Surface Elevation Changes and Sediment Characteristics of Intertidal Surfaces Undergoing Mangrove Expansion and Mangrove Removal, Waikaraka Estuary, Tauranga Harbour, New Zealand

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Abstract

Since the 1940s mangroves have expanded their areal coverage in many estuaries in the northern half of the North Island of New Zealand. The extent of mangrove colonization in Waikaraka Estuary, Tauranga Harbour, has been documented using photogrammetric analysis, and the impacts of subsequent mangrove removal are analysed. Surface elevation changes in response to mangrove removal are measured using RSETs (Rod Surface Elevation Table) and erosion pins, and sediment accumulation rates were calculated from sediment trap results. Temporal changes to surface sediment texture are analysed. Mangrove physiognomy is described from analysis of mean plant height, plant density and pneumatophore density. Plant heights reflect the shrubby growth form of mangroves growing toward their southern climatic limit, with mean plant heights under 1.5 m. Mangrove coverage has increased from approximately 16,000 m^2 in 1943 to 115,000 m^2 in 2003. Since May 2005, 9,600 m^2 of mangrove vegetation has been removed from the estuary. For the monitoring period of March 2006 to March 2007, rates of surface elevation change in cleared areas ranged from - 9 mm to - 38 mm yr^1 (mean -14 mm yr^{-1}). Conversely, surface elevation under mangrove forest varied between sites, ranging from -5 mm to 14 mm yr^{-1} (mean 3 mm yr^{-1}). Results from RSETs and erosion pins and a coarsening of surface sediment texture at the cleared sites, are consistent with sediment release after mangrove removal.

Keywords: estuarine sedimentation rates, sediment traps, RSET.

Mathematics Subject Classification: 86A99.

JEL Classification: Q20.

1 Introduction

Sedimentation on intertidal flats has been studied extensively (Fan et al. 2004 and references therein) with a number of studies, specifically relating to mangroves, elucidating on the sedimentation and trapping mechanisms of mangrove vegetation (see for example Cahoon and Lynch 1997, Furakawa and Wolanski 1996, Krauss et al. 2003, Rogers et al. 2006, Spencely 1977). In contrast, the remobilisation and transport of sediment across intertidal areas as a result of mangrove removal has rarely been reported.

Although active sedimentation is a typical condition of most estuarine environments (Healy et al. 1996, Nichols & Biggs 1985), studies of sedimentation rates in New Zealand estuaries report increased rates of infilling since European settlement (Ellis et al. 2004, Hume and Herdendorf 1992, Hume and McGlone 1986, Sheffield et al. 1995, Swales et al. 1997). This has been attributed to land use changes, particularly where native forest has been removed for agriculture, forestry or urbanization (Hayward et al. 2006, Healy et al. 1996, Hume and McGlone 1986). Rapid sedimentation will not only influence the geomorphology of an estuary, but can negatively impact on estuarine ecology through smothering benthic fauna and muddying water which can result in lower productivity of benthic and pelagic organisms (Thrush et al. 2003, Thrush et al. 2004).

A number of studies have reported sediment accumulation within mangrove vegetation, both overseas (Alongi et al. 2005, Cahoon and Lynch 1997, Van Santen et al. 2006, Victor et al. 2006, Wolanski et al. 2006) and in New Zealand (Ellis et al. 2004, Young and Harvey 1996). The vegetation density increases friction, resulting in a reduction of water flow velocities (Massel et al. 1999) and the above-ground root structures act to create micro-turbulence capable of maintaining sediment in suspension during flood tides which then settles during periods of slack water (Furukawa and Wolanski 1996). The mangrove root zone also acts to bind sediment once it has settled, as noted in Woodroffe (1992).

Spatial gradients are often highlighted in studies of mangrove sedimentation, with higher rates of accretion recorded in the mangrove fringe (Alongi et al. 2005, Cahoon and Lynch 1997, Furukawa and Wolanski 1996, Rogers et al. 2006, Saad et al. 1999). Other factors such as sediment supply (Woodroffe 1992), tidal range (Rogers et al. 2006) and forest root structures (Cahoon and Lynch 1997, Krauss et al. 2003, Young and Harvey 1996), have also been found to influence sedimentation rates in mangrove vegetation.

An increase in mangrove coverage over recent decades has been documented in many harbours and embayments in the upper North Island of New Zealand (Burns and Ogden 1985, de Lange and de Lange 1994, Ellis et al. 2004, Swales et al. 2007, Young and Harvey 1996). It has been suggested that the increase in mangrove coverage is a response to estuarine infilling, and may also be linked to periods of calm weather and increased nutrient inputs associated with human land-use (Swales et al. 2007). Waikaraka Estuary is one of a number of embayments within Tauranga Harbour where the mono-species stands of *Avicenna marina* subsp.

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australasica are expanding their range. The catchments surrounding Tauranga Harbour have been converted to horticultural and agricultural land, with an urban fringe closer to the harbour margins. To date, no details of sedimentation rates are available for Tauranga Harbour, however it is likely to follow increased sediment run-off trends associated with forest clearance around other New Zealand estuaries (e.g. Sheffield et al. 1995). Muddier sediments have been reported in the headwaters of other embayments within Tauranga Harbour where mangroves are present (Hope 2002, White 1979).

Mangrove expansion in New Zealand is often viewed negatively by the community, arising from the perception that mangrove expansion is choking estuaries, contributing to increased mud accumulation, and altering estuarine ecology. In recent years some local councils and community groups have been granted approval to remove fringe mangrove vegetation and any propagules that establish on the tidal flats. At Waikaraka Estuary, the community group "Waikaraka Estuary Managers", commenced mangrove clearance in 2003, but the most significant removal has occurred since 2005. Mangroves were removed using manual, petrol-fuelled brushcutters. Only above-ground vegetation was cut (including pneumatophores), put into piles on-site, and later incinerated.

There is little information available pertaining to sedimentation rates under dwarfed mangrove vegetation and a greater paucity of information available to predict the effects of mangrove removal. Accordingly, the aim of this paper is to document the dynamics of mangrove expansion at Waikaraka Estuary and present preliminary results on the sedimentation rates in the presence of mangroves and topographical and sedimentological changes measured after mangrove removal. Description of plant height, plant density and pneumatophore density is incorporated to increase our understanding of the mangrove stand dynamics where plants are growing near their southern climatic limits.

2 Setting

Tauranga Harbour is situated within the Bay of Plenty region, on the east coast of the North Island of New Zealand (Lat. 37° 40'S, Long. 176° 03'E, Figure 1). It is a large barrier-enclosed estuarine lagoon (over 200 km^2) with extensive sandy tidal flats, exposed at low tide (Healy et al. 1996). On the landward side of the estuarine lagoon a number of re-entrant bays drain local catchments. The Waikaraka Estuary is bound by a small catchment of just under 10 km^2, and the estuary area itself, including mangroves, is 0.5 km^2. The surrounding catchment incises ignimbrite geology underlying some Holocene and Late Pleistocene alluvium and tephras closer to the harbour margins (Briggs et al. 1996, Harmsworth 1983). All native forest has been removed from the Waikaraka catchment, which is now dominated by kiwifruit and citrus orchards.

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Freshwater discharge into Waikaraka Estuary is considerably smaller than neighbouring embayments. The main tributary, Minden Creek, contributes a mean annual flow of 92 l^{s-1}, compared to the neighbouring Te Puna estuary which receives 792 l^{s-1} (Hope 2002). Tides at the entrance of Waikaraka estuary have been measured as meso-tidal, ranging from 2.1 m at spring tides, to 1.4 m during neap tides, with the tidal range decreasing to 0.6 - 0.7 m in the upper estuary (Hope 2002). Mangrove stands in the middle and upper estuary are inundated only during the final stage of high tide and the mangrove and cleared plots closer to the estuary mouth (Site 4, see Figure 1) are covered 30 to 45 minutes earlier.

