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Impacts of Sediment Burial on Mangroves

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Aerial roots are a common adaptation of mangrove trees to their saline wetland habitat, allowing root respiration in the anaerobic substrate. While mangroves flourish on sedimentary shorelines, it is shown here that excess input of sediment to mangroves can cause death of trees owing to root smothering. Descriptions of 26 cases were found in the literature or described here, where mangroves have been adversely affected by sediment burial of roots. The impacts ranged from reduced vigour to death, depending on the amount and type of sedimentation, and the species involved. There are insufficient data to establish specific tolerances. For rehabilitation, where the disturbance was a past event, the elevation change must be assessed in selection of species for replanting, and field trials are required in areas where rapid accretion is an ongoing problem. © 1999 Elsevier Science Ltd. All rights reserved

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Mangrove forests occur in the intertidal zone of the tropics, with a world mangrove area estimated at 14197635 hectares (Lacerda *et al.*, 1993). The most extensive areas of mangrove swamp occur on sedimentary shorelines, where large rivers discharge onto low gradient coasts. Despite this, excess input of sediment to mangroves can cause death of forest areas. Accounts of mangrove response to burial by sediment are compiled here, assessing the state of knowledge of impacts, and issues of rehabilitation.

Aerial roots are a major adapation of the majority of mangrove species to the environmental stresses of their intertidal habitat, allowing root respiration in anaerobic, waterlogged soils. They differ in architecture between species, from tall prop roots in *Rhizophora*, to lower pneumatophores in *Avicennia* and *Sonneratia*, knee roots in *Bruguiera* and *Xylocarpus mekongensis*, buttresses in *Ceriops* and plank roots in *Heritiera* and *Xylocarpus granatum*. The importance of aerial root architecture in determining tolerance thresholds of mangrove species to sediment burial is investigated in this review.

Rates of Mangrove Tidal Swamp Accretion

First, it is necessary to establish natural rates of sedimentation, for mangroves are known to promote sedimentation. Scoffin (1970) showed that the roots of *Rhizophora mangle* can significantly reduce the velocity of tidal water, and provide a better sediment binding capacity compared with a variety of sea-grasses and algal mats. Furukawa and Wolanski (1996) and Furukawa *et al.* (1997) demonstrated that a combination of vegetational friction on water movement and sediment flocculation promotes sedimentation within mangrove swamps. Spenceley (1982) from a study of inserted pegs in mangroves on Magnetic Island, off Townsville (Queensland) found higher sedimentation rates among mangrove roots than in the open. Young and Harvey (1996) used artificial pneumatophore roots to show a positive correlation between root density and sediment accretion.

Recent sedimentation rates in mangrove swamps (<100 years) have been measured using iron filings (Chapman and Ronaldson, 1958), brickdust (Bird, 1971), stakes (Bird and Barson, 1977; Spenceley, 1977, 1982) and feldspar clay (Cahoon and Lynch, 1997). Using Cs^{137} and Pb^{210}, Lynch *et al.* (1989) and Cahoon and Lynch (1997) showed accretion rates of up to 2.2 $mm.y^{-1}$ at Rookery Bay, Florida, and at Terminos Lagoon, Mexico, found accretion rates of 3.2–4.4 $mm.y^{-1}$ at a river dominated site, and up to 2.0 $mm.y^{-1}$ at a tidal dominated site.

These short-term records of mangrove sedimentation show that the majority accreted at rates of <5 $mm.y^{-1}$, with a maximum 10 $mm.y^{-1}$ (Table 1). In these cases, the mangrove forests were not adversely affected by sedimentation, indicating rates that are tolerable.

Burial of Mangrove Roots by Sediment

There are several accounts, from deltaic areas that receive massive amounts of sediment, of mangroves that opportunistically colonise suitable habitats and may get disrupted by changes in sediment supply and microtopography. West (1956 p. 117), described deposition of sand in stands of *Rhizophora* at the Atrato delta in Colombia killing mature trees. Thom (1967) described

TABLE 1
Summary of short-term natural sedimentation rates found in mangrove swamps.

