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Impact of solid shrimp pond waste materials on mangrove growth and mortality: a case study from Pak Phanang, Thailand

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Abstract One of the most serious threats to tropical mangrove ecosystems caused by shrimp farming activities is the poor management of pond waste materials. We hypothesise that mangroves can tolerate chemical residues discharged from shrimp farms and can be used as biofilters, but the capability of mangroves to cope with solid sediments dredged from shrimp ponds is limited. Our study in Pak Phanang, Thailand, confirmed that the excess sediments discharged from nearby shrimp ponds reduced mangrove growth rates and increased mortality rates. A series of transformed multi-temporal satellite images was used in combination with the field data to support this claim. In addition, a comparison between four dominant mangrove species revealed that *Avicennia marina* could tolerate sedimentation rates of >6 cm year^{-1}, while *Bruguiera cylindrica* tolerated sedimentation rates of 5 cm year^{-1} (total sediment depth = 25 cm) before dying, while *Excoecaria agallocha* and *Lumnitzera racemosa* performed intermediate. This outcome implied that in our situation *A. marina* and to lesser extent *E. agallocha* and *L. racemosa* could be more effective as biofilters than *B. cylindrica*, as they may survive the sedimentation longer in the disposal areas. Further studies on the impact of sedimentation and chemical pollution of shrimp farm wastes on mangrove mortality and growth are required.

Keywords Environmental impact · Mangrove · Remote sensing · Sedimentation · Shrimp farm

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Resilience and Restoration of Soft-Bottom Near-Shore Ecosystems

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Introduction

Tropical mangrove ecosystems in many Asian countries are under pressure from a number of threats from surrounding shrimp ponds (Naylor et al., 1998; Boyd & Massaut, 1999; Huitric et al., 2002; Boyd, 2003; Barbier & Sathiratai, 2004). One of the most serious concerns is the poor management of pond waste materials (Tookwinas, 1996; Gautier et al., 2001; Boyd, 2003; Gräslund et al., 2003; Das et al., 2004; Erler et al., 2004). The waste materials discharged from shrimp farms comprise foul liquid biochemical substances and both non-soluble and soluble solid biochemical substances, including fertilisers, pesticides and disinfectants, antibiotics, immunostimulants, vitamins, and feed additives (Gräslund et al., 2003). The toxicity of these substances, particularly to flora and fauna of the aquatic ecosystem, has been reported in several studies (e.g., Halling-Sørensen et al., 1998, 1999, 2000; Halling-Sørensen, 2000; Wollenberger et al., 2000).

Detailed laboratory studies (e.g., toxicity analyses) on the effects of these shrimp farm waste products on tropical mangroves are still few in number. However, experimental studies confirm the potential buffering effect of mangroves for water treatment applications (Twilley et al., 1992; Robertson & Phillips, 1995; Tam & Wong, 1995; Sansanayuth et al., 1996; Massaut, 1999; Rivera-Monroy et al., 1999; Gautier et al., 2001). For example, Sansanayuth et al. (1996) showed that a gravel-based water treatment system performed poorer than a system planted with mangrove ferns. Moreover, Chu et al. (1998) showed in their greenhouse experiments that mangroves not only tolerated polluted water, but even removed effectively nutrients and heavy metals from the water. In a field trial, Gautier et al. (2001) obtained similar results, indicating that mangroves can function as biofilters (i.e., mangroves remove polluted substances from the water). Relatively few studies found toxic effects of effluents on mangrove performance (e.g., Peters et al., 1997; MacFarlane & Burchett, 2002).

Although mangroves can tolerate the chemical contents of shrimp farm wastes (Sansanayuth et al., 1996; Chu et al., 1998; Gautier et al., 2001), the capacity of mangroves to cope with the excessive amount of solid sediments discharged from the pond may not be tolerated by the mangroves, as mangroves in general are not able to tolerate extreme sedimentation (Ellison, 1998). Shrimp farms in Thailand, for example, produce sediments up to 600,000 kg ha^{-1} $year^{-1}$ (Boyd & Musig, 1992; Satapornvanit, 1993; Briggs & Funge-Smith, 1994). This tremendous amount of sediment can negatively affect mangrove survival and growth when it is directly discharged into mangrove forests (West, 1956; Thom, 1967; Lugo & Cintrón, 1975; Atmadja & Soerojo, 1994; Terrados et al., 1997; Ohimain et al., 2004).

