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 adaptation 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 Wolsanski (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), brick dust (Bird, 1971), stakes (Bird and Barson, 1977; Spenceley, 1977, 1982) and feldspar clay (Cahoon and Lynch, 1997). Using Cs137 and Pb210, 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
the distributions of mangroves in the Tabasco delta, Mexico, as being subject to the sedimentation patterns of the river. Atmadja and Soerjo (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* (Frohmand, 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*. Widespread 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 deposition 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

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**Table 1**

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

<table>
<thead>
<tr>
<th>Location</th>
<th>Rate (mm/y)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic Island</td>
<td>-11.0 to 9.0</td>
<td>Spenceley, 1977, 1982</td>
</tr>
<tr>
<td>Cairns</td>
<td>3.0 to 10.0</td>
<td>Bird and Barson, 1977</td>
</tr>
<tr>
<td>Melbourne</td>
<td>1.0</td>
<td>Furukawa et al., 1997</td>
</tr>
<tr>
<td>Auckland, NZ</td>
<td>1.7</td>
<td>Chapman and Ronaldson, 1958</td>
</tr>
<tr>
<td>Florida</td>
<td>1.4 to 1.7</td>
<td>Lynch et al., 1989</td>
</tr>
<tr>
<td>Florida</td>
<td>0.6 to 3.7</td>
<td>Cahooon and Lynch, 1997</td>
</tr>
<tr>
<td>Mexico (Fluvial)</td>
<td>3.2 to 4.4</td>
<td>Lynch et al., 1989</td>
</tr>
<tr>
<td>Mexico (Tidal)</td>
<td>1.0 to 2.0</td>
<td>Lynch et al., 1989</td>
</tr>
</tbody>
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*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, Deveo (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 localized 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 filling (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 died (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 30 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.
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.
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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International Tropical Timber Organization and International Society for Mangrove Ecosystems, Okinawa.