Location	Rate (mm/y)	Reference
Magnetic Island	−11.0 to 9.0	Spenceley, 1977, 1982
Cairns	1.0	Furukawa *et al.*, 1997
Cairns	3.0 to 10.0	Bird and Barson, 1977
Melbourne	8.0	Bird and Barson, 1977
Auckland, NZ	1.7	Chapman and Ronaldson, 1958
Florida	1.4 to 1.7	Lynch *et al.*, 1989
Florida	0.6 to 3.7	Cahoon and Lynch, 1997
Mexico (Fluvial)	3.2 to 4.4	Lynch *et al.*, 1989
Mexico (Tidal)	1.0 to 2.0	Lynch *et al.*, 1989

the distributions of mangroves in the Tabasco delta, Mexico, as being subject to the sedimentation patterns of the river. Atmadja and Soerojo (1994) observed that some Indonesian mangroves are subject to excessive sedimentation from river floods, causing death of some mangrove species, especially *Avicennia* and *Sonneratia*. Lugo and Cintron (1975 p. 840), described excess sedimentation in Puerto Rican mangroves as a result of floods, leading to interruption of root and soil gas exchange, and eventual death of the trees.

Other examples have recently been described on the Mangrove Research Discussion List. In French Guiana massive sediment deposition occurs adjacent to river mouths, causing death of *Avicennia germinans* (Fromard, 1998). New deposits can be colonised by *Laguncularia racemosa*. In the south-east Mekong delta, several locations are described as showing mangroves dying because of excess sedimentation (van Mensvoort, 1998). This jeopardised a reforestation effort, with young *Rhizophora* trees buried by soft mud.

Similar problems have been demonstrated experimentally by Terrados *et al.* (1997). This study showed that sediment burial of 8 cm and above retarded growth and increased mortality of *Rhizophora apiculata* seedlings. They suggested that rapid sediment accretion altered oxygen supply to the hypocotyl root system.

Sediment deposition in mangroves is also recorded as a result of storms. In Florida, Craighead and Gilbert (1962) described the effects of Hurricane Donna on mangroves of southern Florida, particularly *Rhizophora mangle*, *Avicennia germinans*, *Laguncularia racemosa* and *Conocarpus erectus*. Widespead death occurred, averaging 25–75% death over large areas and locally reaching 90% . This was not due to mechanical damage and defoliation, since some trees put forth new leaves, but was due to deposition of several inches of sediment that caused root damage and oxygen deficiency. The depth of depostion was up to 5 inches (12.7 cm), and evidence is presented (pp. 25–26) of death of deeper roots.

In February 1990, Cyclone Ofa in American Samoa killed 1.6 ha of 16 m tall *Bruguiera gymnorrhiza* at Aoa on the east shore, and some 4 ha at Masefau on the north shore. Fig. 1 shows that aerial knee roots were buried in sediment.

There are numerous accounts of sedimentation as a result of human disturbance causing problems in mangroves, but generally few quantitative details. Hutchings and Saenger (1987; p. 307) described that if dredge spoil

Fig. 1 *Bruguiera gymnorrhiza* forest at Aoa, American Samoa, that died from sediment burial following Cyclone Ofa. The knee roots are practically buried, a few can be seen in the bottom right of the plate.

is discharged over the roots of mangroves, it leads to their death. In Trinidad, Ramcharan (1997) described 10–15 cm deposition of marine dredge on *Avicennia germinans* and *Laguncularia racemosa* as causing death. In NW Australia, at King Bay, 2 ha of mangroves were buried and deteriorated when an adjacent dredge stockpile eroded (Gordon, 1988). At Point Samson, harbour dredge spoil smothered pneumatophores and killed fringing *Avicennia marina* (Gordon, 1988).

In Singapore, Lee *et al.* (1996; p. 32) described mangroves adjacent to a reclamation project. 'At this location, the mature individuals of *Avicennia* spp. and *Sonneratia alba* are either in the moribund state, dying or dead. The most probable cause for this happening is the fast accretion of sediments along the embankments, hence burying or covering the pneumatophores of the breathing roots'. A photograph of the pneumatophores (p. 30) shows that these still emerge from the sediment by several centimeters, but the burial is sufficient to cause oxygen stress to the tree.

In the Federated States of Micronesia, Devoe (1992) reported from Yap of sedimentation in mangroves adjacent to road construction, causing 'destruction' of the mangroves. In the Solomon Islands, Kwanairara (1992) reported degradation of mangroves with siltation from adjacent development.

In New Caledonia, large-scale nickel mining results in massive soil erosion (Wodzicki, 1981), and siltation in mangrove swamps of mine waste is a problem (Bird *et al.*, 1984). These authors reported (p. 23) that red clay deposits in the mangrove swamps, particularly after storms, caused localised areas of mangrove decline. The depth of root burial is not indicated. However, new mud banks seaward of mangrove swamps provide sites for new colonisation.