In 1996, a large mangrove extent of the Pak Phanang area, located in the south of Thailand, was damaged after dredged shrimp farm wastes were illegally dumped in the area. The aim of our study is to investigate the effects of these wastes on mangrove mortality and growth. A series of multi-temporal satellite images was used in combination with a field survey. Additionally, long-term mangrove mortality and growth rates were also determined from field measurements after the dumping event. This study focuses only on assessing the physical effects of the waste sediments on the mangroves and does not take the impact of the chemical residues into account, because we assumed that mangroves can withstand the chemical contents of the shrimp farm wastes (Sansanayuth et al., 1996; Chu et al., 1998; Gautier et al., 2001).

Materials and methods

Study site

Our study site is at Cape Talumpuk, the Pak Phanang district, Nakorn Sri Thammarat, Thailand (Fig. 1). A narrow edge along the east-end of the cape is an extending sand beach, while the majority of the mudflat area on the western side is covered by a 57 km^2 dense tropical mangrove forest. The area is dominated by sediment influx from the river at the south and by tidal influences from the east and north. After a dam was completed on 1 October 1999, the river was no longer the major source of sediments to the bay as fresh water flows are normally blocked in the dry season for upland agricultural purposes. Shrimp farms are located along the beach line as well as clustered around the south of the cape (Fig. 1).

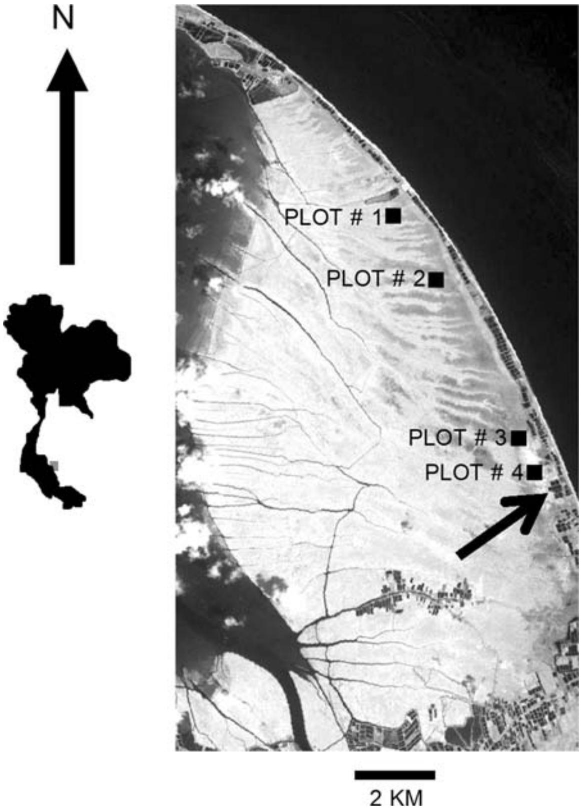

Fig. 1 An index map of Thailand linked to a 2001-satellite picture of the study site (Cape Talumpuk, Pak Phanang) along with the locations of the four study plots. A narrow edge along the east-end of the cape is an extending sand beach with a road and shrimp farms along side, while the majority of the mudflat area on the western side (the large light-tone area on the left) is covered by a 57 km^2 dense tropical mangrove forest. (Please note that the black arrow pointing to a patch of shrimp farms in the fig. will be referred to in the following analysis)

Shrimp farming in this area started in 1957, and boomed in 1987 (CORIN, 1991), but further expansion of these shrimp farms towards the mangroves stopped after the Thai government took control of the situation in 1987 (Huitric et al., 2002).

Following the aerial survey of the Thai Forestry Department (TFD) during May-June 1996, it was found that the dominant mangroves on the eastern coast of the cape, including *Avicennia marina, Bruguiera cylindrica, Excoecaria agallocha*, and *Lumnitzera racemosa*, were severely disturbed by the illegal deposits of shrimp pond wastes dredged from the surrounding shrimp farms (Fig. 2).

