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Coastal Sediment Elevation Change Following Anthropogenic Mangrove Clearing

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1 COASTAL SEDIMENT ELEVATION CHANGE FOLLOWING ANTHROPOGENIC
2 MANGROVE CLEARING

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14 Key Words: accretion, Belize, deforestation, ecosystem service, erosion,
15 mangrove

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1 ABSTRACT

2
3 Coastal mangrove forests along tropical shorelines serve as an important
4 interface between land and sea. They provide a physical buffer protecting the
5 coastline from erosion and act as sediment “traps” catching terrestrial sediment,
6 thus preventing smothering of subtidal coral reefs. Coastal development that
7 removes mangrove habitat may impact adjacent nearshore coral reefs through
8 sedimentation and nutrient loading. We examined differences in sediment
9 elevation change between patches of open-coast intact and anthropogenically
10 cleared red mangroves (*Rhizophora mangle*) on the east side of Turneffe Atoll,
11 Belize, to quantify changes following mangrove clearing. Samples were collected
12 over a 24 month period at five study sites, each containing paired intact
13 (+mangrove) and cleared (-mangrove) plots. Five sediment elevation pins were
14 deployed in each plot: behind areas cleared of mangroves (-mangrove) and
15 behind adjacent intact mangroves (+mangrove). Sediment elevation increased at
16 intact mangrove sites (M= +3.83 mm, SE=0.95) whereas cleared mangrove
17 areas suffered elevation loss (M= -7.30 mm, SE=3.38). Mangroves inshore of
18 partial or continuous gaps in the adjacent fringing reefs had higher rates of
19 elevation loss (M=-15.05mm) than mangroves inshore of continuous fringing
20 reefs (M=-1.90mm). Our findings provide information on potential effects of
21 mangrove clearing and the role of offshore habitat characteristics on coastal
22 sediment trapping and maintenance of sediment elevation by mangroves. With
23 implications for coastline capacity to adjust to sea level rise, these findings are
24 relevant to management of coastal fringing mangrove forests across the
25 Caribbean.

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2 I. INTRODUCTION

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Mangrove forests serve integral ecological functions in tropical coastal zones (Mumby et al. 2004), yet damage to and loss of mangrove forests has been extensive worldwide (Crooks and Turner 1999). Mangrove forests have been rapidly cleared and converted for real estate speculation, construction of tourist resorts, agricultural land reclamation and other coastal development; shrimp aquaculture; and to a lesser extent, collection of lumber (Kaly et al. 1997, Stevenson 1997, Valiela et al. 2001). Mangrove forest loss due to anthropogenic clearing has occurred at an alarming rate (-1% annually in the 1980's [FAO 2003]; -0.66% annually between 2000-2005 [FAO 2007]) resulting in a significant decrease in global mangrove forest cover (estimated losses of up to 35% during the last two decades of the 20th century [Valiela et al. 2001]). Similarly, mainland Caribbean mangroves have suffered a 1.7% annual decline in aerial cover (Ellison and Farnsworth 1996). Some researchers project a complete loss of this ecosystem type from certain regions within the next 100 years (Duke et al. 2007).

Mangroves play a key role in ecological functioning of adjacent nearshore habitats and provide a number of ecosystem services to surrounding coastal communities. Coastal mangrove forests serve as a key habitat for ecologically and commercially important species (e.g., Mumby et al. 2004, Igulu et al. 2014) and are important for carbon storage (Blue Carbon, e.g., Donato et al. 2011). This coastal ecosystem also serves as an key physical buffer, protecting coastal zones from erosion, extensive wave action, and flooding during tropical storms and hurricanes (Field 1998, Ellison 2000, Danielsen et al. 2005, Kar 2005,

1 Granek and Ruttenberg 2007). As oceanic storms increase in frequency and
2 intensity with warming sea surface temperatures (Williams 2005) and as sea
3 level rises, the importance of mangroves is expected to increase. Finally, coastal
4 mangroves serve as sediment “traps” accreting terrestrial sediment and
5 preventing it from smothering subtidal coral reefs (Bird 1971, Wolanski and Ridd
6 1986, Augustinus 1995, Blasco et al. 1996, Woodroffe 2002, Golbuu et al. 2003,
7 Thampanya et al. 2006, Victor et al. 2006).

