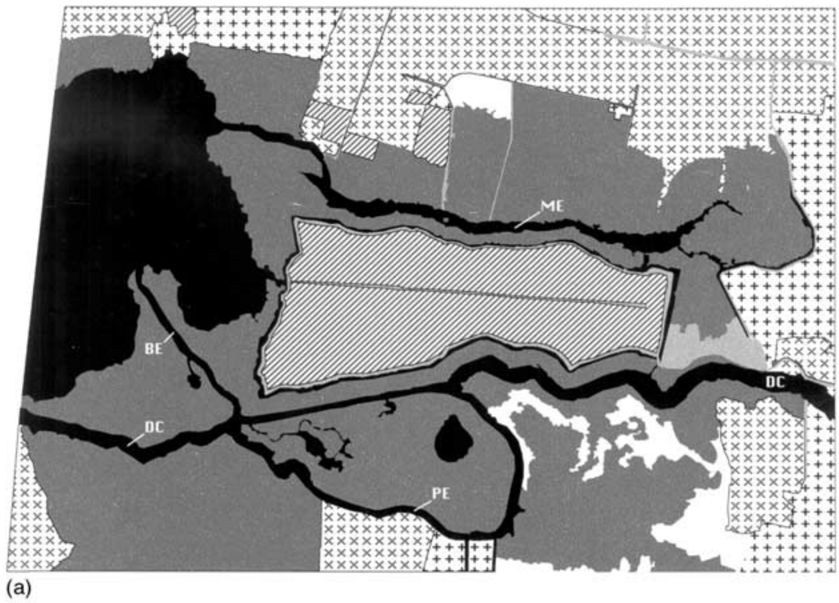

Figure 3. Land-use map of the Pambala–Chilaw Lagoon complex in 1994 (a) and 1998 (b). The borders of the territory of the Voice of America (VOA) broadcasting infrastructure are approximate, and some original vegetation may still be present within the territory. Refer to Figure 2 for scale and orientation of the map. Numbers correspond to the shrimp farms of which the managers were interviewed (see text). ME = Marambettiya Ela; BE = Bate Ela; PE = Pol Ela; DC = Dutch Channel.

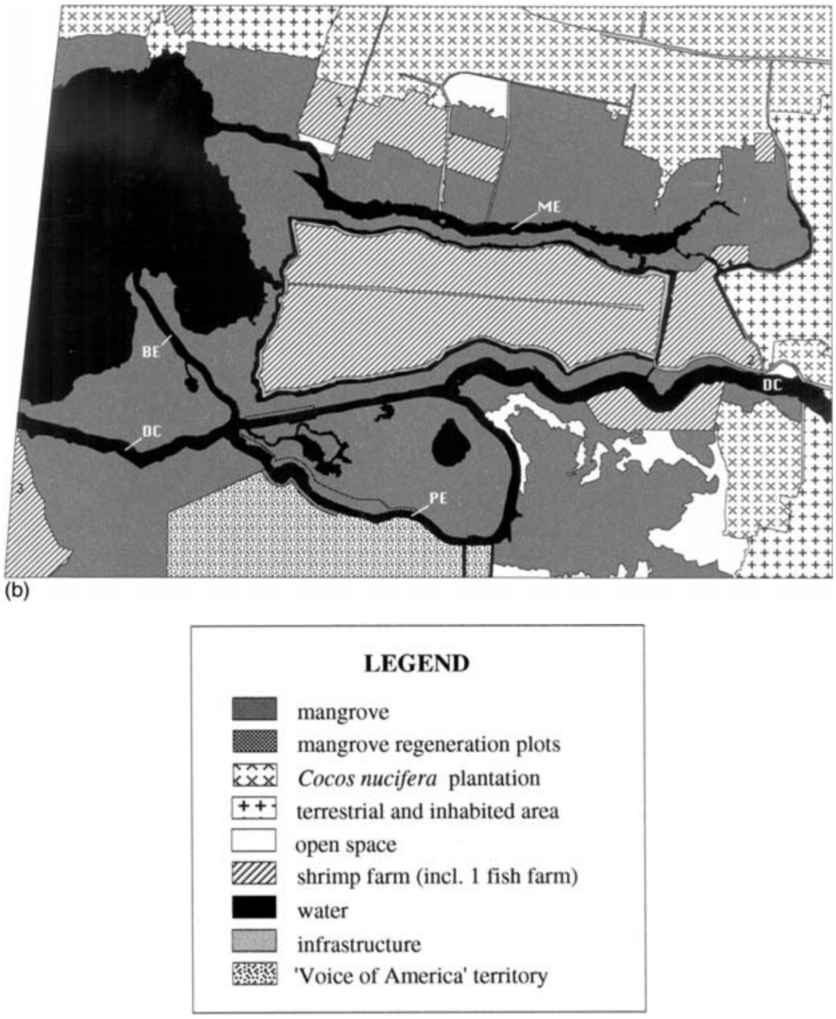

Figure 3. (*Continued*)