Tree growth and mortality

Immediately after the damage of the Pak Phanang mangroves was detected by the aerial survey between May–June 1996, we measured the growth and mortality of the mangroves during two visits on 20 July 1996, and on 20 September 1996. The sampling design comprised four 20×20 m^2 field plots (Fig. 1). The locations of the four plots were chosen by a stratified random sampling method. We used three criteria for the stratification: (1) the similarity of the mangrove species composition between the four plots, (2) the degree of damage, and (3) the accessibility of the plots. Two control plots (PLOT#1 and PLOT#2) were chosen at the natural forests in the north of the cape. These two plots were not disturbed by the shrimp farm disposal. The two treatment plots (PLOT#3 and PLOT#4) were located next to the shrimp farms in the south of the cape where both plots were regularly filled with the shrimp pond wastes (Fig. 2). According to interviews with the local residents, the waste dumping activity started in 1992. Contrary to the healthy control plots, the affected areas lacked undergrowth, and nearly all *B. cylindrica* and *E. agallocha* trees had already died at the time of the first field visit (i.e., the trees bore no leaves).

Each living mangrove tree (i.e., >1.2 m high) in each plot was marked with a unique number at the first field visit for monitoring purposes. During each visit, the diameter at breast height (DBH) and the total height of the marked trees was measured using a DBH tape and clinometer, respectively.

Remote sensing analyses

An image analysis, using a series of multi-temporal satellite images and aerial photos, was used to study the changes in the spatial extent of the impact of shrimp pond wastes on mangrove forest development. Using aerial photographs of 20 February 1995 and 2 July 2001, the total destructive area could be delineated. The content of the 1995 photo represented the original condition of the Pak Phanang mangroves, the 2001 photos the impacted situation. All photos were rectified and geo-referenced using commercial software (ERDAS imagine).

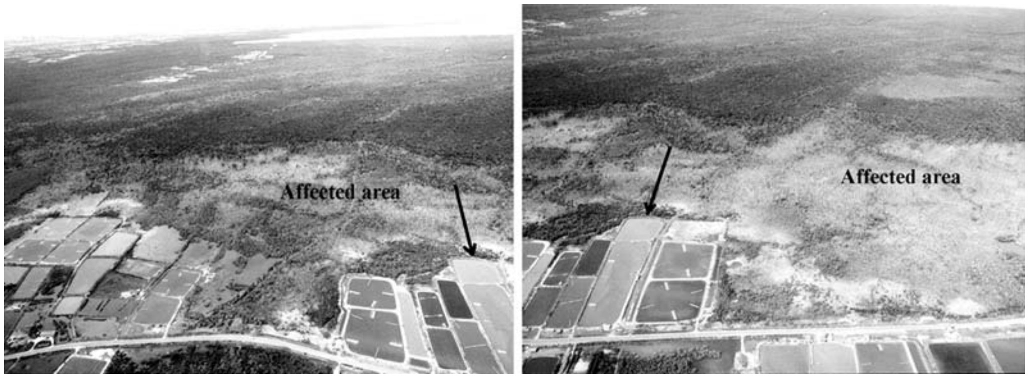

Fig. 2 Two overlapping, oblique aerial photographs of the affected area, taken during the mangrove survey mission During May–June 1996 by the TFD (please note that the arrow points to the shrimp farms indicated in Fig. 1)

Next, a series of multispectral LANDSAT satellite images of the delineated area taken respectively on 19 April 1995, 8 April 1997, and 27 April 1998 was transformed into three corresponding Normalized Difference Vegetation Index (NDVI) images. NDVI transformation is an effective image processing method of highlighting areas covered with vegetation (Lillesand & Kiefer, 2000; Jensen, 2006). This method transformed each image pixel into a decimal value between –1.0 and 1.0. In our case, the area covered with mangrove forests possessed a positive value where the value between 0.0 and 0.3 represented sparse forests, and the value between 0.3 and 0.7 was assigned to dense forests. In contrast, the non-vegetated area (e.g., bare soils, roads, shrimp farms) was assigned with a negative value.

Soil properties

In July 1996, two soil samples were collected (one from the control plot, PLOT#1, and one from the treatment plot, PLOT#3) to compare their physical and chemical properties.

Sedimentation depth and tree mortality

To establish the effect of sedimentation on tree mortality, sedimentation height and the condition of trees of four dominant mangrove species adjacent to the two treatment plots (10 trees per species per plot) were monthly measured between July 1996 and August 2001. Ten living trees of *A. marina*, *B. cylindrica*, *E. agallocha* and *L. racemosa* growing adjacent to the treatment plots were marked. A plastic ruler with a millimetre scale was attached to the bottom section of each tree trunk. One end of the ruler was set at the original soil level. The original soil level was visually determined by the clear boundary between the new soils that have a darker colour than the original soils due to the high organic contents from the shrimp farm waste materials. Whenever any of the marked trees was found dead (i.e., no leaf count), the depth between the original soil level and the present level was recorded. Although solid waste deposition from shrimp farms was lawfully forbidden since 1996, the treatment site was an exception, because it was designated as a waste disposal area.