3 Methods

3.1 Mangrove Physiognomy

Plant height, stem girth at 0.05 m above stratum, and pneumatophore density were measured at four sites along the estuary (Figure 1). At each of these sites, three 4 x 4 m plots were randomly selected, marked out, and all trees measured for the above-mentioned parameters. Pneumatophores were counted in three separate, randomly selected 1 m^2 quadrats within each plot. Mean values reported in Table 2 represent results of the three plots combined for each site.

3.2 Sediment characteristics

In July 2006 (southern hemisphere winter) triplicate sediment samples were collected along transects at Sites 2, 3 and 4. In February 2007 (summer), sites were resampled, with the inclusion of Site 1, to provide baseline grain size data in light of potential mangrove removal in the future. Two sampling stations were located inside mangrove habitat, and three stations on the bare flats (Figure 3f). Samples were also collected at three locations within cleared plots 1, 2 and 3, in May 2005 and again in summer 2006 and 2007.

Sediment samples were treated with 10% H_2O_2 to remove organic material. Calgon was then added for deflocculation, and samples analysed for grain size distribution using the Malvern Mastersizer S Version 2.19.

Three sediment cores, 1.5 m – 3 m in length, were collected in 70 mm diameter aluminium tubes using a vibracorer (Figure 3). Cores were returned to the lab for stratigraphic logging and sub-samples were removed for grain size analysis and color notations, using Maunsell color charts.

It was only possible to collect cores in proximity to the main access point, which is midway along the estuary, roughly 25 m South of Site 4 (see Figure 1 for site location). Core (a) represents the sediment profile beneath a recently cleared mangrove zone; Core (b) adjacent mudflats within

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25 m of the cleared mangrove zone, and Core (c) was collected toward the middle of the intertidal flats, approximately 15 m east of the main tidal channel (Figure 6). A short core (35 cm deep) was collected within the mangroves in the vicinity of Site 2, in the middle, longitudinally, of the mangrove zone.

3.3 Surface elevation changes from erosion pins and RSET

Surface elevation changes on the mudflat surface were measured with a series of Rod Surface Elevation Tables (RSET), as described in Cahoon et al. (2002) (Figure 3). Benchmark poles were driven 3 m into the substrate with around 50 cm protruding from the estuary floor, then further stabilized with cement. A detachable arm with nine measuring pins attaches to the benchmark pole via a rod-collar coupling device, and for this study was rotated 180°, giving a total of 18 readings per RSET, which were then averaged after each visit to give a single value of surface elevation. Confidence intervals for the measured height of an individual pin was measured at {+/-} 1.3 mm in a mangrove forest (Cahoon et al. 2002). Each RSET benchmark was manually surveyed one month after installation, and again 14 months later to ensure the poles had maintained their original position.

Three transects of four RSETs were positioned in the upper estuary in the vicinity of Sites 2 and 3 (see Figure 1 for site location and Figure 3f for transect lay-out). RSETs are a permanent fixture in the environment and because of the potential for injury or interference, only three transects were installed. The intertidal RSETs along Transect 1 were positioned in Cleared Plot 3 (10 m from mangrove fringe) and Cleared Plot 1 (20 m from mangrove fringe) while RSET Transects 2 and 3 were positioned within mangroves and on bare tidal flat to assess variation in surface elevation changes in the absence of mangrove removal.

Stainless steel erosion pins were installed at 15 locations within the cleared areas as well as the mangrove zones at Sites 1 and 4, the locations of which are displayed in Figure 7. Erosion pins (0.7 m long, 5 mm diameter) were deployed in clusters of seven pins (Figure 3) and driven into the substrate with 0.2 m remaining above the sediment surface. The height above substrate of the seven pins was averaged to provide a single measurement of elevation change. Erosion pins have been used in other mangrove environments (e.g. Spenceley 1977), and though the accuracy has not been specified in published surveys, it can be estimated to the nearest millimetre (Thomas and Ridd 2004).

Site 4 was partially cleared of mangroves in mid-March 2006, roughly one year after sections in the vicinity of Site 2 and 3. Cleared Plot 1 (CP1) was cleared on 21 May 2005; CP2 on 13 August 2005 and CP3 on 30 August 2005 (Figure 2).

In this study, recorded measurements from RSETs and erosion pins are referred to as ‘surface elevation change’. These devices measure the rise or fall in the substrate, therefore any

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sediment compaction, shallow subsidence, root decomposition, or root growth are incorporated in the result of elevation change (as per Cahoon et al. 2000).

3.4 Sediment traps

Gross sediment deposition was measured using sediment traps (Figure 3) which were deployed for approximately one month in May and June 2006 (winter) and January and February 2007 (summer). Transects of sediment traps were installed at the four monitoring sites, with two traps inside the mangroves and one on the bare flats (Figure 3f). Sediment accumulation rates of dry sediment are expressed in g m^2 mth^{-1}. A combination of tampering, mishandling and growth of filamentous algae over traps, has reduced the final analyses however.

4 Results

4.1 Mangrove Expansion

Temporal change of the planimetric distribution of mangrove vegetation in the estuary has been mapped using aerial photographs dated 1943, 1982, 1996 and 2003. Mangrove coverage in 1943 was approximately 16,000 m^2. In 1982 mangroves had colonized seaward, increasing the area of mangrove vegetation to 29,000 m^2 and by 1996 mangroves had expanded to cover approximately 100,000 m^2, including the previously bare sandier areas south-east of the estuary mouth (in the vicinity of Site 4, see Figure 2). Between 1996 and 2003 further colonization increased mangrove coverage to 115,000 m^2 (Table 1).

4.2 Mangrove Physiognomy

Average plant heights, measured within each 16 m^2 plot, range from 0.68 m (± 0.11 m) to 1.21 m (± 0.18 m). Standard error around mean plant height was sufficiently low that the three plots at each site were grouped together for further analysis. Mean plant height appears to have no correlation with the age of the mangrove stands studied, with the youngest (Site 4) and oldest (Site 1) stands displaying similar mean plant heights of 1.03 m and 1.04 m respectively (Table 2). Stem density is highest and stem diameter lowest at Site 3, where mean plant height is lower than all other stands (0.76 m).

Average pneumatophore density at Site 4, where shrubs have been growing for less than 20 years, is 282 per m^2, which is less than 50% of the 694 per m^2 measured at Site 1.

4.3 Surface Sediment Characteristics

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The greatest mud (particle size < 63 µm, as defined by Folk (1968), incorporating % clay and % silt) content of surface sediments is found within Site 1 (93%), toward the head of the estuary. Mud content exceeds 50% for all mangrove and cleared sites, however some spatial variability between, and within, mangrove sites is evident. The undisturbed bare flats at Sites 1, 2 and 3, however, possess mud content <40% and therefore contain >60% sand (Table 3).

An increase in grain size across bare flats of Transect 2 in summer 2007 compared to winter 2006 is apparent, with the opposite trend occurring at bare flat locations of Transects 3 and 4 (Figure 4). No clear seasonal fluctuation is discernible in mangrove habitat due to the range of grain sizes recorded.