The quantifications of the changes in land-use patterns between 1994 and 1998 are shown in Table II. The shrimp farms have expanded to include another 25 ha of land, an increase of almost 50%, compared to the area on the photograph of 1994. This expansion mainly occurred at the expense of mangroves, almost 13 ha, and coconut plantations, 11 ha. In addition to the shrimp farms there was one fish farm, covering 0.73 ha, in the area. It was however temporarily out of use or abandoned when visited in 1998 (also in 1999).

Calculations of the area of the shrimp farms in relation to the remaining mangroves, within the maps, show a ratio of about 1 : 4 in 1994 and 1 : 2.6 in 1998 (Table II). It was also noted that there are few other mangrove areas, which could serve as support, in the vicinity outside of the aerial photograph shown. In fact, the ratio of mangroves to shrimp farms over the entire lagoon was approximately

TABLE II. Areas occupied by the three major land-use patterns in 1994 and 1998 in Pambala, with indication of the ratio of the area of shrimp farm to mangrove, and the changes with respect to the situation in 1994. Between brackets is the percentage of total land area.

Land use	1994 (ha)	1998 (ha)	Changes (%)
(1) Shrimp farms	51.87 (14.7%)	76.99 (21.8%)	+48.4 (+7.1)
(2) Mangroves	209.29 (59.4%)	196.53 (55.6%)	−6.1 (−3.8)
(3) Coconut plantation	91.30 (25.9%)	80.08 (22.7%)	−12.3 (−3.3)
(1) : (2) ratio	1 : 4	1 : 2.6	

1 : 1, and increasingly less mangrove and more shrimp farms can be observed (Dahdouh-Guebas, unpublished data, 1999). An IKONOS satellite image taken in January 2002 corroborates this observation (Dahdouh-Guebas, unpublished data, 2002).

A mangrove rehabilitation project ran by SFFL, lead to the plantation of about 50 000 mangrove seedlings in Pambala Lagoon (Anuradha Wickramasinghe and Daglas Thisera, SFFL, pers. comm., 1997). The reforestation plots were visited in the field and estimated to cover about 2.4 ha.

4.2. Interviews with pond managers

The interviews revealed that most of the farms were privately owned by local people, except for a recently established one that had Swiss ownership (this farm occupies the entire area indicated as number 3 in Figure 3b). It was not possible to interview anybody from the very large shrimp farm since it had also been out of operation for more than one year, due to problems with the White Spot Syndrome Virus (WSSV). None of the shrimp farm managers interviewed acknowledged that any mangroves had been cleared during construction of their ponds, even though this clearly seems to have been the case, as is evident from a comparison between the two land-use maps. In many cases coconut plantations were said to have been converted, but it is likely that these areas had been mangrove forests before as well. Most embankments were created with the dug soil by use of heavy machinery, except for farm No 3 (Figure 3), which had concrete ponds. The farms had been established by private investment and bank loans. None of the operators had received other financial support, for example, subsidies or tax reductions.

According to the interviews, the production of the different farms varied between 3000 and 6000 kg ha^{-1} per cycle and two cycles per year could generally be completed. All farms used supplementary feed, with formulated feed imported from India, Taiwan, Indonesia and Malaysia. The formulated feed usually contained fishmeal and wheat flour, and also shrimp meal. The feed reportedly had a high protein content, of around 40%, and feeding was generally conducted two to five times a day, and the rations were also adjusted depending on the phase of the grow-out cycle. Feeding was done by hand, and none of the farmers mentioned additional feeding with locally available material, such as agricultural waste or local bivalves.

All farms used mechanical aeration by paddling/stirring to maintain sufficient oxygen levels in the pond water. Farm No 3 also had aerometers pumping the water in their ponds. These were all run on electricity and some farms had their own generators in case of power cuts.