Statistical analyses

The intra-specific differences of the DBH sizes and the tree heights between the control plots and the treatment plots were tested using an independent *t*-test. This intra-specific study was aimed at checking for the consistency of the mangrove conditions between the plots selected under the same stratified random sampling scheme. The growth (i.e., incremental DBH sizes and tree heights) between 20 July 1996 and 20 September 1996 of the trees in the treatment plots (PLOT#3 and #4) were compared with the growth in the control plots (PLOT#1 and #2) using an unpaired t-test. A one-way ANOVA was used for analysing differences in mangrove height and tree mortality over the 5-year periods. The ANOVA test was used for detecting differences in maximum sedimentation height of recently died mangrove trees between the three selected mangrove species (*B. cylindrica*, *E. agallocha* and *L. racemosa*).

Results

Tree growth and mortality

All plots contained four different mangrove species, but only two of the species (*A. marina* and *L. racemosa*) were present in all plots (Table 1). The DBH and height for the different species between the two controlled plots (PLOT#1 and PLOT#2) did not differ in July 1996 (*A. marina* DBH: $t = 0.31$, df $= 12.32$, $P > 0.05$; *A. marina* height: $t = 1.29$, df $= 12.44$, $P > 0.05$; *L. racemosa* DBH: $t = 1.50$, df $= 2.06$, $P > 0.05$; *L. racemosa* height: $t = 0.70$, df $= 2.22$, $P > 0.05$). All trees were healthy, and dense understorey plants were found. In contrast, the trees in the treatment plots (PLOT#3 and PLOT#4) appeared stressed (i.e., yellow leaves, low leaf count, and dried branches). Many *B. cylindrica* and *E. agallocha* trees in the treatment plots were dead (i.e., zero leaf count), and there was no understorey present. The total number of live trees in the plots was $N_{PLOT\#3} = 42$ and $N_{PLOT\#4} = 13$, respectively. Tree height and DBH in the two treatment plots did not differ significantly for the two species (*A. marina* and *L. racemosa*) that were present in both plots, except for the DBH of *A. marina*, which was slightly larger in PLOT#4 than in PLOT#3 (*A. marina* height: $t = 0.73$, df $= 4.59$, $P > 0.05$; *A. marina* DBH: $t = 3.66$, df $= 9.49$, $P < 0.01$; *L. racemosa* DBH: $t = 0.45$, df $= 10.09$, $P > 0.05$; *L. racemosa* height: $t = 1.55$, df $= 9.30$, $P > 0.05$). We concluded that the two controlled plots as well as the two affected plots were relatively similar in tree DBH and heights.

Between July and September 1996 the mean DBH and height of the trees increased in every plot; however, the trees in the affected area (PLOT#3 and PLOT#4) had smaller growth than the trees in the controlled area (PLOT#1 and PLOT#2). The DBH and height growth between the affected and controlled areas were significantly different (Fig. 3 and Table 1, *A. marina*

Table 1 Mean height and DBH including standard deviations (in parentheses), mean monthly growth (GR), and the number of trees (N) per mangrove species per study plot, observed between 20 July 1996 and 20 September 1996 (N/A = tree absent from the plot)