8 These ecological functions can be disrupted when natural disturbance
9 events cause mangrove mortality (e.g., Cahoon et al. 2003). However, the
10 sediment trapping response of these systems to anthropogenic clearing is largely
11 absent from the literature. Comparative research assessing differences in
12 sediment elevation between intact and anthropogenically cleared mangrove
13 stands is an existing data gap. We quantify how coastal development that
14 removes mangrove habitat impacts shoreline sediment levels since sediment
15 loss has potential implications for nutrient loading and sedimentation on adjacent
16 nearshore habitats as well as on shoreline loss in the face of climate change.
17 We tested the hypothesis that in coastal fringing red mangrove (*Rhizophora*
18 *mangle*) ecosystems on Turneffe Atoll, Belize, sediment elevation levels decline
19 following mangrove clearing relative to levels in adjacent intact mangroves.

20 21 II. METHODS

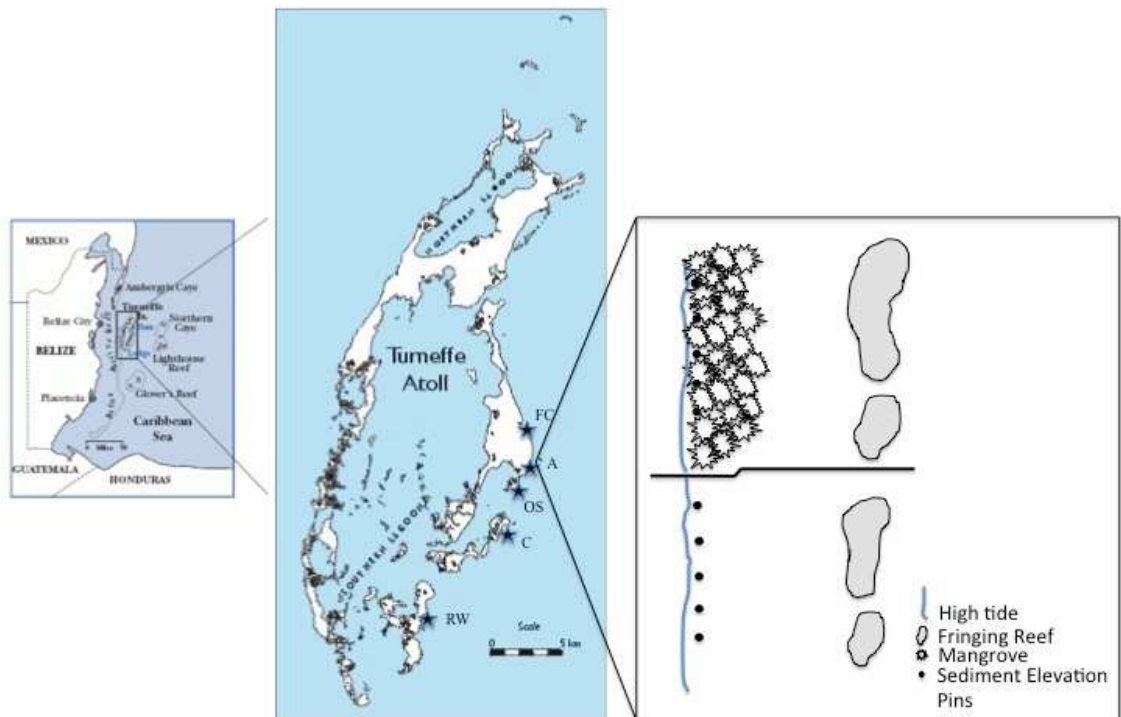
22 23 *Study Site*

24 The study was conducted on Turneffe Atoll off the Caribbean coast of
25 Belize. Turneffe Atoll is a carbonate atoll with little or no allochthonous sediment
26