In Saudi Arabia, large areas of mangroves (principally *Avicennia marina*) have been destroyed or degraded by coastal infilling (Price *et al.*, 1987; Aleem, 1990). There are few details given of the depth of burial or the specific effects on the trees, other than they have declined in health (Aleem, 1990; p. 14). Similar reports from that region come from Waisel (1997), who described 50–100 cm of sand depositing on *Avicennia marina*, which caused a decline in vitality. In Mexico, Flores-Verdugo (1997) described 200 ha of *Avicennia germinans* as being killed by sand suffocation of the pneumatophores, adjacent to a dam construction.

Allingham and Neil (1995) described mangrove death from smothering at Mud Island, off Brisbane in Queensland. This was from deposition of dredge spoil on the island as shingle ridges, and mangroves died from smothering adjacent to these. The depth of burial is not given, but a photograph (p. 289: Fig. 13) indicated that the pneumatophores of *Avicennia marina* were not buried.

Grindrod (1988) reconstructed chenier ridge development in mangrove environments of Princess Charlotte Bay. He showed in core 7a the disruption of an established *Rhizophora* forest, caused by the initiation of a shingle ridge adjacent, and burial of aerial roots. Chappell and Grindrod (1984) described recent burial of mangroves by 70 cm of shell adjacent to a chenier ridge. *Rhizophora* is described as dead, while large *Avicennia* trees seemed to have survived despite pneumatophore burial, perhaps because this was loose gravel.

Degradation of mangroves from sand and silt sedimentation is reported from Guinea-Bissau by Simao (1993). Invasion of sands into mangroves is described as a stress by Echevarria and Sarabia (1993) from Peru, especially in the Tumbes River. In Colombia, Alvarez-Leon (1993) described mining at Cartagena Bay causing sedimentation in adjacent mangroves, as is the case for soil erosion from catchment deforestation. Mangroves are described as 'damaged' by such activities, but no details are given. In Cuba, Padron *et al.* (1993) described sand accumulation over prop roots and pneumatophores as affecting mangroves, but no details are given.

The author has documented cases of burial causing mangrove death. At Point Samson (North West Australia) construction of a boat ramp has buried adjacent *Avicennia marina* by over 50 cm. The pneumatophores were smothered and the trees dead (Fig. 2). Similar events with causeway construction are described from this area by Gordon (1988). At Gladstone (Southern Queensland), the Fisherman's Landing causeway has caused burial of adjacent mangroves. *Avicennia marina* with its pneumatophores entirely buried was dead (Fig. 3), and was under stress and dying from around 5 cm of burial (Fig. 4), although its pneumatophores still emerged from the sediment. The causeway construction has caused 3–4 cm of silt deposition over large areas of *Rhizophora stylosa* forest, but with no apparent effects. This would suggest that *R. stylosa* is more tolerant of sediment burial than *A. marina*, as is clearly indicated in Fig. 3.

At Doughty Creek, Bowen (North Queensland) up to 0.5 ha of *Avicennia marina* was killed by sediment inwash adjacent to the Bowen Coke Works, in the late 1980s (Fig. 5). Roots of one dead tree (Fig. 5) were excavated to show buried pneumatophores, with a mean depth of buried roots of 4.0 cm below the surface. The mean root height of a regrowth *Avicennia* at the site 2 location was 8.8 cm, indicating that the amount of burial since the excavated tree was alive was around 12 cm. Since purchase of Bowen Coke Works in 1993, Mount Isa Mines have contained site sediment with embankments, and have commenced monitoring of sedimentation rates in adjacent mangroves.

Discussion

Mangroves flourish on sedimentary shorelines, and a review of the natural rates of sedimentation from eight locations shows that most accrete at rates of <0.5 cm.y^{-1}, with a maximum around 1 cm.y^{-1}. Sedi-

Fig. 2 *Avicennia marina* trees that died from sediment burial adjacent to Point Samson boat ramp, North West Australia. Note trees are stunted at this location due to aridity.