		Controlled						Affected					
		PLOT#1			PLOT#2			PLOT#3			PLOT#4		
		Jul	Sep	GR	Jul	Sep	GR	Jul	Sep	GR	Jul	Sep	GR
A. marina	DBH (cm)	30.68 (11.56)	32.69 (12.01)	2.01	32.16 (11.18)	34.74 (11.24)	2.58	15.05 (2.74)	15.31 (2.63)	0.26	19.50 (2.12)	20.05 (2.19)	0.55
	Height (m)	4.31 (1.31)	4.80 (1.40)	0.49	5.01 (1.28)	5.54 (1.29)	0.53	3.57 (0.55)	3.62 (0.54)	0.05	4.00 (1.27)	4.03 (1.24)	0.03
	N	8	8		21	21		13	9		5	5	
B. cylindrica	DBH (cm)	18.43 (8.07)	19.26 (8.22)	0.83	N/A								
	Height (m)	3.34 (0.92)	3.53 (0.86)	0.19									
	N	24	24										
E. agallocha	DBH (cm)							29.00 (18.38)	29.15 (18.60)	0.15	N/A		
	Height (m)	N/A						3.45 (1.34)	3.46 (1.38)	0.01			
	N							6	3				
L. racemosa	DBH (cm)	38.43 (27.22)	41.00 (28.58)	2.57	14.67 (7.21)	15.60 (7.54)	0.93	12.78 (3.98)	12.97 (4.05)	0.19	11.89 (5.13)	12.11 (4.99)	0.22
	Height (m)	4.36 (2.05)	4.73 (2.19)	0.37	3.51 (1.07)	3.85 (1.20)	0.34	3.14 (0.80)	3.17 (0.81)	0.03	2.44 (1.19)	2.45 (1.18)	0.01
	N	3	3		15	15		23	12		8	5	

DBH growth: $t = 49.80$, df $= 39.18$, $P < 0.001$; *A. marina* height growth: $t = 62.17$, df $= 36.56$, $P < 0.001$; *L. racemosa* DBH: $t = 8.34$, df $= 18.16$, $P < 0.001$; *L. racemosa* height: $t = 10.74$, df $= 17.21$, $P < 0.001$). By comparison, *A. marina* performed better in affected plots than *L. racemosa* or *E. agallocha*.

In addition to the poorer growth rates of the trees in the affected area, we also found differences in mortality rates between the plots, with mortality rates between 0 and 50% in the affected areas against 0% in the controlled areas (Table 2).

Soil properties

The soil properties of the control and treatment plots are reported in Table 3. The results showed that soils from the affected and controlled areas were relatively similar except for a lower salinity levels (EC) and higher organic matter (OM) contents in the affected plots.

Remote sensing analyses

In Fig. 4, the extent of the damaged area was assessed by comparing the aerial photograph of 20 February 1995 (i.e., the situation before the damage) with the one taken on 2 July 2001 (i.e., about five years after the incident). The loss of mangrove forest can be noticed in the 2001 photo (i.e., bright-tone area), estimated at approximately 1.0 km^2.

Three transformed multi-temporal satellite images of the same area show the increase of the affected area (Fig. 5). For each image, we sliced raw NDVI values into three different classes: the red areas are non-vegetated areas (e.g., bare soils, roads, shrimp farms; NDVI values < 0); bright green areas are sparsely vegetated areas (NDVI values 0.0-0.3); dark green areas are dense mangrove forests (NDVI values > 0.3). The general pattern found in the transformed images indicated that the mangroves deteriorated over the 1995–1998 period, as the sparsely vegetated areas encroached on the healthy dense mangroves. This outcome confirmed our field observations, indicating that the dumping activity increased mangrove mortality.

Sedimentation depth and tree mortality

B. cylindrica, *E. agallocha*, and *L. racemosa* survived respectively up to 25 cm, 31 cm, and 33 cm of the waste deposition, before they were found dead (Fig. 6); all *A. marina* trees survived the deposition. A statistical analysis (one-way ANOVA) between the three dominant mangrove species confirmed that *B. cylindrica* was significantly the weakest species as it sustained the sediment deposition less than the other two species ($n = 30$, $F = 10.16$, $P < 0.001$). *A. marina* was excluded from the analysis since not a single tree had died.

Discussion

The field observations demonstrated that the trees in the affected area had a lower growth rate (Fig. 3) and a higher mortality rate (Table 2) than the trees in the controlled plots. These findings confirmed that solid shrimp farm waste depositions have negative effects on the Pak Phanang mangrove development. Nevertheless, controlled experiments are required so that site effects (such as small differences in the initial DBH of the trees) can be ruled out, and generalizations can be made for sedimentation tolerance levels of the different species. The outcome of the multi-temporal NDVI analysis of images taken between 1995 and 1998 (Fig. 5) strengthened this claim. The analysis indicated that the effects of the shrimp farm waste depositions were not localised within the sampled areas but affected a large extent of the Pak Phanang mangroves. It has been shown that satellite image classification, together with field studies, can assist in monitoring mangrove forest development in shrimp pond areas. Additionally, it was also found that *A. marina* in the affected area is the strongest mangrove species, possessing the highest growth and lowest mortality rates. *A. marina* is a pioneer species, relatively tolerant to large abiotic fluctuations (MacFarlane & Burchett, 2002; Joshi & Ghose 2003), and is therefore not surprisingly the species that best sustained the heavy sedimentation.