Temporal variation in sediment texture of the cleared plots is displayed in Figure 5. Results exhibit an apparent increase in grain size from winter 2005 to summer 2006, however this is obscured by the considerable variation in grain sizes recorded for summer 2006. In August 2005, mean grain size collected within cleared plots ranged from 22 µm (± 3) at Clear Plot 2, to 53 µm (± 24) at Clear Plot 3, being medium silt to very fine sand. In February 2007, mean grain size ranged from 82 µm (± 43) at Clear Plot to 94 µm (± 27) at Clear Plot 3 (very fine sand) (Table 3).

4.4 Sediment Cores

Sedimentary features of three cores are displayed in Figure 6. A comparison of the surface facies indicates a deeper, finer-grained surface layer in the mangrove zone (Core (a)). Mangrove rootlets are most dense in the upper 15 cm of black silty sand. Shell material is absent in Core (a) whereas coarse and fine sands are coupled with shell hash and shell material in Cores (b) and (c), indicative of intertidal deposits.

The most noticeable change to the sedimentary units occurs at depths of around 50-55 cm in all cores, where overlying sandy beds are replaced with unconsolidated silts which penetrate to depths beyond 1 m in Core (c), 85 cm in Core (b) and just under 1 m in Core (a). Shell material is not present in these lower facies, except for a 4 cm sandy layer with shell hash found at 80 cm in Core (b), representative of a tidal channel or intertidal sand-flat environment. The coarse silt found between 55 cm and 95 cm in Core (a) is "soupy" which could indicate groundwater penetration, a zone of poor water filtration, or a bed of degrading volcanic sediment containing smectite (Harmsworth 1983).

The short core collected at Site 2 was found to have a surface layer to 8 cm consisting of olive-black, medium silt (16-22 µm). Mean grain size then changed to coarse silt and very fine sand to a depth of 25 cm, below which was medium and fine sands to 35 cm. Comparison between the short core and Core (a) suggests the finer silt fraction has been removed from the surface of Core (a), which was cleared of mangroves three months prior to collection.

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4.5 Surface Elevation Change

Annual rates of surface elevation change displayed in Figure 7 show a reduction in surface elevation ranging from 9 mm yr^{-1} to 38 mm yr^{-1} within the zones cleared of mangrove vegetation, and mostly an increase in surface elevation within mangrove vegetation, ranging from – 5 mm yr^{-1} to 14 mm yr^{-1}. Highest rates of surface elevation increase were recorded inside mangrove habitat along RSET Transect 2 (6 mm yr^{-1} and 14 mm yr^{-1}).

Figure 8 demonstrates the cumulative drop in surface elevation recorded within the areas cleared of mangroves. Cumulative surface elevation change along the RSET transects shows an apparent stability of the bare flats in the vicinity of RSET Transect 2, whereas the bare flats of the cleared plots (RSET Transect 1) experienced a continual fall in surface elevation. Migration of a small channel was observed in the vicinity of RSET Transect 3 and is reflected in the fall in surface elevation at the 20 m RSET in March 2007. Figure 8 also illustrates an overall increase in surface elevation measured over time at most mangrove RSET stations, though some temporal variation is evident.

4.6 Sediment Accumulation Rates from Sediment Traps

Sediment trap results exhibit variation in sediment accumulation rates, with the greatest accumulation occurring on the bare flats where values ranged from 1,200 to 6,000 g m^2 mth^{-1} (Figure 9). Site 4, closer to the estuary mouth, generally shows the highest values of sediment accumulation.

Figure 10 suggests there is no linear relationship between rates of sediment accumulation and total rainfall or highest rainfall intensity for the trap deployment periods (rainfall data from NIWA Climate Data Centre, Tauranga Aerodrome recording station).

5 Discussion

The purpose of this study is to report on the mangrove expansion at Waikaraka Estuary and investigate the physical changes that occur as a result of mangrove removal. Photogrammetry documented a 23% increase in mangrove coverage over the total estuary area between the years 1943 to 2003, with the greatest rate of expansion occurring between 1982 and 1996. The expansion rate has subsequently slowed, possibly as a result of human intervention via physical removal of propagules from the estuary. The main driver for mangrove expansion at this site can only be speculated. The Waikaraka Estuary catchment area has experienced considerable land clearance since European settlement (approximately 150 - 200 years) and during this time sediment loads entering the estuary may have been greater than the present-day. Prior to the

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1980s, stock grazing, land reclamation and rubbish dumping were all permissible activities in New Zealand estuaries which may have truncated any estuarine vegetation establishment during that time. Recent prohibition of these activities may play some role in the success of mangrove expansion. Other possible factors include increases in nutrient run-off as a result of agricultural and horticultural activities, or a reduction in the occurrence of chilling temperatures during the establishment phase of mangrove propagules.

Mangrove shrubs in Waikaraka Estuary display a mean plant height of <1.5 m, in contrast to other New Zealand sites where tree heights range between 2 and 6 m in similar physical conditions (Alfaro 2005, Ellis et al 2004, May 1999, Morrisey et al. 2003, Osunkoya and Creese 1997, Young and Harvey 1996). The study site is located toward the southern limit of mangrove distribution in New Zealand, and the limited plant growth can be attributed to climatic stress (Beard 2006). Spatial variation in plant height is commonly found in mangrove habitat (e.g. Burns and Ogden 1985, Crisp et al. 1990) and in this study could not be attributed to age. Other possible causes such as salinity (Crisp et al. 1990) and nutrient availability (Fry et al. 2000, Naidoo 2006) were not measured.

Pneumatophore densities measured in this study are higher than those reported in other New Zealand estuaries (Alfaro 2005, Ellis et al. 2004, Morrisey et al. 2003, Young and Harvey 1996) which may be due to the high mud content of surface sediments (Ellis et al. 2004). The low pneumatophore density measured within the youngest stand of mangroves in Waikaraka Estuary is consistent with a reported correlation between increasing plant age and higher pneumatophore densities (Morrisey et al. 2003). Pneumatophore density has also been found to correlate with increased sediment trapping capability (Young and Harvey 2004). Sediment trapping occurs within the mangrove vegetation at the study site, evidenced by the recorded increase in surface elevation. Surface elevation change averaged 3 mm yr^{-1} which is less than that recorded in other New Zealand estuaries (Ellis et al. 2004, Swales et al. 2007, Swales et al. 1997) although this is a similar range to values recorded in Florida (Cahoon and Lynch 1997), Vietnam (Van Santen et al. 2006) and temperate Australia (Rogers et al. 2005, Rogers et al. 2006).

Sedimentation rates are influenced by sediment supply into the estuary and hydrodynamic processes (Furukawa et al. 1997), and as Waikaraka Estuary receives a relatively low volume of freshwater inflow, it is likely that suspended sediment input will also be relatively low, particularly in light of the small catchment area (10 km^2).

The establishment of mangrove vegetation on previously bare tidal flats initiates a substantial change in surface sediment characteristics. Interpretation of core stratigraphy and surface sediment analysis suggests that bed material of fine and medium sand representative of the bare intertidal flats, is replaced by silt-dominated sediment once mangroves become established. The depth of mud is likely to vary spatially within the estuary, and was found to extend to a depth of 8 cm in the vicinity of a well-established mangrove stand located roughly

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equi-distant between the mouth and head of the estuary. Interestingly, medium and coarse silts were also found at depths of around 55 cm below the surface, suggesting that the study site has experienced accumulation of finer-grained material in the past.

Rates of surface elevation change associated with mangrove vegetation at Waikaraka Estuary ranged from -5 mm to 14 mm yr^{-1}. The rate of surface elevation change is spatially and temporally variable with no clear seasonal fluctuations discernible over the monitoring period. A relationship between sedimentation and distance from estuary head has been reported in other studies (Young and Harvey 1996), but was not evident at this site. Higher values of surface elevation change recorded mid-estuary coincide with lower values along the RSET transects either side, suggesting the existence of a narrow depositional zone within this section of the estuary. This could be the result of tidal currents pushing released sediment from neighbouring cleared zones into this mangrove zone (approximately 200 m downstream), or may simply be due to a topographical/hydrodynamic anomaly favouring deposition at this location.