After each cycle of production the ponds were completely emptied. The waste water was emitted into the same water body as intakes were made from, however tides were taken into account in order to help separate effluent from intake. During operation, different ponds used somewhat different methods of water exchange, but most changed half of the pond every week. This was done directly with the water in the canals or lagoon. No farm used sedimentation ponds, but farm No 3 had a recycling system that could be used in case of quality problems with the intake water.

Farm No 3 had its own hatchery, where 95% of the hatching eggs were for their own farming purposes. Gravid females were caught in the wild, and they had a special working unit to ensure their origin. They had earlier experienced problems with shrimp that had been sold as collected wild from the ocean, whereas in fact they had been raised in other shrimp farms. These shrimp had lower production rates and could bring in infections. A wild female can produce 100 000–400 000 eggs, which were kept in hatchery tanks until the larvae were large enough to be moved to rearing tanks and later to be stocked in the ponds. The regulations around the hatchery tanks and ponds of this farm were strict to minimise the risk of infection. To keep a favourable growth temperature for the larvae the water was also heated, by solar power, when necessary.

5. Discussion and conclusions

Aerial photographs offer a realistic way of continuously monitoring the mangroves, and the usefulness of aerial photographs coupled to GIS is clearly demonstrated in the case study. However, to draw conclusions on the more long-term changes in the mangrove areas, sequential aerial photography must be considered (Dahdouh-Guebas et al., 2000; 2001), which at present does not exist for the Pambala–Chilaw Lagoon complex. Recent very high resolution satellite data could also be helpful, since these data are up-to-date, continuous and increasingly more ‘on-line’, though very expensive. However, aerial photographs remain more useful when investigating the past evolution of a region, since satellite data obviously are only available for relatively recent periods or when requiring a very high resolution (Dahdouh-Guebas et al., 2000; Dahdouh-Guebas, 2002; Verheyden et al., 2002).

The land-use patterns in Pambala are of great concern for the future of the coastal and marine ecosystems in this area. The large extent of intensive agriculture has already put the mangroves under pressure, but the more recent development of shrimp farms is an even greater threat. Mangroves as well as coconut plantations have been converted into shrimp farms, but the low-lying coconut groves in Sri Lanka have originally been reclaimed from mangroves as well (Macnae, 1968).

The recent land-use change has been rapid, resulting in a 48% increase in shrimp farm area between 1994 and 1998. At the same time, documents by the IUCN (1996) for this area strongly recommend management priorities such as conservation of undisturbed habitats and restoration of disturbed and degraded habitats, protection through proper enforcement of laws and institutional reorganisation for maximising the administrative efficiency, to achieve ecological sustainability and protection of the mangrove ecosystems. The latter management objectives are clearly jeopardised by political patronage, a phenomenon reported by Foell et al. (1999) for the District in Sri Lanka in which Chilaw Lagoon is located. To overcome this problem Foell et al. (loc. cit.) suggest the acknowledgement that patrons are 'primary stakeholders' that need to be addressed and convinced that ICZM (i.e. sustainable economic growth) must have priority over short-term economic growth, which implies a pragmatic approach with political skills.

The production rates of the shrimp farms of the Pambala–Chilaw Lagoon complex would place the farms in the 'medium scale' or 'large scale' category of the classification used by De Silva and Jayasinghe (1993), or they could be classified as 'intensive' (Boyd and Clay, 1998) ($>2000\,\mathrm{kg\,ha^{-1}}$ + aeration, C.E. Boyd, pers. comm., 2000). Robertson and Phillips (1995) estimated that intensive shrimp farms in Thailand needed a *Rhizophora*-dominated forest area that was 22 times larger than the ponds themselves in order to assimilate nutrients in pond effluents (7.2 : 1 for nitrogen and 21.7 : 1 for phosphorus). Larsson et al. (1994) reported that the ecological footprint, the area to supply the resources and ecological services that sustain an activity (e.g. Kautsky et al., 1997; Folke et al., 1998), for a semi-intensive shrimp farm in Colombia, where shrimp larvae are caught in the wild, was 35–190 times larger than the surface area of the farm. Even though shrimp farms in Sri Lanka use hatchery-produced larvae, the above ratios pose immediate sustainability questions related to the low ratio of mangroves to shrimp farms for Pambala (2.6 : 1) and for the entire lagoon (1 : 1). Mangrove areas have clearly become insufficient to treat the effluents from the farms, and the farms are not at all sustainable. The consideration of the tides when releasing the effluents from the farms might not be meaningful, since the spring tidal amplitude in Sri Lanka is inferior to 1 m (Spalding et al., 1997), and in Pambala monthly variations in the lagoon's water level seldom exceed 20 cm except during heavy showers (Dahdouh-Guebas personal measurements, 1998). In the long-term, this may imply eutrophication risks and impacts in the lagoon and coastal waters, as well as an increase of health problems, such as the recent outbreaks of the WSSV. The water quality, which is also impacted by the shrimp pond sediments, has been shown to adversely affect shrimp production eventually as well (Burford et al., 2000). A decline of fisheries catches may also be observed in the long run, and the first victims will be the local people that depend upon this resource, for living and for a living.