1 input; sediment in the mangroves is autochthonous, derived from accumulation of
2 biogenic material, primarily mangrove subsurface peat with lenses of calcareous
3 sand (McKee et al. 2007). The coastline of Turneffe Atoll is characterized by
4 open coast fringing *R. mangle* (red mangrove) trees, except in locations where
5 mangroves were removed for development and/or agriculture. The submerged
6 vegetation in front of the study sites is dominated by *Thalassia testudinum* (turtle
7 grass). Five locations were sampled along the east coast of Turneffe Atoll with
8 each study site consisting of paired intact (+mangrove) and cleared (-mangrove)
9 areas. All study sites were along the open coast and located within a 15km
10 stretch of coastline (Figure 1 and Table 1). Wave energy is comparable within
11 each pair. The distance between the mangrove or cleared shoreline and the
12 fringing reef and the continuity of the fringing reef are consistent within pairs but
13 variable among sites, leading to potential between site differences in wave
14 energy reaching the shoreline.

15 The following criteria were used for site selection: 1) at least 75m along-
16 shore length of cleared *R. mangle* adjacent to stretches of at least 100m of intact
17 *R. mangle* habitat; and 2) >2km from major human development to reduce
18 potential sources of anthropogenic nutrients and sediment. The cleared
19 mangrove areas ranged from 75m to 250m in length along the shore and ranged
20 from recent (within 2 years of study onset) to historic (40-200 years prior)
21 clearings (Table 1). At the recently cleared sites, above ground root structure
22 was still present, though no above ground roots were evident at the historically
23 cleared sites. Elevations were similar within pairs at recently cleared sites at the

1 beginning of the study; however, at Calabash there was some seagrass growing
 2 in the cleared sediment elevation pin plot indicating lower elevation than its
 3 adjacent paired intact site.
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 6 Figure 1. Location of study area in the Caribbean Sea (left) with sites marked on
 7 Turneffe Atoll map (center): from north to south, sites include Fisherman's Cut
 8 (FC), Airport (A), Oceanic Society (OS), Calabash (C), and Ropewalk (RW);
 9 Airport study site (right) with sediment elevation pins in intact and cleared
 10 mangrove areas inshore and fringing reef offshore.

11
 12 Areas with intact mangroves were characterized by monospecific stands
 13 of *R. mangle* with submerged prop roots and infrequent aerial roots colonized
 14 with sponges, epibiotic algae, tunicates and anemones. Recently cleared
 15 mangrove areas retained some structure from the submerged decaying prop
 16 roots; the soil was “muddy” with roots throughout. Historically cleared areas had

1 little to no submerged decaying prop roots, with soil consisting of coarse sand
2 with seagrass moving into former mangrove habitat.

3 Cleared areas were absent of mature trees and had sparsely dispersed
4 settlement of seedlings (~1 seedling per m²) compared to adjacent intact
5 mangrove forest with mature trees and high seedling densities (~8 seedlings per
6 m²). The cleared areas lack forest structure. The mangroves settled in cleared
7 areas were “dwarfed” (~1 m tall) relative to individuals in intact areas (up to 4 m
8 tall).

9 Additional anthropogenic disturbances impacted two sites during the study
10 period (in 2009). In the intact mangrove area at Airport (Figure 1), a section of
11 mangroves was cleared and dredging was conducted for condominium
12 development. Two sediment elevation pins were lost during the clearing.
13 Adjacent to the cleared site at Ropewalk, dredging was conducted to facilitate
14 boat access, increasing suspended sediment in the cleared area.

15

16 *Sediment Elevation Pins*

17 Tubes of PVC piping with 2.5 cm external diameter x 1.5 m length were used as
18 sediment elevation pins to quantify changes in elevation (e.g., Stokes et al. 2009).
19 Elevation changes may be due to accretion or erosion. Drivers of erosion include
20 sediment leaving the system, compaction, and shrink/swell of aerially exposed
21 sediment. Drivers of accretion include sediment trapping and subsurface expansion
22 from root growth and groundwater influx (Krauss et al. 2014, Cahoon et al. 2003). At
23 each site, five sediment elevation pins were deployed behind areas cleared of

1 mangroves (-mangrove) and five pins were deployed at the same distance from the
2 seaward edge of the mangroves behind intact forest (+mangrove). At all sites except
3 Calabash, these pins were placed during a previous study by S. Waddington and E.
4 Granek. The protocol employed for placing the sediment elevation pins was adopted
5 from dune studies by Moreno-Cassola (1986) and Arens and Slings (2004). The
6 research plots are located near fishing camps, developed resorts, homes, and a Belize
7 National Coast Guard Station. The current method of measuring mangrove sediment
8 accretion/erosion, Surface Elevation Table (SET) (Cahoon et al. 2003) equipment, was
9 infeasible at our study site due to the risk of equipment removal by transient fishers.
10 Therefore we employed a low-tech, low-cost technique to measure sediment elevation
11 change relative to a ~1-m deep benchmark.