Sediment availability (determined from sediment traps) is lower within mangrove habitat than on the adjacent bare flats, further demonstrating the trapping capabilities of mangroves at the study site, particularly as the higher sediment accumulation rates of the bare flats do not result in a net gain in surface elevation. This trend of decreasing sediment load between the bare tidal flats and vegetation zone, coupled with increasing sedimentation into fringing mangrove habitat, has been discussed by other authors and is considered to be a function of both the trapping capability of high vegetation density (Furukawa and Wolanski 1996) and erosional episodes of the less stable sediments on the bare tidal flats (Van Santen et al. 2006). The monitoring undertaken in this study coincided with mangrove clearing activities therefore the sediment accumulation rates quoted may not reflect typical, or ambient, sediment availability but is likely to reflect the injection of released sediment from cleared zones. A positive correlation between rainfall and sediment accumulation has been reported in other studies (Saad et al. 1999, Van Santen et al. 2006), however this trend was not evident during the periods of trap deployment at Waikaraka Estuary, possibly due to this remobilisation of sediment.

Since May 2005 approximately 9,600 m^2 of mangrove vegetation has been removed from Waikaraka Estuary, resulting in significant changes to surface topography. Surface elevation within cleared areas fell at rates of 9 to 38 mm yr^{-1} (average 14 mm yr^{-1}). The decomposition of mangrove root material has been found to contribute significantly to falls in surface elevation, following a study of mass tree mortality (Cahoon et al. 2003). Unfortunately, marker horizons were unsuccessful in this study and as such it is not possible to separate the processes of sediment erosion and root-mass decomposition. An apparent increase in grain size between winter 2005 and summer 2007, mostly of no more than 30 μm, is skewed by a systematic and substantial increase in grain size documented for summer 2006, coupled with a considerable range of mean values. Possible explanations for this anomaly are a) a function of spatially variable root-mass decomposition resulting in zones of released sediments along with trapped,

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coarser sediments within areas where root mass is still significant, b) the temporary exposure of underlying coarser material, c) the response to a period of increased flow velocities; d) an artifact of sample collection. A fining of surface texture between winter 2006 and summer 2007 occurred on bare flats adjacent to cleared zones at two of three sampling locations which could possibly be due to deposition of silt released from nearby cleared areas.

6 Conclusion

The distribution and expansion of mangrove habitat in Waikaraka Estuary over the last 60 years is reported and the changes in surface topography and surface sediment as a result of mangrove removal are documented. Mangrove coverage has increased from 16,000 m^2 in 1943, to 115,000 m^2 in 2003, determined by photogrammetry. The measured mean tree heights of less than 1.5 m are significantly shorter than mangroves growing in warmer regions of New Zealand, inferring climatic limitations to growth. Annual rates of surface elevation change within mangrove habitat (using erosion pins and RSETs) averaged 3 mm, which demonstrates sediment trapping by mangrove vegetation. In contrast, after mangrove clearance a reduction in surface elevation occurred, ranging from 9 mm to 38 mm yr^{-1} (mean 14 mm yr^{-1}). Concurrent to this fall in surface elevation is an increase in mean grain size (<53 µm to ~ 78 µm), indicating remobilisation of some of the silt fraction as a result of a) the loss of above-ground plant architecture which dampens water flow; and b) decomposition of root material which previously held sediment. This study demonstrates that the removal of mangroves results in some remobilisation of sediment, mostly in the silt fraction. It is important to note, however, that 18 months after mangrove clearing the remaining sediment is still finer than that of the surrounding bare flats.

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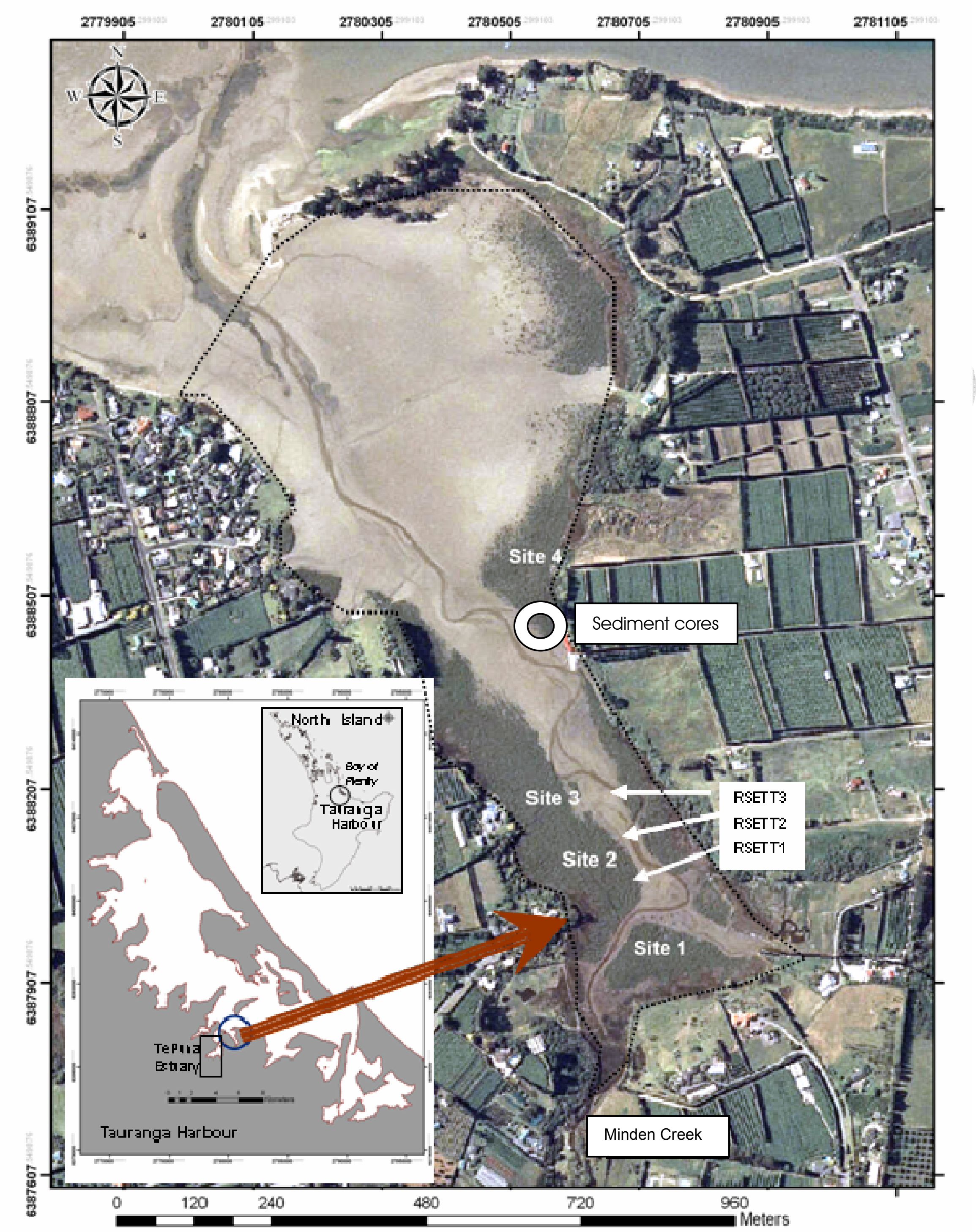

Figure 1: Waikaraka Estuary, a narrow estuary positioned along the western margins of Tauranga Harbour. Sample collection sites and RSET locations are labeled. 'Estuary area' represented by hatched line, outlined for determination of mangrove coverage as % of estuary area. Aerial photograph (2003) courtesy of Environment Bay of Plenty.