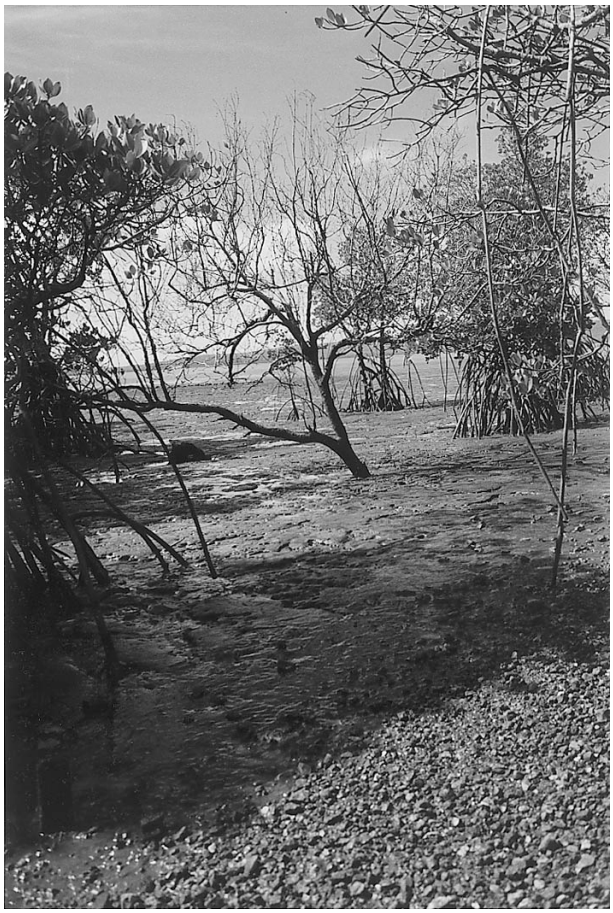

Fig. 3 Dead *Avicennia marina* and surviving/stressed *Rhizophora stylosa* adjacent to the Fishermans Landing causeway, Gladstone, Queensland. Around 50 cm of burial occurred in this vicinity.

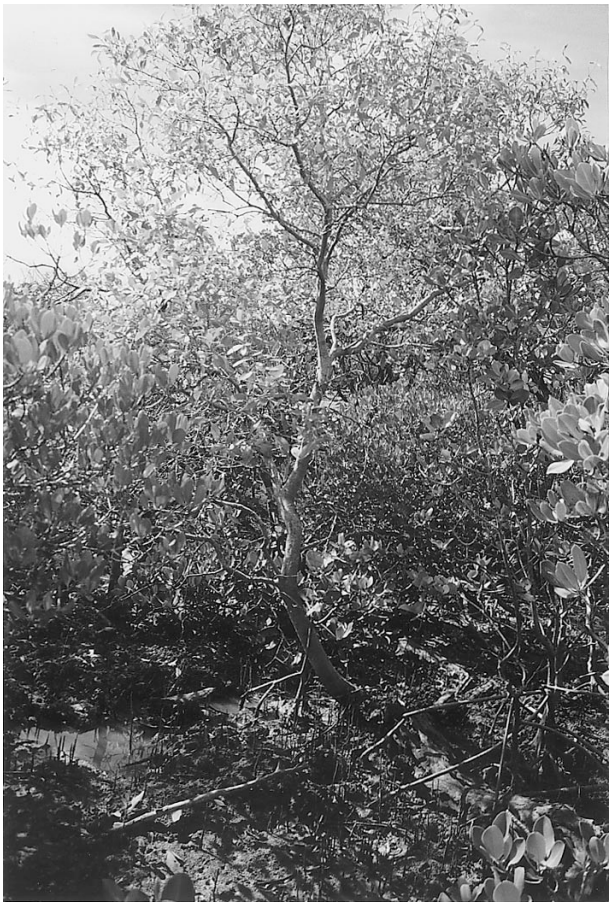

Fig. 4 Stressed *Avicennia marina* tree adjacent to the Gladstone causeway. About 5 cm of burial occurred, but observe that the pneumatophores still emerge from the sediment.