12 The 1.5m long PVC piping tubes were buried in the substrate with 60cm of tube
13 remaining above ground. Differences in rates of sediment elevation change were
14 quantified by measuring the length of tube above the sediment at 0-, 6-, 12- and 24-
15 months post deployment. The PVC tubes were measured to the nearest 0.1 cm from
16 the top of the tube to the sediment on the ocean and terrestrial sides. Each pin was
17 gently pulled upward and pushed downward to confirm that pins were secure and not
18 floating in the hole. All pins were secure at each sampling period.

19 *Data analysis*

20
21 The five sediment elevation pins per plot were averaged and examined at 12-
22 and 24- months post deployment. Changes in sediment elevation between intact and
23 cleared mangrove plots and among sites were examined using a two-way ANOVA. A

1 multi-factor ANOVA was used to examine whether sedimentation rates differed by
2 continuity of adjacent reef structure, site, and mangrove condition (intact vs. cleared).

3

4 III. RESULTS

5 Sediment elevation increased ($M= 3.83\text{mm}$, $SE=0.95$) at the intact mangrove
6 plots but decreased ($M= -7.30\text{ mm}$, $SE=3.38$) at the cleared mangrove plots over the
7 course of the study (Table 1). Between June 2008 and June 2010, sediment elevation
8 change differed between intact and cleared areas ($F= 79.52$, $p=0.001$), across sites
9 ($F=6.41$, $p<0.001$), and the differences in elevation change between intact and cleared
10 areas varied by site ($F=9.57$; $p<0.001$)(Figure 2).

11 In cleared areas, elevation loss rates were greater at sites with gaps in the
12 adjacent fringing reef (Airport and Oceanic; $M=-15.05\text{mm}$) than at sites with continuous
13 fringing reef ($M=-1.90\text{mm}$; $F=18.59$, $p<0.001$). In intact mangrove forest, elevation gain
14 did not differ between sites with reef gaps ($M=4.11\text{mm}$) and sites with continuous reef
15 ($M=3.65\text{mm}$). Sediment elevation gain was greater in intact than cleared areas ($F=81$,
16 $p<0.001$) and the effects of reef continuity on sediment elevation gain or loss varied by
17 mangrove condition ($F=32.33$, $p<0.001$).

18

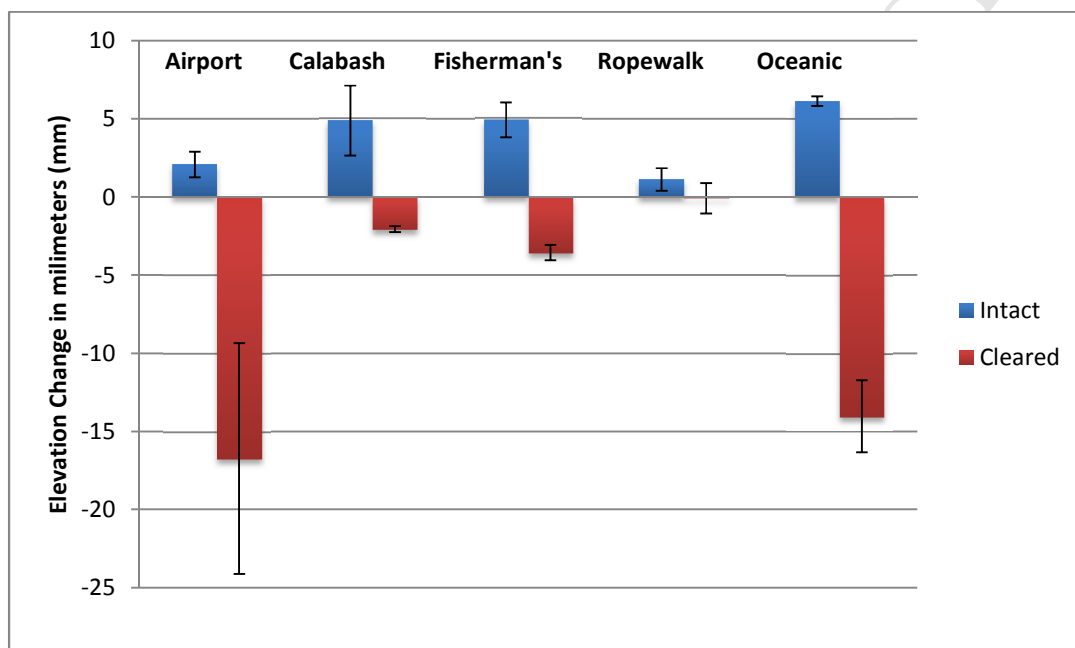
19 Table 1. Fringing reef structure, anthropogenic disturbances during study period, and
20 mean (and standard error) sediment elevation gain (+) and loss (-) rates at cleared and
21 intact plots for each site (Year 1 = June 2008 to June 2009, Year 2 = June 2009 to June
22 2010).

