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Coastal sediment elevation change following anthropogenic mangrove clearing

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ABSTRACT

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

1. Introduction

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 et al., 1999; 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 and 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 a 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; Granek and Ruttenberg, 2007). As oceanic storms increase in frequency and intensity with warming sea surface temperatures (Williams, 2005) and as sea level rises, the importance of mangroves is expected to increase. Finally, coastal mangroves serve as sediment “traps” accreting terrestrial sediment and preventing it from smothering subtidal

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coral reefs (Bird, 1986; Wolanski and Ridd, 1986; Augustinus, 1995; Blasco et al., 1996; Woodroffe, 2002; Golbuu et al., 2003; Thampanya et al., 2006; Victor et al., 2006).

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

2. Methods

2.1. Study site

The study was conducted on Turneffe Atoll off the Caribbean coast of Belize. Turneffe Atoll is a carbonate atoll with little or no allochthonous sediment input; sediment in the mangroves is autochthonous, derived from accumulation of biogenic material, primarily mangrove subsurface peat with lenses of calcareous sand (McKee et al., 2007). The coastline of Turneffe Atoll is characterized by open coast fringing *R. mangle* (red mangrove) trees, except in locations where mangroves were removed for development and/or agriculture. The submerged vegetation in front of the study sites is dominated by *Thalassia testudinum* (turtle grass). Five locations were sampled along the east coast of Turneffe Atoll with each study site consisting of paired intact (+mangrove) and cleared (-mangrove) areas. All study sites were along the open coast and located within a 15 km stretch of coastline (Fig. 1 and Table 1). Wave energy is comparable within each pair. The distance between the mangrove or cleared shoreline and the fringing reef and the continuity of the fringing reef are consistent within pairs but variable among sites, leading to potential between site differences in wave energy reaching the shoreline.

The following criteria were used for site selection: 1) at least 75 m along-shore length of cleared *R. mangle* adjacent to stretches of at least 100 m of intact *R. mangle* habitat; and 2) >2 km from major human development to reduce potential sources of anthropogenic sediment. The cleared mangrove areas ranged from 75 m to 250 m in length along the shore and ranged from recent (within 2 years of study onset) to historic (40–200 years prior) clearings (Table 1). At the recently cleared sites, above ground root structure was still present, though no above ground roots were evident at the historically cleared sites. Elevations were similar within pairs at recently cleared sites at the beginning of the study; however, at Calabash there was some seagrass growing in the cleared sediment elevation pin plot indicating lower elevation than its adjacent paired intact site.

Areas with intact mangroves were characterized by monospecific stands of *R. mangle* with submerged prop roots and infrequent aerial roots colonized with sponges, epibiotic algae, tunicates and anemones. Recently cleared mangrove areas retained some structure from the submerged decaying prop roots; the soil was "muddy" with roots throughout. Historically cleared areas had little to no submerged decaying prop roots, with soil consisting of coarse sand with seagrass moving into former mangrove habitat.

Cleared areas were absent of mature trees and had sparsely dispersed settlement of seedlings (~1 seedling per m^2) compared to adjacent intact mangrove forest with mature trees and high seedling densities (~8 seedlings per m^2). The cleared areas lack forest structure. The mangroves settled in cleared areas were "dwarfed" (~1 m tall) relative to individuals in intact areas (up to 4 m tall).

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

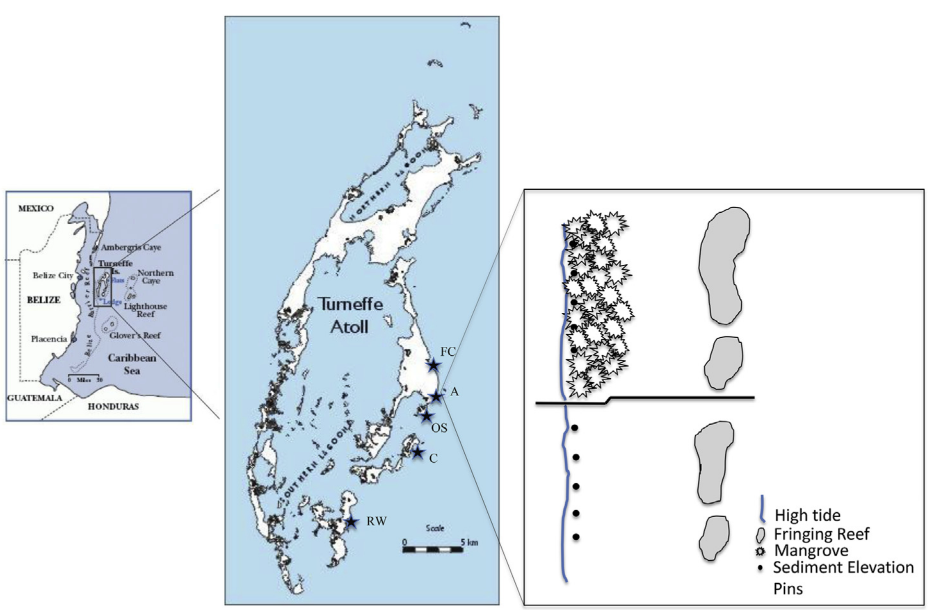

Fig. 1. Location of study area in the Caribbean Sea (left) with sites marked on Turneffe Atoll map (center): from north to south, sites include Fisherman's Cut (FC), Airport (A), Oceanic Society (OS), Calabash (C), and Ropewalk (RW); Airport study site (right) with sediment elevation pins in intact and cleared mangrove areas inshore and fringing reef offshore.