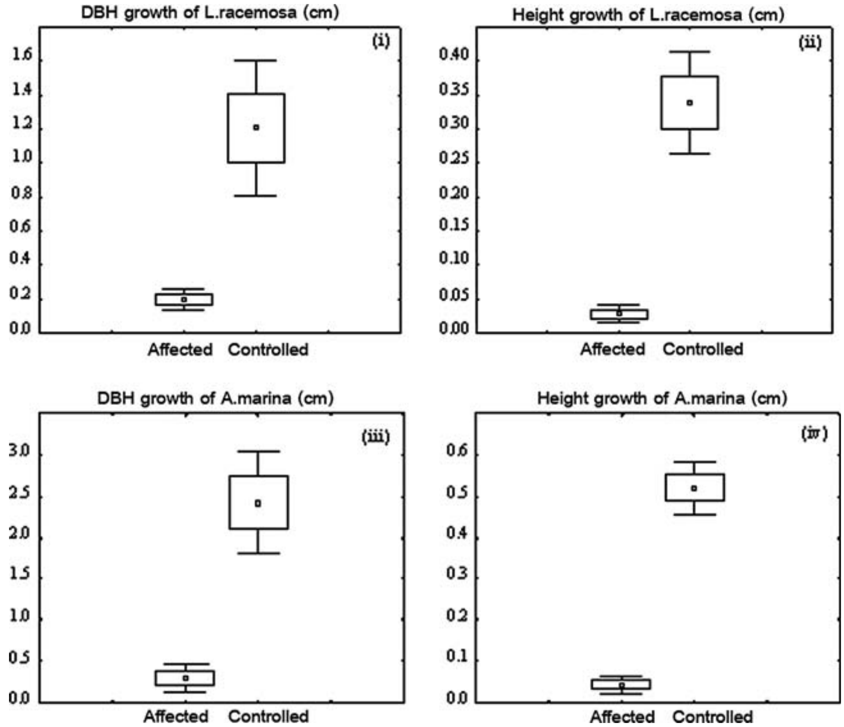

Fig. 3 Comparisons of the mean monthly growth in DBH and height of mangrove tree species in the affected and controlled areas: (i) *L. racemosa*'s DBH, (ii) *L. racemosa*'s height, (iii) *A. marina*'s DBH, and (iv) *A. marina*'s height (☐ = Mean, ☐ = ±SE, and I = ±1.96*SE)

This study is based on the assumption that the mangrove deterioration in Pak Phanang was not caused by the chemical contents of the wastes discharged from the shrimp ponds, as it is well known that mangroves in general are able to tolerate these chemical contents. In many cases mangroves are even used as biofilters to treat the shrimp pond effluents (Twilley et al., 1992; Robertson & Phillips, 1995; Tam & Wong, 1995; Sansanayuth et al., 1996; Massaut, 1999; Rivera-Monroy et al., 1999; Gautier et al., 2001). More importantly, in tropical areas like the study area, the monsoons and heavy rainfalls also wash away or dilute these foul chemical substances. The soils in the affected area seem to have a lower salinity level and higher organic matter content than the control soils, possibly stimulating mangrove development. The low sample size does not, however, warrant such conclusions.

Our 5-year sedimentation record in the affected area showed that the amount of sediments deposited from the nearby shrimp farms

Table 2 Mortality rates of the mangrove trees per plot between 20 July 1996 and 20 September 1996 (N/A: tree was absent from the plot)

Species	Mortality (%)			
	Controlled		Affected	
	Plot#1	Plot#2	Plot#3	Plot#4
A. marina	0%	0%	31%	0%
B. cylindrica	0%	N/A	N/A	N/A
E. agallocha	N/A	N/A	50%	N/A
L. racemosa	0%	0%	48%	38%

Table 3 A comparison between soil properties of the affected and controlled areas, collected in 20 July 1996