Despite this, plans exist to further expand the shrimp farms (Jayasekara, 1997). This might reflect either ignorance of the importance of ecological services to sustain the aquaculture industry, or negligence of the same, adopting a very short-term view on economic development instead. There is an urgent need to adopt a number of priorities, strategies and in-depth planning for the development of aquaculture in light of the future economic, social and environmental issues and advances in aquaculture technologies (NACA/FAO, 2000; Costa-Pierce, 2000). A further expansion of shrimp aquaculture in Chilaw Lagoon is not advised, as it would probably cause lower returns for the existing farms and increased problems of water quality and disease in an unknown, although probably very short, time scale. The catches of the local fishermen might also further decrease if the loads on the natural ecosystems increase and more mangroves and associated ecosystems are degraded. The expansion of shrimp farms should thus be halted and sedimentation ponds and more integrated cultures could be introduced to reduce emissions and decrease the use of on ecological services (e.g. Costa-Pierce, 1988; Gautier et al., 2000). In the Pambala–Chilaw Lagoon complex the shrimp farms that were recently established should ideally be removed or converted to such integrated aquaculture. At the same time, more mangrove (re-)afforestation should be done, thus evolving towards integrated silvo-aquaculture. In this framework, abandoned shrimp farms could be both rehabilitated, and serve mangrove regeneration purposes (Stevenson et al., 1999). A conflict exists, or may arise, between the ethical (or at most the 'ethnobiological') and the conservation issues, with a drastic reduction of shrimp farms as the ideal solution from a conservation point of view, but not the optimal solution for people working in the aquaculture sector. However, without a decrease in shrimp farm area (with a parallel increase in mangrove area), the eventual situation is likely to be an adverse one for all of the stakeholders, either because the aquaculture sector, or the mangrove ecosystem (on which the aquaculture sector depends) collapses, or both. Unless measures like the ones proposed above are taken, it is likely that the Pambala–Chilaw Lagoon complex will experience more problems, with eutrophication, poor fry availability, poor water quality and consequently disease problems in addition to its competition for space. Moreover, increasing conflicts for markets, for water, for innovative technologies or biotechnologies conferring strategic advantages and better profit, and between Malthusian ideas or philosophies concerning social evolution goals (productionists vs. conservationists, pragmatics vs. idealists) are repeatedly predicted for the aquaculture sector (Harache, 2000).

Acknowledgements

We are grateful to Mr. Daglas Thisera (co-ordinator Mangrove Conservation Education and Demonstration Centre from the Small Fishers Federation of Lanka, Pambala-Kakkapalliya, Sri Lanka) for joining the shrimp farm visits and translating the interviews with the owners. We would also like to thank Fatuma M. Saidi for her practical help in the field and William De Genst, Frank Canters and Niels Kool for their assistance. The first author is a postdoctoral researcher from the Fund for Scientific Research (FWO – Flanders), and this research was also financed by the European Commission (Contract EBR IC18-CT98-0295), the Fund for Collective Fundamental Research (FKFO), and with a specialisation fellowship of the

Institute for the Promotion of Innovation by Science and Technology in Flanders (IWT). This work was in part presented at the European Aquaculture Society's International Conference "AQUA 2000: Responsible aquaculture in the new millenium.", 2–6 May 2000, Nice, France.

References

Aschbacher, J., Ofren, R., Delsol, J.P., Suselo, T.B., Vibulsresth, S. and Charrupat, T.: 1995, 'An integrated comparative approach to mangrove vegetation mapping using advanced remote sensing and GIS technologies: preliminary results', *Hydrobiologia* **295**, 285–294.

Baran, E.: 1999, 'A review of quantified relationships between mangroves and coastal resources', *Phuket Marine Biology Centre Research Bulletin* **62**, 57–64.