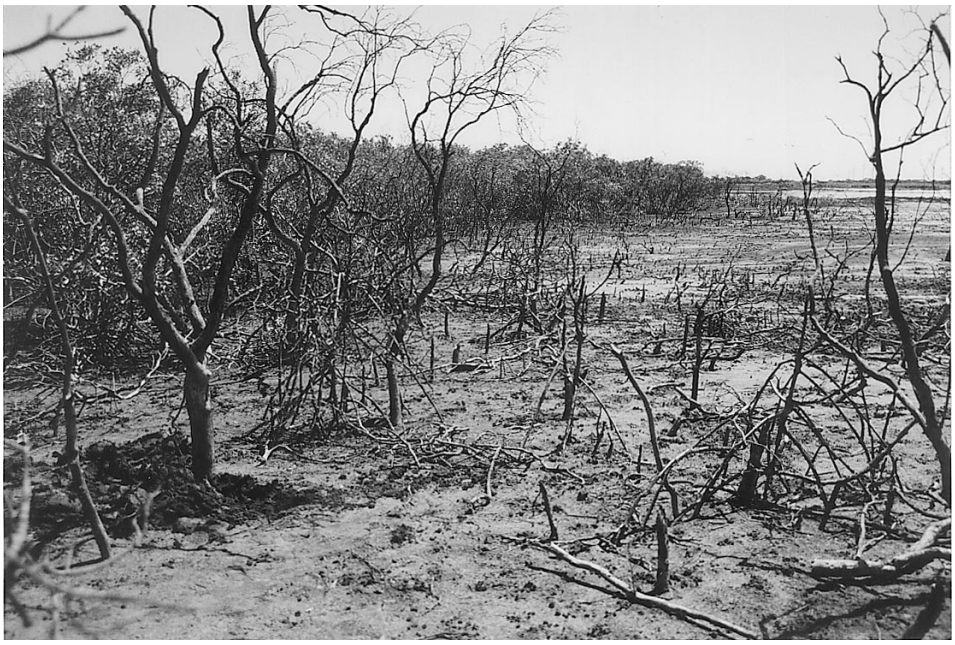

Fig. 5 Dead area of *Avicennia marina* at Doughty Creek, Bowen, northwest of Bowen Coke Works, showing the excavated tree on the left.

ment burial in mangrove environments is therefore defined as sedimentation in excess of these rates, related to a disturbance.

The effects on mangroves of root burial are summarised in Table 2. Many of these reports have few details (indicated by question marks), the purpose of including these is to summarise the numerous accounts of mangrove destruction from excess sediment deposition. This can be used by coastal zone scientists to comment on the adverse effects of sedimentation on mangroves with coastal development. Of the accounts that have more detail of particular mangrove species affected by depths of root burial, the following conclusions can be drawn.

When the pneumatophores of *Avicennia* or the knee roots of *Bruguiera* are completely buried, the trees usually die, illustrated in Figs. 1–3. This allows a predictive capacity with assessment of deposition effects, as measurement of the mean height of these types of aerial roots gives the depth of sediment deposition that will cause forest death.

When sediment burial occurs that is less than the heights of the aerial roots of these species, the trees can still be adversely affected, or die. This is illustrated by Allingham and Neil (1995), Lee *et al.* (1996), and Fig. 4.

Of the few accounts that do have sediment depth quantified, most involve *Avicennia*. These indicate that root burial of around 10 cm causes death of these species.

The higher stilt root architecture of *Rhizophora* species does not necessarily mean that they can tolerate much deeper root burial. Fig. 4 suggests that *Rhizophora stylosa* is more tolerant of burial than *Avicennia marina*, but several cases in Table 2 show *Rhizophora* being affected, particularly seedlings (Terrados *et al.*, 1997; van Mensvoort, 1998). Respiration occurs through lenticels, and study of the root system of *Rhizophora mangle* has shown that the concentration of lenticels declines rapidly with height above the substrate (Gill and Tomlinson, 1977; p. 153).

The ability of mangrove species to cope with root burial of several centimetres a year probably varies between species as a function of root architecture. The pneumatophores of *Avicennia* and *Sonneratia* and the knee roots of *Xylocarpus mekongensis* may be able to extend upwards (Hutchings and Saenger, 1987; p. 28). Some *Rhizophora* species may be able to develop higher root arches, a tree with knee roots may be able to develop roots with higher knees, and those with buttress roots may be able to develop secondary thickening on the top of the buttress to extend it upwards. These responses take time, but mangrove trees could adjust to gradual burial in this manner.

Nypa does not have aerial roots, but can grow vegetatively from an underground rhizome. This gives it the ability to relocate to a higher level in conditions of rapid sedimentation. This may be why large areas of *Nypa* occur, in relation to mangrove forest in sediment-rich environments such as the Fly River, PNG (Robertson *et al.*, 1991.