Area	pH	EC 1:5 (millimhos, 25°C)	%OM	P (ppm)	K (ppm)	S (ppm)	Na (ppm)	Ca (ppm)	Mg (ppm)	%Sand	%Silt	%Clay	Texture
Affected	6.7	8.26	8.26	41	2000	3333	20000	3953	4881	18	30	52	Clay
Controlled	7.7	13.71	2.72	285	1700	2000	21000	3462	4732	12	34	54	Clay

were well beyond the mangrove tolerance level (i.e., approximately 5 mm of sedimentation per year; Ellison, 1998). It is therefore likely that the excess in sediment supply is the major cause of the mangrove decline. Furthermore, our results suggest that *B. cylindrica* was the weakest species to survive, as it tolerated an average sedimentation depth up to only 25 cm while the *E. agallocha* and *L. racemosa* species performed better at 31 cm and 33 cm, respectively. This outcome indicates that *E. agallocha* and *L. racemosa*, together with *A. marina*, are able to withstand the effect of sedimentation better, and are therefore more suitable species to be used in biofilter experiments than *B. cylindrica*.

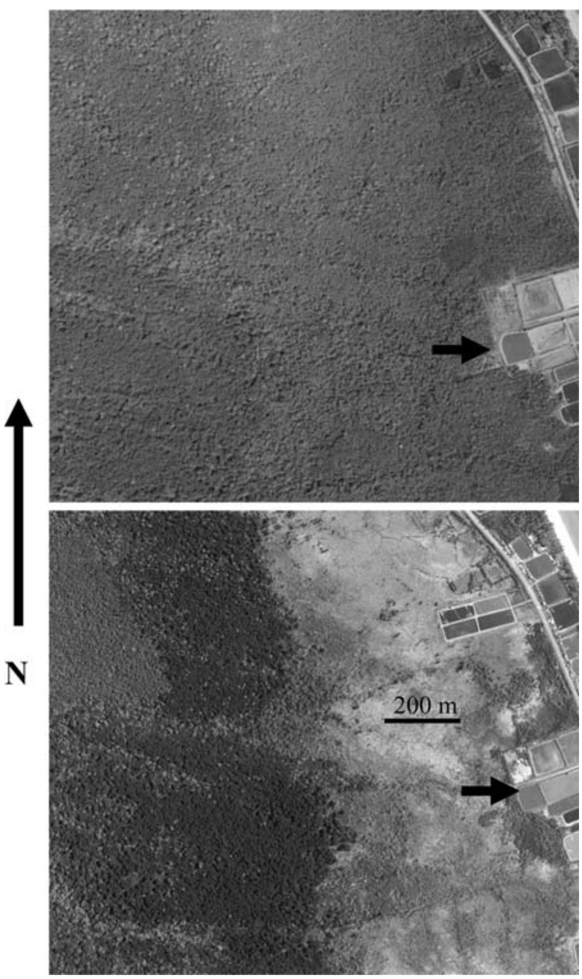

Fig. 4 Aerial photographs enabling a comparison between the situations in February 1995 (above) and July 2001 (below) of the affected area. The darker tone area in the mid-west of the 2001-photo is dominated by dense mangrove forests. The lighter-tone area on in the mid-east is the affected region where the soils underneath the mangroves are exposed to the camera due to the low mangrove density. Please note that the black arrow is pointed to the same patch of shrimp farms indicated in Fig. 1

Lastly, it was a surprise that there was almost no natural colonization of the mangroves in the affected area during the 5-year monitoring period (Fig. 4) even though the dumping activity had been banned since 1996. Instead, the areas covered with dense mangroves gradually receded over the years (Fig. 5). Poor soil properties were unlikely to be the reason for this unsuccessful regeneration of the mangroves. This statement is supported by a pilot experiment of Bamrongrugsa (unpublished), who found that the seedlings of *Rhizophora apiculata* and *Rhizophora mucronata* can be successfully grown in the affected area with a high survival rate (Fig. 7). Instead, we hypothesise that natural mangrove colonization is limited by the increasing height of the affected area as a result of the accumulation of the shrimp farm wastes. The increasing elevation reduces the chances for natural dispersion of mangrove seedlings, as the average tidal range of the study area is only 100 cm (Hydrographic Department, 1996). Therefore, an increase in elevation of 25 cm or more, such as the case found in this study can severely disrupt the tidal pattern. In addition, it is anticipated that the alteration of the inundation frequency will also cause changes of other physico-chemical properties (e.g., an increase in soil salinity) of the affected area.