Site	Airport	Calabash	Fisherman's	Ropewalk	Oceanic
Fringe Reef Protection	<i>Few gaps</i>	Complete	Complete	Complete	<i>Gaps</i>
Dominant sediment type	Sandy	Sandy	Detrital mud	Sandy	Sandy
Years since clearing	4	~40	2	8	~200
Anthropogenic disturbances	Dredging & clearing	None	None	Dredging 2009	None

		2009				
Mean soil accretion (mm) in intact plots	Year 1	+1.62	+5.33	+2.04	+0.73	+3.58
	Year 2	+2.08 (0.82)	+4.89 (2.23)	+4.92 (1.12)	+1.13 (0.72)	+6.14 (0.31)
Mean soil elevation loss (mm) cleared areas	Year 1	-10.7	-0.35	-2.3	-0.25	-6.32
	Year 2	-16.73 (7.39)	-2.06 (0.19)	-3.56 (0.48)	-0.09 (0.97)	-20.18 (2.3)

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4 Figure 2. Sediment elevation change rates (in mm) between June 2008 and June 2010
5 at five study sites on Turneffe Atoll.

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8 IV. DISCUSSION

9

10 Coastal mangrove forests function as important physical buffers protecting
11 coastlines from erosion and nearshore marine ecosystems from sedimentation (Gillis et
12 al. 2014). When mangroves are naturally or anthropogenically thinned or removed, this
13 function is reduced or eliminated (e.g., Cahoon et al. 2003; Stokes et al. 2009).

13 Similarly, intact mangroves on Turneffe Atoll demonstrate sediment elevation gains

1 whereas adjacent cleared areas suffered sediment elevation losses over the same time
2 period. Cleared sites with discontinuous fringing reef offshore suffered higher sediment
3 elevation loss rates than sites with continuous fringing reefs. These data add to the
4 growing body of evidence quantifying the ecological function provided by coastal
5 mangrove forest habitat to maintain soil elevation (e.g., Stokes et al. 2009, Cahoon et
6 al. 2003, Krauss et al. 2003) and facilitate coastline adaptations to sea level rise (e.g.,
7 Krauss et al. 2014).

8 Natural variability in fringing reef structure can affect sediment patterns (Table 1;
9 Gillis et al. 2014). Study sites with (50-100 m alongshore gaps in the fringing reef
10 (Airport and Oceanic), had higher sediment elevation loss rates (-16 to -20 mm) in the
11 cleared areas. Gaps in the fringing reef reduce protection from incoming wave action
12 (Kunkel et al. 2006, Sheppard 2005), which can result in higher sediment elevation loss
13 rates when mangroves are removed. On the other hand, Calabash and Fisherman's
14 have extensive and continuous reef protection and are located further from the reef
15 (Fisherman's is ~500 m and Oceanic is ~100 m inshore); these sites experienced lower
16 sediment elevation loss rates in the cleared areas (2-3.5 mm). These sites demonstrate
17 landscape-scale facilitation between reefs and mangroves (Gillis et al. 2014).