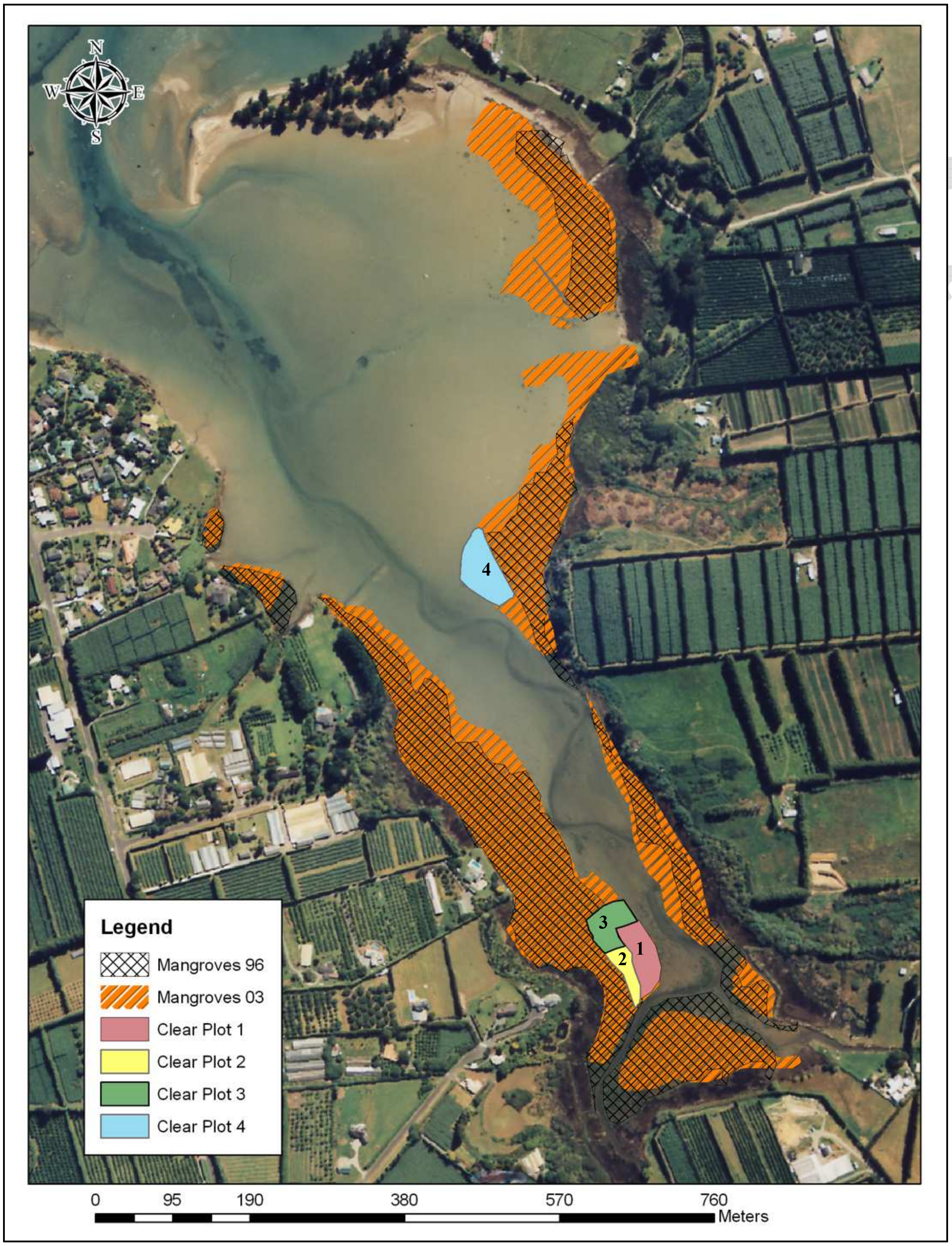

Figure 2: Aerial vertical image of Waikaraka Estuary, 2003. Mangroves have expanded to cover approximately 115,000 m^2. Four plots have been cleared of mangrove vegetation since April 2005, totaling 9,600 m^2.

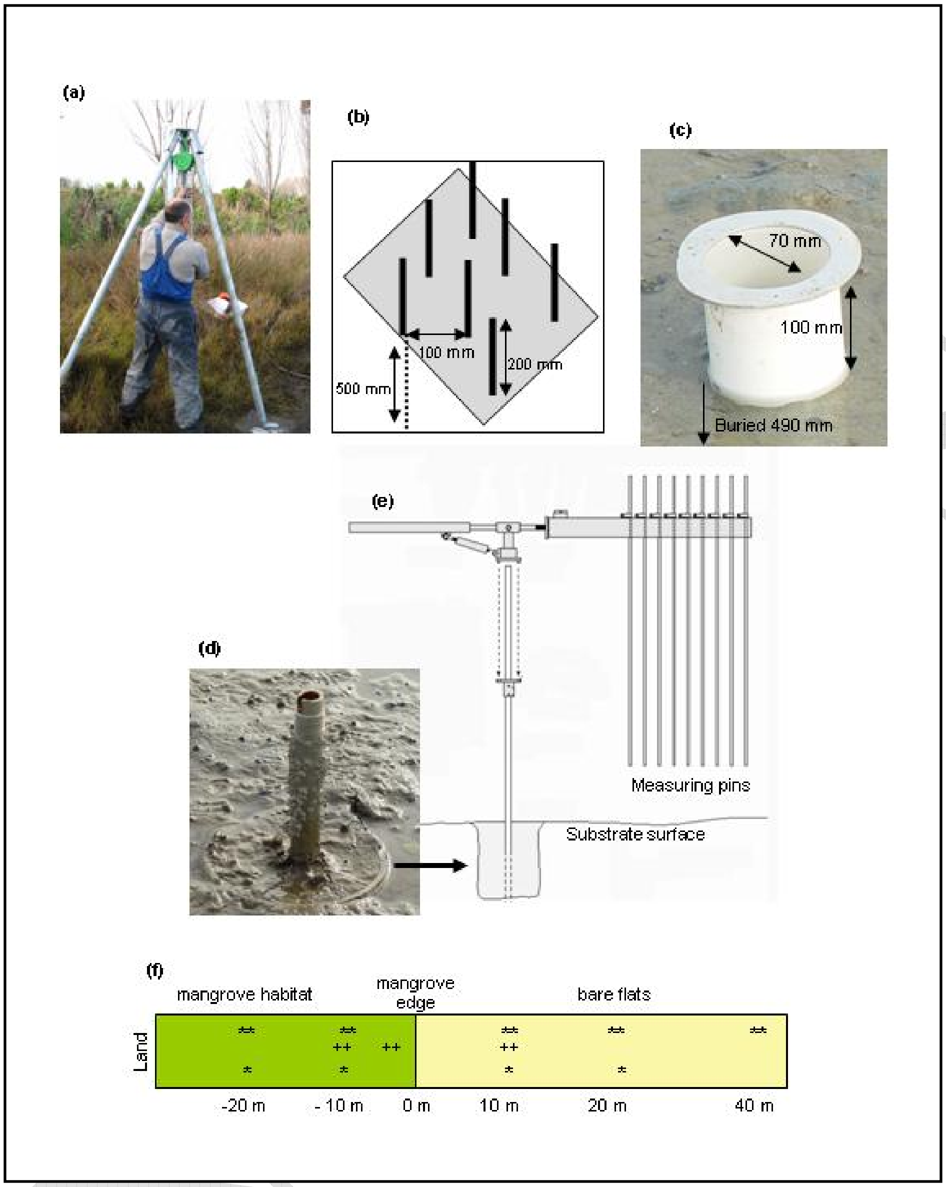

Figure 3: Images of instruments used in this field study. (a) Tripod component of the motorised vibracorer used to collect sediment cores; (b) schematic diagram of erosion pin cluster, (c) sediment traps installed on bare intertidal flats and within mangrove zones; (d) the permanent benchmark of the RSET device; (e) conceptual diagram of the portable RSET arm with adjustable measuring pins (from Cahoon et al. 2002); (f) spatial lay-out of transects for * RSET positions, ** collection of surface sediments, ++ sediment traps.