Baran, E. and Hambrey, J.: 1998, 'Mangrove conservation and coastal management in southeast Asia: What impact on fishery resources?', *Marine Pollution Bulletin* **37**(8–12), 431–440.

Blasco, F., Gauquelin, T., Rasolofoharinoro, M., Denis, J., Aizpuru, M. and Caldairou, V.: 1998, 'Recent advances in mangrove studies using remote sensing data', *Marine and Freshwater Research* **49**(4), 287–296.

Boyd, C.E.: 2000, 'Reduction in environmental impact of pond aquaculture through proper site selection, design and construction', in *Responsible Aquaculture in the New Millenium.* Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, 89 pp.

Boyd, C.E. and Clay, J.W.: 1998, 'Shrimp aquaculture and the evironment', *Scientific American* June, 42–49.

Burford, M.A., Longmore, A., Preston, N.P. and Dennison, W.C.: 2000, 'The effect of shrimp pond sediments on water quality', in *Responsible Aquaculture in the New Millenium.* Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, 99 pp.

Clarke, J.: 1996, *Coastal Zone Management Handbook.* Lewis Publishers, New York, USA.

Corea, A.S.L.E., Jayasinghe, J.M.P.K., Ekaratne, S.U.K. and Johnstone, R.: 1995, 'Environmental impact of prawn farming on Dutch Canal: the main water source for the prawn culture industry in Sri Lanka', *Ambio* **24**(7–8), 423–427.

Costa-Pierce, B.A.: 1988, 'Traditional fisheries and dualism in Indonesia', *Naga: The ICLARM Quarterly* **11**(2), 3–4.

Costa-Pierce, B.A.: 2000, 'Aquaculture ecosystems', in *Responsible Aquaculture in the New Millenium.* Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, 150 pp.

Dahdouh-Guebas, F.: 2001, *Mangrove Vegetation Structure Dynamics and Regeneration.* PhD dissertation, Vrije Universiteit Brussel, Brussels, Belgium. 317 pp.

Dahdouh-Guebas, F.: 2002, The use of remote sensing and GiS in the sustainable management of tropical coastal ecosystems. In F. Dahdouh-Guebas (ed.) Remote sensing and GiS in the sustainable management of tropical coastal ecosystems, *Environment, Development and Sustainability* **4**(2), 93–112.

Dahdouh-Guebas, F., Coppejans, E. and Van Speybroeck, D.: 1999, 'Remote sensing and zonation of seagrasses and algae along the Kenyan coast', *Hydrobiologia* **400**, 63–73.

Dahdouh-Guebas, F., Verheyden, A., De Genst, W., Hettiarachchi, S. and Koedam, N.: 2000, 'Four decade vegetation dynamics in Sri Lankan mangroves as detected from sequential aerial photography: a case study in Galle', *Bulletin of Marine Science* **67**(2), 741–759.

Dayaratne, P., Lindén, O. and De Silva, M.W.R.N.: 1995, 'Puttalam Lagoon and Mundel Lake, Sri Lanka: a study of coastal resources, their utilisation, environmental issues and management options', *Ambio* **24**(7–8), 391–401.

Dayaratne, P., Lindén, O. and De Silva, M.W.R.N.: 1997, *The Puttalam/Mundel Estuarine System and Associated Coastal Water.* National Aquatic Resources Research and Development Agency, Colombo, Sri Lanka/SIDA, Marine Science Programme, Department for Research Cooperation, SAREC, Stockholm, Sweden.

de Graaf, G.J. and Xuan, T.T.: 1998, 'Extensive shrimp farming, mangrove clearance and marine fisheries in the southern provinces of Vietnam', *Mangroves and Salt Marshes* **2**(3), 159–166.

De Silva, J.A. and Jayasinghe, J.M.P.K.: 1993, 'The technology and economics of small-scale commercial shrimp farms in the west coast of Sri Lanka', *Journal of Aquaculture Trop.* **8**, 141–149.

De Silva, K.H.G.M. and Balasubramaniam, S.: 1984–85, 'Some ecological aspects of the mangroves on the west coast of Sri Lanka', *Ceylon J. Sci. (Bio. Sci.)* **17**–**18**, 22–40.

FAO: 1998, FAO Fisheries Circular, No. 815, Revision 10, Food and Agricultural Organisation, Rome, Italy, 197 pp.