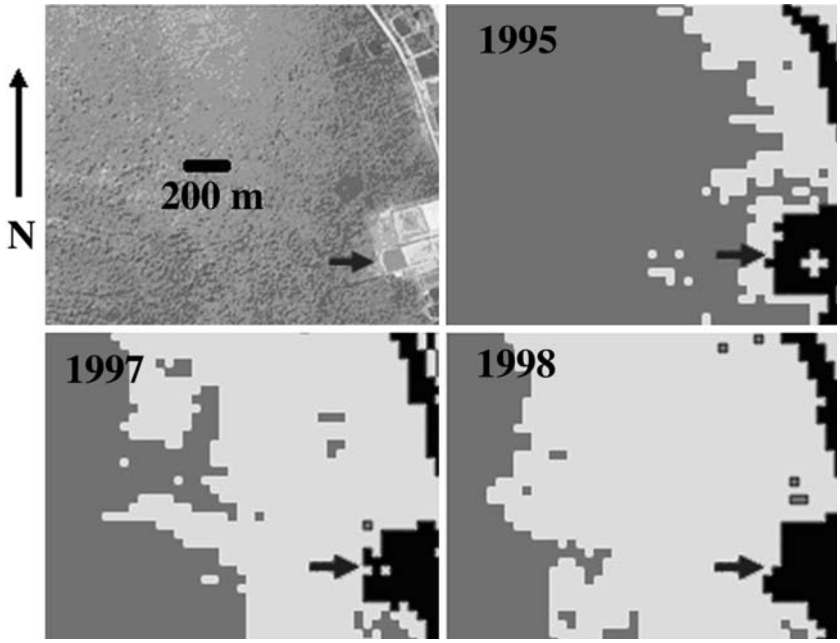

Fig. 5 NDVI transformed images showing the encroachment of the bright grey areas (sparse mangrove forests) on the dark grey areas (dense mangrove forests) over the period from 1995 to 1998. The black areas are non-vegetated areas (e.g., shrimp farms, roads, bare soils) where the NDVI values are negative. The top-left image is the same 1995 photo shown in Fig. 4. The index shrimp farm is indicated by an arrow

Conclusion

This study demonstrated a case of mangrove destruction in the Pak Phanang district in the south of Thailand, caused by the deposition of the shrimp farm waste materials in the mangroves. Despite the capability of natural mangroves to withstand the chemical constituents of the shrimp farm wastes, the excessive amount of the waste materials deposited in the Pak Phanang mangroves is beyond the mangrove tolerance levels. We suggest that studies of the effects of the chemical contents of the shrimp

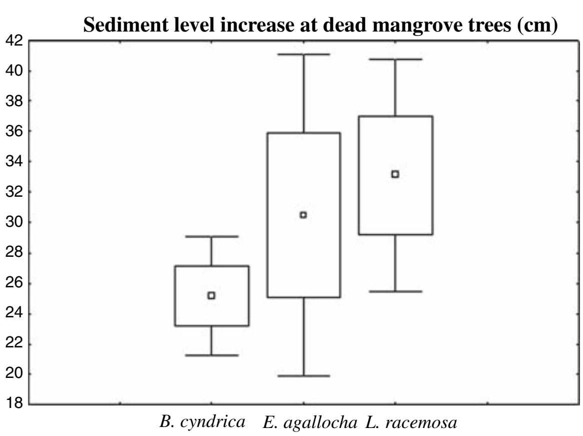

Fig. 6 A comparison between the mean sedimentation levels of dead mangrove trees of three dominant species in the Pak Phanang area (□ = Mean, ☐ = ±SE, and I = ±1.96*SE)

Fig. 7 An experiment of growing *Rhizophora* mangroves in the area affected by shrimp farm disposal

farm wastes on mangrove mortality and growth should be carried out to complement the outcome of this study. In light of this study (see also Ellison, 1998), more studies are also needed to confirm the causal factors behind the reduction in mangrove growth and increase in mortality, so that suggestions for effective mangrove biofilters are based on our understanding of the processes involved. Lastly, we hope that the painful experience of the Pak Phanang mangroves reported in this case study will be a warning to the shrimp farm stakeholders, emphasising the need to guarantee that effective mitigating steps are taken to minimize the effect of shrimp farm wastes on mangrove ecosystems.

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