Table 1. Area (m^2) and percent coverage of total estuarine area of mangrove coverage measured from aerial photographs dated 1943, 1982, 1996 and 2003.

Year	Area of estuary covered by mangroves (m^2)	% of estuary covered by mangroves
1943	16,000	3
1982	29,000	6
1996	100,000	20
2003	115,000	23

Table 2. Plant height, density, stem diameter and pneumatophore density values displayed by site (mean ± SD)

SITE	Mean plant density (m^2)	Mean plant height (m)	Mean stem diameter (m)	Mean pneumatophore density (m^2)
Site 1	1.5	1.04 (0.22)	.049 (.032)	694 (99)
Site 2	0.9	1.10 (0.16)	.048 (.030)	470 (86)
Site 3	2.5	0.76 (0.15)	.029 (.020)	535 (202)
Site 4	1.3	1.03 (0.22)	.035 (.026)	282 (33)

Table 3. Surficial sediment textural analyses for sites under mangroves, cleared of mangroves and on undisturbed bare flats in the Waikaraka Estuary. Samples collected February 2007.

	Mangroves					**Area cleared of mangroves**					**Undisturbed intertidal flats**				
	site name	% clay	% silt	% sand	mean grain (μm)	site name	% clay	% silt	% sand	mean grain (μm)	site name	% clay	% silt	% sand	mean grain (μm)
Site 1	TP1-1	17	76	7	22	TP1-3	6	49	45	93	TP1-5	5	31	64	138
	TP1-2	15	78	7	21	TP1-4	6	46	48	88					
Site 2	TP2-1	14	62	24	55	TP2-3	7	49	43	94	TP2-5	4	22	73	213
	TP2-2	10	46	44	114	TP2-4	5	46	49	98					
Site 3	TP3-1	9	41	50	173	TP3-3	7	52	41	85	TP3-5	5	33	62	136
	TP3-2	14	69	17	39	TP3-4	7	50	43	91					
Site 4	TP4-1	0	70	13	32	TP4-3	13	72	15	33	TP4-5	5	47	48	84
	TP4-2	15	65	20	47	TP4-4	11	66	23	44					
Mean		12	64	23	63		8	54	39	78		5	33	62	143
Std Dev		5	13	16	53		3	10	13	25		1	10	11	53

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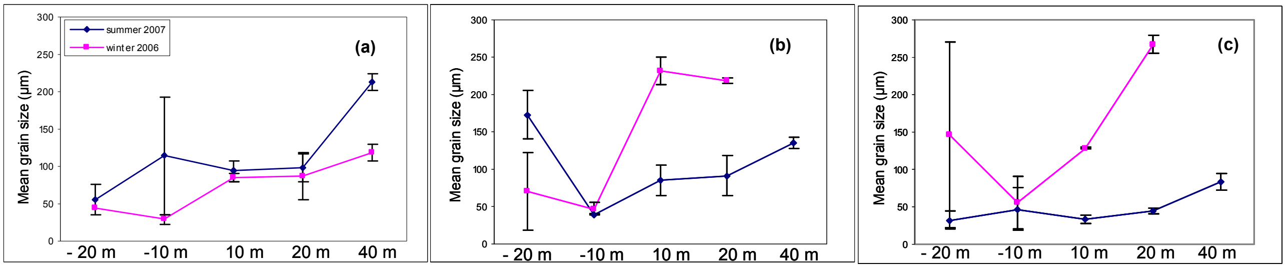

Figure 4: Seasonal grain size variation measured in winter 2006 and summer 2007 along transects at Site 2 (a), Site 3 (b) and Site 4 (c). Samples collected 20 m (-20 m) and 10 m (-10) landward of mangrove fringe and 10, 20 and 40 m seaward of the mangrove fringe.

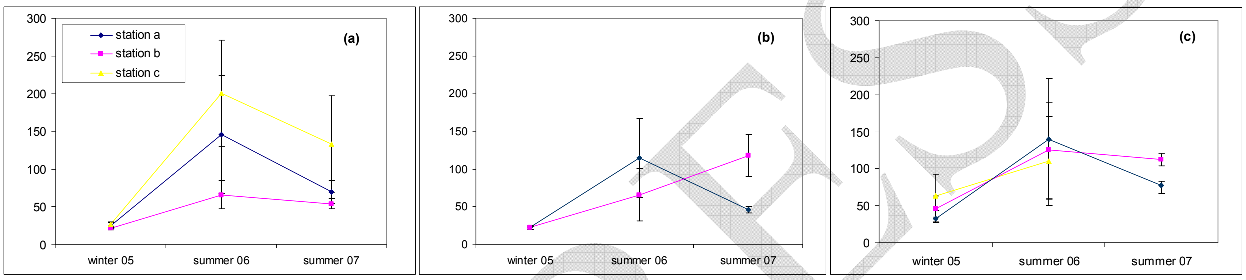

Figure 5: Surface grain size (µm) and standard deviation of the average of 3 samples per collection station within Cleared Plot 1 (a), Cleared Plot 2 (b) and Cleared Plot 3 (c) from samples collected within 3 months of mangrove clearance (winter 2005), and the following summer 2006 and summer 2007.