Farnsworth, E.J. and Ellison, A.M.: 1997, 'The global conservation status of mangroves', *Ambio* **26**(6), 328–334.

Field, C.D.: 1995, *Journey amongst Mangroves.* International Society for Mangrove Ecosystems, Okinawa, Japan. 140 pp.

Field, C.D.: 1996, *Restoration of Mangrove Ecosystems.* International Society for Mangrove Ecosystems, Okinawa, Japan.

Foell, J., Harrison, E. and Stirrat, R.L.: 1999, *Participatory Approaches to Natural Resource Management – the Case of Coastal Zone Management in the Puttalam District.* Summary findings of DFID-funded research 'participatory mechanisms for sustainable development of coastal ecosystems' (Project R6977), School of African and Asian studies, University of Sussex, Falmer, Brighton, UK.

Folke, C., Kautsky, N., Berg, H., Jansson, A. and Troell, M.: 1998, 'The ecological footprint concept for sustainable seafood production: a review', *Ecological Applications* **8**(1), 63–71.

Gautier, D., Mogollón, J.V., Ruiz, M. and Amador, J.: 2000, 'The integration of mangrove and shrimp farming: a case study', in *Responsible Aquaculture in the New Millenium.* Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, 232 pp.

Hamilton, L.S., Dixon, J.A. and Miller, G.O.: 1989, 'Mangrove forests: an undervalued resource of the land and of the sea', in E. Mann Borgese, N. Ginsburg and J.R. Morgan (eds.), *Ocean Yearbook 8*, The University of Chicago Press, Chicago, USA, pp. 254–288.

Harache, Y.: 2000, 'Responsible aquaculture in the next century: an evolutionary perspective', in *Responsible Aquaculture in the New Millenium.* Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, pp. 267–268.

IUCN: 1996, *Conservation Management Plan for Ten Selected Mangrove Sites in Northwestern Sri Lanka*, World Conservation Union, Gland, Switzerland, 80 pp.

Jayasekara, A.M.: 1997, Rural aquaculture development programme, Sri Lanka, Small Fishers Federation, Voice of Fisher Folk, Special Issue (May 1997), Pambala, Sri Lanka.

Jayasinghe, J.M.P.K. and De Silva, J.A.: 1993, 'Prawn culture development and present land-use patterns in coastal areas of Sri Lanka', in W. Erdelen, C. Preu, N. Ishwaran and C.M. Madduma Bandara (eds.), *Proceedings of the International and Interdisciplinary Symposium Ecology and Landscape Management in Sri Lanka*, Margraf Scientific Books, Weikersheim, Germany.

Jayasinghe, J.M.P.K. and Macintoch, D.J.: 1993, 'Disease outbreaks in the shrimp culture grow-out system of Sri Lanka', *Tropical Agricultural Research* **5**, 336–349.

Jayatissa, L.P., Dahdouh-Guebas, F. and Koedam, N.: 'A review of the floral composition and distribution of mangroves in Sri Lanka', *Botanical Journal of the Linnean Society* **138**, 29–43.

Jayewardene, R.P.: 1986, 'Sri Lanka', in R.M. Umali, P.M. Zamora, R.R. Gotera, R.S. Jara and A.S. Camacho (eds.), *Mangroves of Asia and the Pacific: Status and Management*, Technical Report of the UNDP/UNESCO Research and Training Pilot Programme on Mangrove Ecosystems in Asia and the Pacific (RAS/79/002), Manila, Philipines, pp. 219–230.

Kautsky, N., Berg, H., Folke, C., Larsson, J. and Troell, M.: 1997, 'Ecological footprint for assessment of resource use and development limitations in shrimp and tilapia aquaculture', *Aquaculture Research* **28**, 753–766.

Larsson, J., Folke, C. and Kautsky, N.: 1994, 'Ecological limitations and appropriation of ecosystem support by shrimp farming in Colombia', *Environmental Management* **18**(5), 663–676.

Liyanage, S.: 1997, 'Conservation of mangrove resources in Pambala–Chilaw Lagoon with community participation', in *Proceedings of the workshop on conservation and management of mangrove ecosystems*, Mangrove Conservation and Demonstration Centre, Small Fishers Federation, Pambala-Kakkapalliya, Sri Lanka, pp. 6–8.

Lugo, A.E. and Snedaker, S.C.: 1974, 'The ecology of mangroves', *Annual Review of Ecology and Systematics* **5**, 39–64.