While the response of mangrove species to root burial is not standardised, each event is also affected by local factors, particularly the sediment texture, the presence of soil fauna, and the tidal range. Burial by sand does not appear to cause death as readily as burial by silt or clay. This could be because soil aeration is better through sand.

TABLE 2
Summary of mangrove burial events and consequences.

Location	Species	Burial	Effect	Reference
Old World Mangroves				
Singapore	*Avicennia*	c. 10 cm	Dying/Death	Lee *et al.*, 1996
	Sonneratia alba			
Mekong	*Rhizophora apiculata*	?	Death	van Mensvoort, 1998
Thailand	*Rhizophora apiculata*	>8 cm	Some death	Terrados *et al.*, 1997
	Rhizophora apiculata	32 cm	Death	Terrados *et al.*, 1997
Samoa	*Brug. gymnorrhiza*	10–20 cm	Death	Fig. 1
New Caledonia	?	?	Death	Bird *et al.*, 1984
Indonesia	*Avicennia, Sonneratia*	?	Death	Atmadja and Soerojo, 1994
Sinai	*Avicennia marina*	50–100 cm	Unhealthy	Waisel, 1997
Saudi Arabia	*Avicennia marina*	?	Unhealthy	Aleem, 1990
Yap, FSM	?	?	Death	Devoe, 1992
Solomons	?	?	Degradation	Kwanairara, 1992
AUSTRALIA				
Mud Island	*Avicennia marina*	?	Death	Allingham and Neil, 1995
	Rhizophora stylosa			
Princess Charlotte Bay	*Rhizophora*	70 cm	Death	Chappell and Grindrod, 1984
	Avicennia	70 cm	Survived	
Port Samson	*Avicennia marina*	20 cm	Death	Fig. 2
King Bay	?	?	2 ha dead	Gordon, 1988
Gladstone	*Avicennia marina*	5 cm	Stressed	Fig. 4
	Avicennia marina	50 cm	Dead	Fig. 3
	Rhizophora stylosa	50 cm	Stressed	Fig. 3
Bowen	*Avicennia marina*	12 cm	0.5 ha dead	Fig. 5
New World Mangroves				
S. Florida	*Avicennia germinans*	<12.7 cm	Death	Craighead and Gilbert, 1962
	Rhizophora mangle			
	Laguncularia racemosa			
Trinidad	*Avicennia germinans*	10–15 cm	Death	Ramcharan, 1997
	Laguncularia racemosa			
Mexico	*Avicennia germinans*	?	200 ha dead	Flores-Verdugo, 1997
Colombia	*Rhizophora mangle*	?	Death	West, 1956
	?	?	?	Alvarez-Leon, 1993
French Guiana	*Avicennia germinans*	200 cm	Death	Fromard, 1998
Puerto Rico	?	?	Death	Lugo and Cintron, 1975
Guinea-Bissau	?	?	Degradation	Simao, 1993
Peru	?	?	Stressed	Echevarria and Sarabia, 1993
Cuba	?	?	Affected	Padron *et al.*, 1993

Rehabilitation Issues

For rehabilitation, sites where mangroves have been damaged or killed by root burial must be classified as either: (1) where the disturbance was a past event; or (2) where rapid accretion is an ongoing problem.

Mangrove species tend to occur in zones according to micro-elevation and frequency of inundation. Where a burial event has killed mangroves, sedimentation may have reduced the inundation frequency so that it is unsuitable to be replanted by the same species, but replanting by species that occur at slightly higher elevations will be successful. This can be determined by survey, both of the affected area, and of elevations of different mangrove species zones in an unaffected control area. Doughty Creek (Fig. 5) shows that natural regeneration occurred by the same species, despite 12 cm of sediment deposition, as this elevation was still within the inundation preference of the species.

Where rapid sedimentation is an ongoing problem, such as an active deltaic area, more research is needed to indicate which mangrove species are most suitable for replanting. *Rhizophora apiculata* seedlings have been shown to suffer in rapid sediment accretion (Terrados *et al.*, 1997). *Nypa fruticans* seems to flourish in high sediment deltas, but is untested as a rehabilitation species. *Laguncularia racemosa*, *Avicennia marina* and *Sonneratia alba* are described as colonising low accreting mud-banks of deltas (Robertson *et al.*, 1991; Fromard, 1998), but *Avicennia* and *Sonneratia* are intolerant of rapid accretion. In these areas, field trials are needed to determine species suitable for replanting.

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