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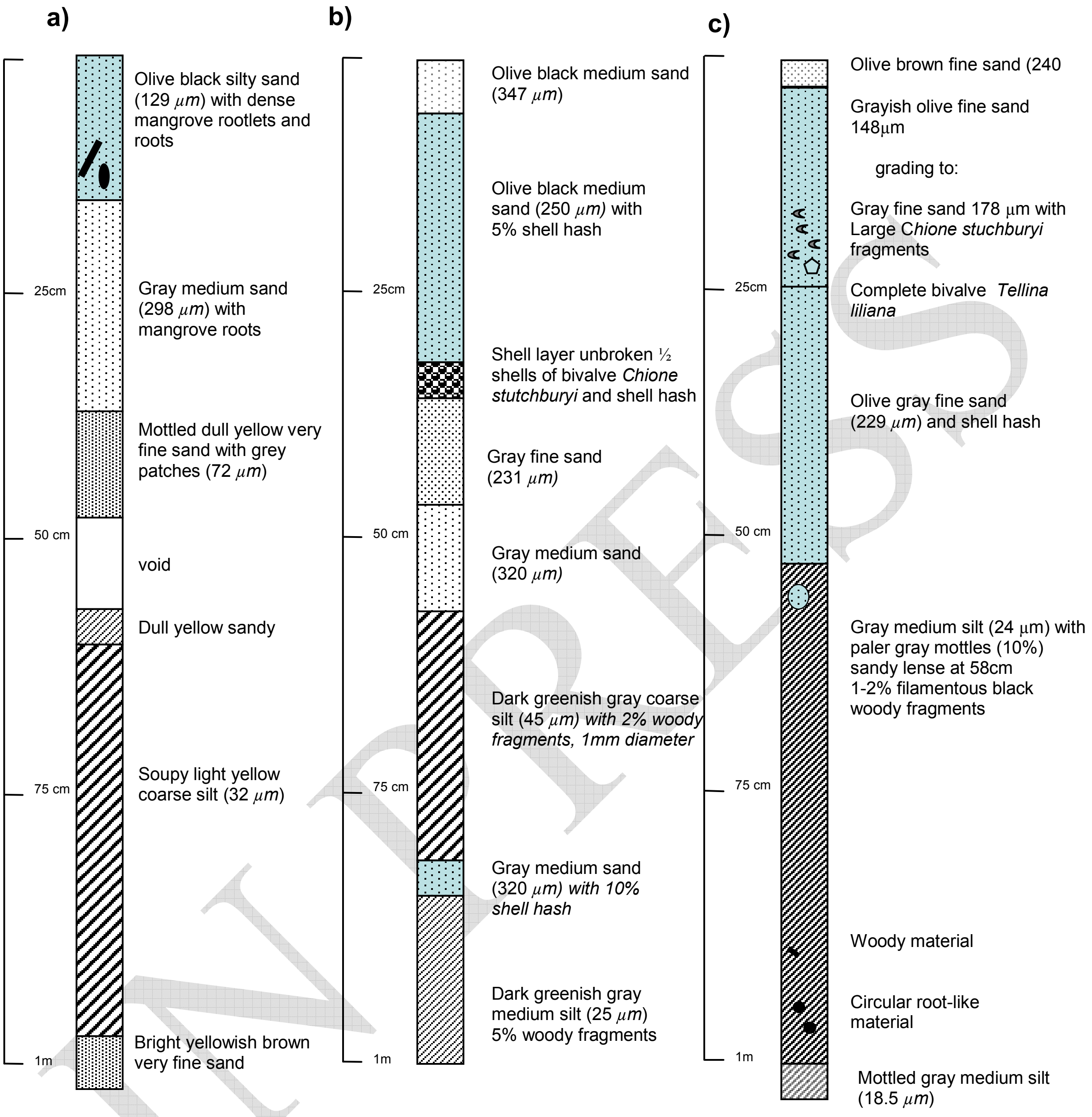

Figure 6: Core stratigraphy for a site cleared of mangroves 3 months before core collection, Core (a); bare flats within 25 m of the cleared mangrove zone, Core (b); and 15 m east of the main tidal channel, Core (c).

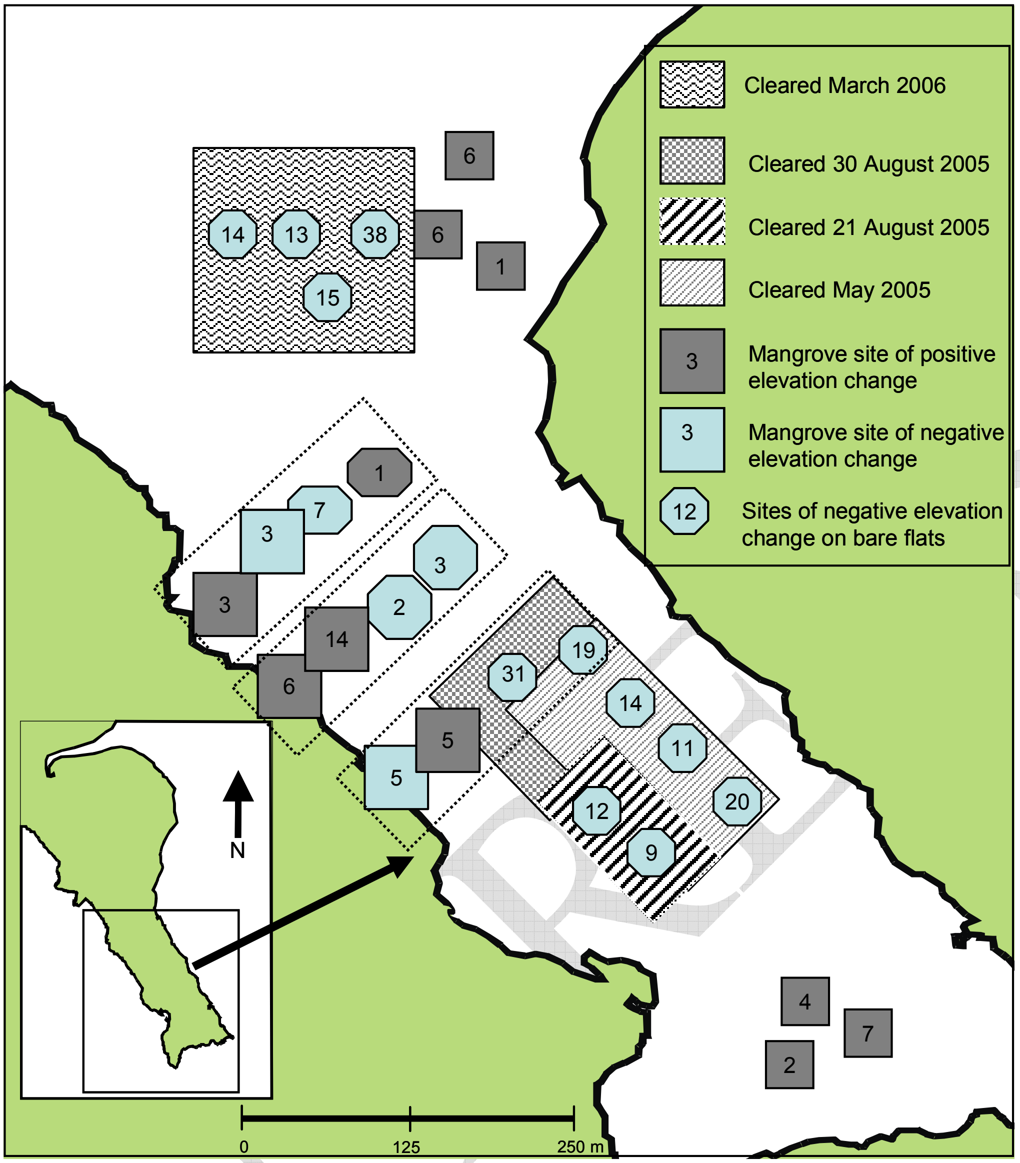

Figure 7: Graphic illustration of annual rates of surface elevation change, calculated from erosion pin and RSET measurements for the monitoring period March/April 2006 to March 2007. RSET transects are outlined with hatched line.