Macnae, W.: 1968, 'A general account of the fauna and flora of mangrove swamps and forests in the Indo-West-Pacific region', *Advances in Marine Biology* **6**, 73–270.

Mueller-Dombois, D.: 1968, 'Ecogeographic analysis of a climate map of Ceylon with particular reference to vegetation', *The Ceylon Forester* **VIII**(3–4), 3–20.

NACA/FAO: 2000, *Aquaculture Development beyond 2000: the Bankok Declaration and Strategy.* Conference on Aquaculture in the Third Millenium, 20–25 February 2000, Bangkok, Thailand, NACA, Bangkok, Thailand, and FAO, Rome, Italy.

Nayak, S.A., Pandeya, A., Gupta, M.C., Trivedi, C.R., Prasad, K.N. and Kadri, S.A.: 1997, 'Application of satellite data monitoring degradation of tidal wetlands of the Gulf of Kachch, Western India', *Acta Astron.* **20**, 171–178.

Naylor, R.L., Goldburg, R.J., Primavera, J.H., Kautsky, N., Beveridge, M.C.M., Clay, J., Folke, C., Lubchenco, J., Moony, H. and Troell, M.: 2000, 'Effect of aquaculture on world fish supplies', *Nature* **405**(29), 1017–1024.

Rajasuriya, A., De Silva, M.W.R.N. and Öhman, M.C.: 1995, 'Coral reefs of Sri Lanka: human disturbance and management issues', *Ambio* **24**(7–8), 428–437.

Robertson, A.I. and Phillips, M.J.: 1995, 'Mangroves as filters of shrimp pond effluent: predictions and biogeochemical research needs', *Hydrobiologia* **295**, 311–321.

Rönnbäck, P.: 1999, 'The ecological basis for the economic value of mangrove forests in seafood production', *Ecological Economics* **29**, 235–252.

Singh, H.R., Chong, V.C., Sasekumar, A. and Lim, K.H.: 1994, 'Value of mangroves as nursery and feeding grounds', in C.R. Wilkinson, S. Sudara and C.L. Ming (eds.), *Proceedings from the Third ASEAN-Australia Symposium on Living Coastal Resources*, Bankok, Thailand, **1**, 105–116.

Spalding, M., Blasco, F. and Field, C.: 1997, *World Mangrove Atlas.* The International Society for Mangrove Ecosystems, Okinawa, Japan.

Stevenson, N.J., Lewis, R.R. and Burbridge, P.R.: 1999, 'Disused shrimp ponds and mangrove rehabilitation', in W. Streever (ed.), *An International Perspective on Wetland Restoration*, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 277–297.

Suresh, A.V.: 2000, 'Fish feed is not cheap: a look at formulation and manufacturing of aquatic feeds', in *Responsible Aquaculture in the New Millenium*, Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, 690 pp.

Verheyden, A., Dahdouh-Guebas, F., Thomaes, K., De Genst, W., Hettiarachchi, S. and Koedam, N. 2002: 'High resolution vegetation data for mangrove research as obtained from aerial photography', In F. Dahdouh-Guebas (ed.) Remote sensing and GiS in the sustainable management of tropical coastal ecosystems, *Environment, Development and Sustainability* **4**(2), 93–112.

Wetland Conservation Project: 1992, *Wetland Site Report. Mundel Lake.* Wetland Conservation Project – Sri Lanka. Central Environmental Authority, Colombo, Sri Lanka/Euroconsult, Arnhem, The Netherlands.

Wickramasinghe, A.: 1997, 'Progress review – mangrove conservation programme in Pambala Lagoon, Small Fishers Federation', in *Proceedings of the Workshop on Conservation and Management of Mangrove Ecosystems*, Mangrove Conservation and Demonstration Centre, Small Fishers Federation, Pambala-Kakkapalliya, Sri Lanka, pp. 9–11.

Wickramasinghe, A. and Dahdouh-Guebas, F.: 2000, 'Eco-friendly rural aquaculture development in Sri Lanka', in *Responsible Aquaculture in the New Millenium*, Rosa Flos and Leroy Creswell (comp.), European Aquaculture Society, Special Publication no. 28, Oostende, Belgium, 751 pp.

Zainal, A.J.M., Dalby, D.H. and Robinson, I.S.: 1993, 'Monitoring marine ecological changes on the east coast of Bahrain with Landsat TM', *Photogrammetrical Engineering and Remote Sensing* **59**(3), 415–421.