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

Site		Airport	Calabash	Fisherman's	Ropewalk	Oceanic
Fringe reef protection		Few gaps	Complete	Complete	Complete	Gaps
Dominant sediment type		Sandy	Sandy	Detrital mud	Sandy	Sandy
Years since clearing		4	~40	2	8	~200
Anthropogenic disturbances		Dredging & clearing 2009	None	None	Dredging 2009	None
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)

increasing suspended sediment in the cleared area.

2.2. Sediment elevation pins

Tubes of PVC piping with 2.5 cm external diameter × 1.5 m length were used as sediment elevation pins to quantify changes in elevation (e.g., Stokes et al., 2009). Elevation changes may be due to accretion or erosion. Drivers of erosion include sediment leaving the system, compaction, and shrink/swell of aerially exposed sediment. Drivers of accretion include sediment trapping and subsurface expansion from root growth and groundwater influx (Krauss et al., 2014; Cahoon et al., 2003). At each site, five sediment elevation pins were deployed behind areas cleared of mangroves (−mangrove) and five pins were deployed at the same distance from the seaward edge of the mangroves behind intact forest (+mangrove). At all sites except Calabash, these pins were placed during a previous study by S. Waddington and E. Granek. The protocol employed for placing the sediment elevation pins was adopted from dune studies by Moreno-Cassola (1986) and Arens and Slings (2004). The research plots are located near fishing camps, developed resorts, homes, and a Belize National Coast Guard Station. The current method of measuring mangrove sediment accretion/erosion, Surface Elevation Table (SET) (Cahoon et al., 2003) equipment, was infeasible at our study site due to the risk of equipment removal by transient fishers. Therefore we employed a low-tech, low-cost technique to measure sediment elevation change relative to a ~1-m deep benchmark.

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

2.3. Data analysis

The five sediment elevation pins per plot were averaged and examined at 12- and 24- months post deployment. Changes in sediment elevation between intact and cleared mangrove plots and among sites were examined using a two-way ANOVA. A multifactor ANOVA was used to examine whether sedimentation rates differed by continuity of adjacent reef structure, site, and mangrove condition (intact vs. cleared).

3. Results

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

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

4. Discussion

Coastal mangrove forests function as important physical buffers protecting coastlines from erosion and nearshore marine ecosystems from sedimentation (Gillis et al., 2014). When mangroves are naturally or anthropogenically thinned or removed, this function is reduced or eliminated (e.g., Cahoon et al., 2003; Stokes et al., 2009). Similarly, intact mangroves on Turneffe Atoll demonstrate sediment elevation gains whereas adjacent cleared areas suffered sediment elevation losses over the same time period. Cleared sites with discontinuous fringing reef offshore suffered higher sediment elevation loss rates than sites with continuous fringing reefs. These data add to the growing body of evidence quantifying the ecological function provided by coastal mangrove forest habitat to maintain soil elevation (e.g., Stokes et al., 2009; Cahoon et al., 2003; Krauss et al., 2003) and facilitate coastline adaptations to sea level rise (e.g., Krauss et al., 2014).

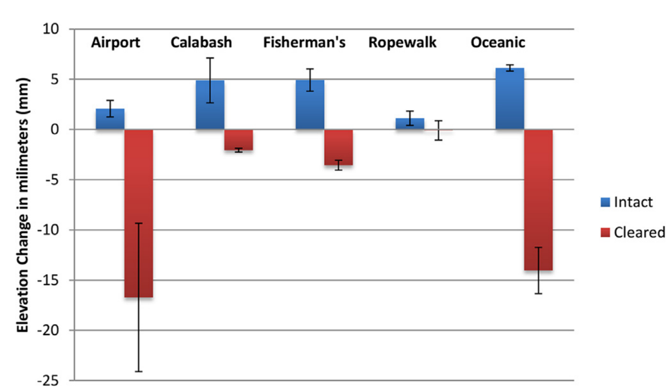

Fig. 2. Sediment elevation change rates (in mm) between June 2008 and June 2010 at five study sites on Turneffe Atoll.

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

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

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

The intact mangroves on Turneffe Atoll likely protect sediment from elevation loss or erosion due to surface and subsurface physical and biological processes including sedimentation, ground water swelling, plant litter, woody debris and root accumulation and algal mat development. These processes result in vertical sediment accretion in Caribbean mangrove ecosystems (Krauss et al., 2014; McKee, 2011; Rogers et al., 2005). McKee (2011) reported low accretion rates in Belizean fringing mangroves but subsurface root growth accounting for 8.8 mm $year^{-1}$ vertical change, with an overall elevation change of 4.1 mm $year^{-1}$ after accounting for compaction, decomposition and hydrodynamics. Given that our accumulation rates in the intact mangrove areas were comparable, we hypothesize similar processes at work.

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

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