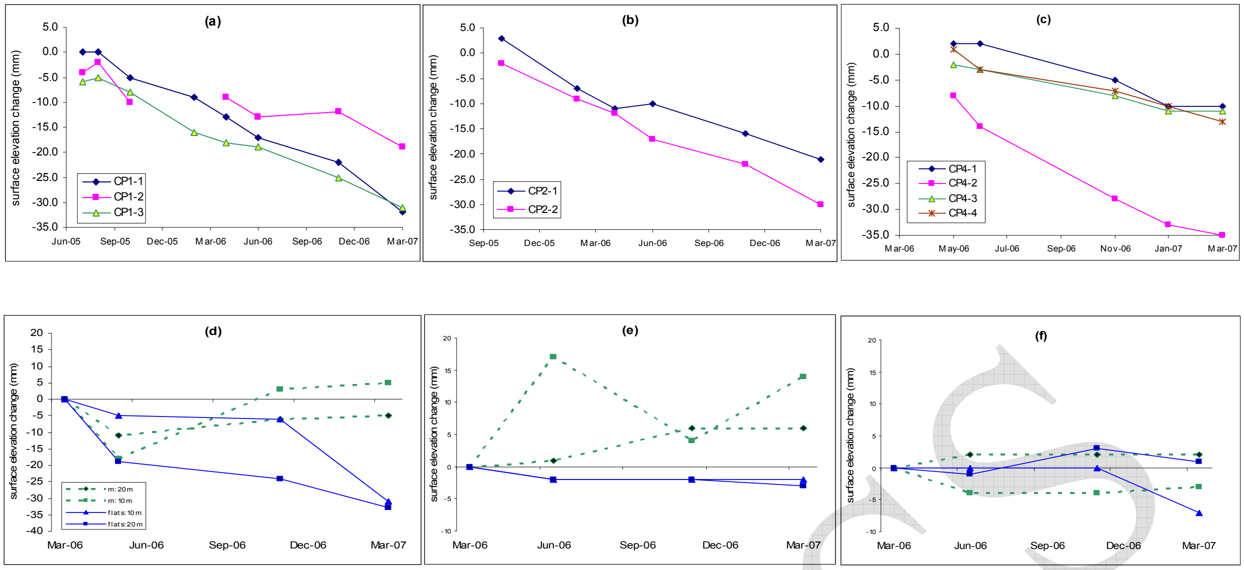

Figure 8: Cumulative surface elevation change within Cleared Plot 1 (a), Cleared Plot 2 (b) and Cleared Plot 4 (c); and along RSET Transects 1 (d), RSET Transect 2 (e) and RSET Transect 3 (f). Mangrove locations of RSET transects are represented by hatched lines.

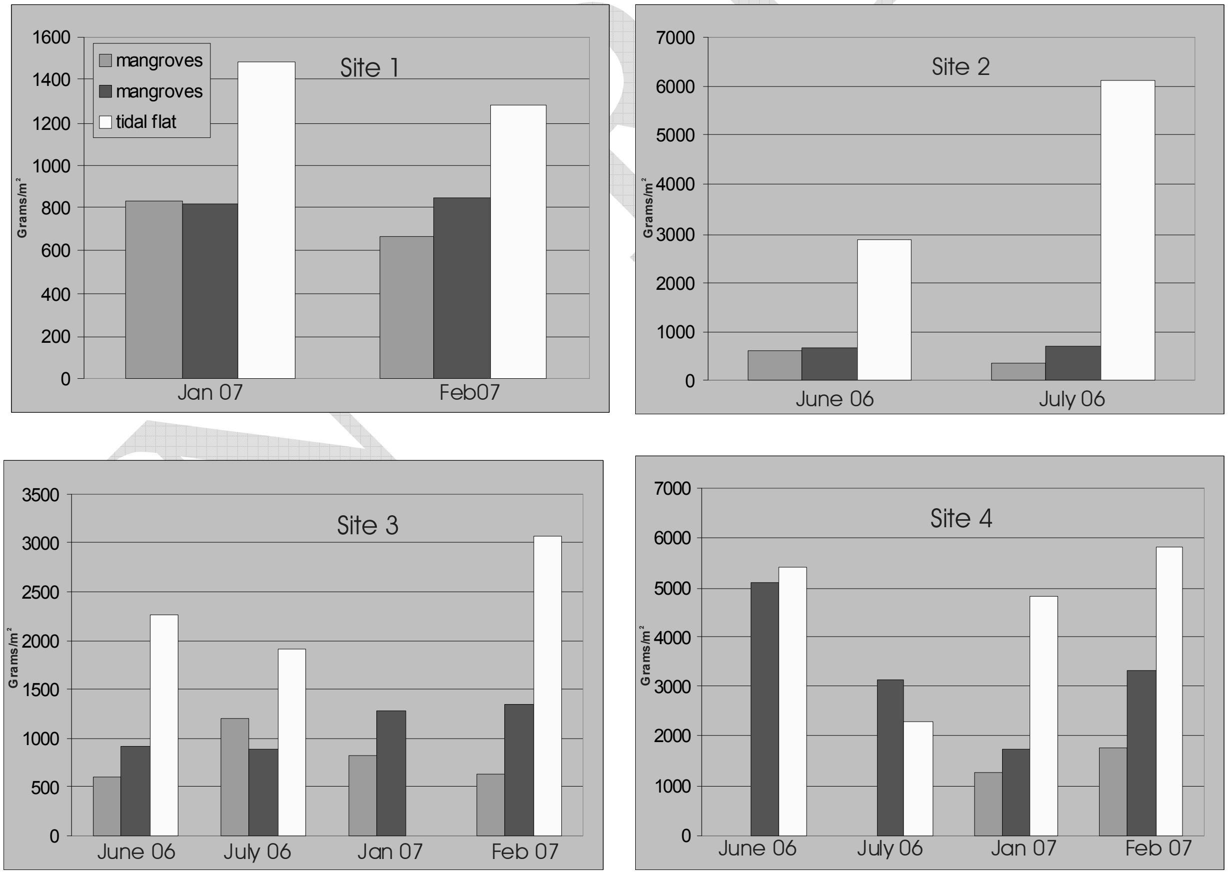

Figure 9: Sediment trap accumulation rates (g m^2 mth^{-1}) for June 2006, July 2006, January 2007 and February 2007. Pale grey columns represent trap locations within mangrove habitat 10 m from mangrove fringe; dark grey columns represent sites 5 m from mangrove fringe, and white columns represent traps positioned on bare flats 10 m from the mangrove fringe.

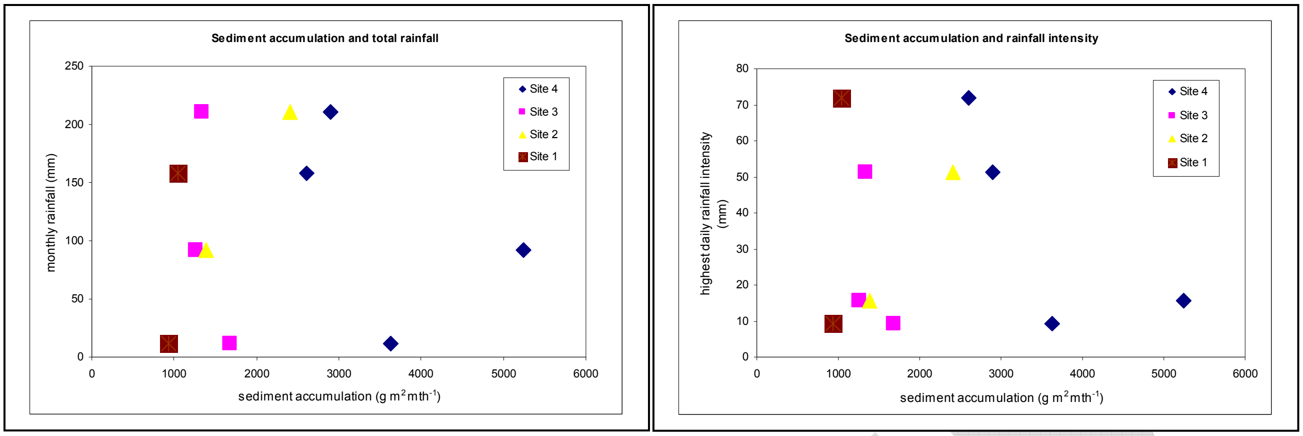

Figure 10: Sediment trap results of sediment accumulation plotted against rainfall intensity and total rainfall for the trap deployment periods June 2006, July 2006, January 2007 and February 2007.

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