18 Anthropogenic disturbance events such as dredging can reduce sediment
19 elevation loss at cleared mangrove sites due to sediment resuspension. At Ropewalk,
20 dredging increased sediment suspension for 4 months during the summer of 2009; we
21 hypothesize that this increased sediment suspension led to increased sediment
22 deposition at the cleared area, counteracting sediment elevation loss due to absent
23 mangrove root structure (Figure 2).

1 Our sites on Turneffe Atoll have variable sediment dynamics due to variability in
2 the fringing reef and the resultant wave energy in the mangroves as well as additional
3 anthropogenic disturbances at certain sites. Though our method cannot identify the
4 specific causes of the sediment elevation loss we report, the losses likely results from a
5 combination of surface and subsurface subsidence from peat collapse due to
6 decomposition of organic material (including roots) and erosion of the substrate due to
7 the absence of root structure and cessation of mangrove organic matter deposition from
8 loss of mangrove trees (Krauss et al. 2014, Cahoon et al. 2003). Reported rates of
9 accretion in mangroves vary by geographic location, ranging from -38mm year^{-1} in
10 Tauranga Harbour, New Zealand (Stokes et al. 2009) to $+10.0$ to $+11.0 \text{ mm year}^{-1}$ in
11 Cairns, Queensland, Australia (Bird and Barson 1977; Spencely 1982). Our reported
12 rates of sediment elevation loss and gain fall within this range. However, to date, little
13 research in mangrove ecosystems has directly compared sediment elevation changes
14 between intact and cleared mangrove areas (but see Stokes et al. 2009). McKee et al.
15 (2007) and McKee (2011) suggest that mangrove removal could lead to land and
16 habitat stability losses due to a cessation of soil accretion concurrent with ongoing
17 decomposition, compaction and erosion processes. Field data quantifying the effects of
18 Caribbean mangrove clearing on sediment retention are absent from the current
19 literature. Our data from sediment elevation pins provide the first quantitative evidence
20 of sediment elevation loss in cleared areas at sites that gain sediment elevation in
21 adjacent land where mangroves are present.

22 The intact mangroves on Turneffe Atoll likely protect sediment from elevation
23 loss or erosion due to surface and subsurface physical and biological processes

1 including sedimentation, ground water swelling, plant litter, woody debris and root
2 accumulation and algal mat development. These processes result in vertical sediment
3 accretion in Caribbean mangrove ecosystems (Krauss et al. 2014; McKee 2011; Rogers
4 et al. 2005). McKee (2011) reported low accretion rates in Belizean fringing mangroves
5 but subsurface root growth accounting for 8.8 mm year^{-1} vertical change, with an overall
6 elevation change of 4.1 mm year^{-1} after accounting for compaction, decomposition and
7 hydrodynamics. Given that our accumulation rates in the intact mangrove areas were
8 comparable, we hypothesize similar processes at work.

9 Our research finds that removal of mangrove vegetation leads to sediment
10 elevation loss with potential for increased submergence and land loss. This loss is
11 exacerbated where fringing reef is discontinuous and can vary as a result of additional
12 disturbance events. These findings highlight the need to consider the role of mangroves
13 in managing coastline protection with ongoing sea-level rise (Alongi 2015) and the
14 importance of carefully considering subtidal features adjacent to sites slated for
15 mangrove removal or transformation. Such information may prove useful in identifying
16 areas that are most vulnerable to sediment elevation loss following mangrove removal
17 and therefore areas of coastline most vulnerable to submergence with sea level rise.
18 Better understanding and consideration of these processes can serve as a potential tool
19 for determining where mangrove clearing will have the greatest impact on coastal
20 protection generally and sea-level driven land loss specifically.

21

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2

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Highlights:

- We compared sediment elevation changes in adjacent cleared and intact mangroves.
- Sediment elevation increased in intact areas and decreased in cleared areas.
- Cleared sites with discontinuous fringing reef experienced greater elevation loss.
- Condition of mangroves and of offshore habitat affect mangrove sediment elevation.