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Comparison of Sedimentation in Bays and Reefs below Developed versus Undeveloped Watersheds on St. John, US Virgin Islands

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Abstract. Increased terrigenous runoff associated with building and development is one of the most serious threats to coral reefs. Here we evaluate how the sediment flux rates and compositions (carbonate, terrigneous [siliceous], and organic matter) differ between reefs and bays below a developed watershed compared to undeveloped watersheds on St. John, US Virgin Islands. Detailed monitoring of sedimentological processes affecting individual reefs is a critical compliment to ecological monitoring and necessary to evaluate the effectiveness of erosion mitigation strategies. During the 2007 rainy season, sediment flux rates were at least 3 and up to 73 times higher on the reefs below a developed watershed compared to reefs below an undeveloped watershed. The developed watershed sediment flux rates (3-630 mg $cm^{-2}d^{-1}$) were sometimes within range of rates previously shown to cause "severe to catastrophic" sediment stress to corals. Mean seasonal terrigenous flux rates were 15 times higher (5 vs. 0.3 mg $cm^{-2}d^{-1}$) and mean organic matter flux rates were 10 times higher (3 vs. 0.3 mg $cm^{-2}d^{-1}$) on the reefs below the developed watershed.

Key words: sedimentation, sediment flux, Virgin Islands, carbonate, TSS

Introduction

Sedimentation is one of the primary causes of coral reef degradation in the US Virgin Islands (Rogers 1990; Rogers 1998). Sedimentation stress to corals depends on the quantity, duration, and composition of sedimentation (Fabricius 2005; Philipp and Fabricius 2003; Riegl and Branch 1995). In order to effectively mitigate the potentially detrimental impacts of sedimentation to a reef, it is critical to determine the rate, mechanism, and quality (type) of sediment flux into a particular reef system.

Here we present preliminary data from an ongoing study to evaluate if development in St. John, US Virgin Islands (Fig. 1) has impacted the quantity, quality, and spatial variability of sedimentation in four bays with fringing reefs—one below a developed watershed (Fish Bay; Fig. 2A) and three below undeveloped watersheds located within the Virgin Islands National Park (VINP) (Great Lameshur, Reef, and Hawksnest Bays; Fig. 2 B-E). We addressed the following research questions: 1. What is the composition and quantity of suspended, settling (sediment trap), and accumulated (bay-floor bottom) sediments? 2. How does the sediment composition and quantity: a) vary spatially within each bay along pathways of sediment dispersal and among the bays? b) vary temporally during the study period (August-November, 2007); and c) vary between the developed and undeveloped bays? St. John, USVI is an ideal location to study the impacts of sedimentation on coral reefs because: a) there is a distinct delineation between developed and undeveloped watersheds due to the VINP (Fig. 1); b) sediment originating from land (terrigenous) is compositionally distinct (siliceous) from marine (carbonate) sediment due to the lack of terrestrial carbonate sources; and c) the fringing reefs on the island are well monitored (Rogers 1998; Rogers and Miller 2006; Edmunds 2005).

On St. John, development and construction activities outside of the VINP boundaries have brought shallow septic systems, dirt roads and impervious surfaces with increased erosion from roadbeds and cut slopes. Previous studies established a comprehensive sedimentation budget for the land area of St. John and established that there is a high "sediment delivery potential" to Fish Bay below its developed watershed (Ramos-Scharrón and MacDonald 2005; MacDonald et al. 2001, Nemeth et al. 2001).

Material and Methods

Sediment trap transects generally followed sediment runoff dispersal routes from guts (seasonal streams) into bays and across fringing reefs (Fig. 2). Bay-floor bottom sediment (upper 3 cm) transects closely replicated the bottom sediment sampling locations of Hubbard et al. (1987) in Fish, Reef and Hawksnest Bays (Fig. 2).

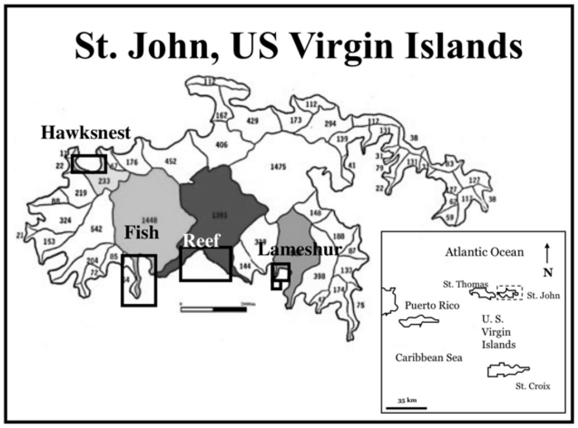
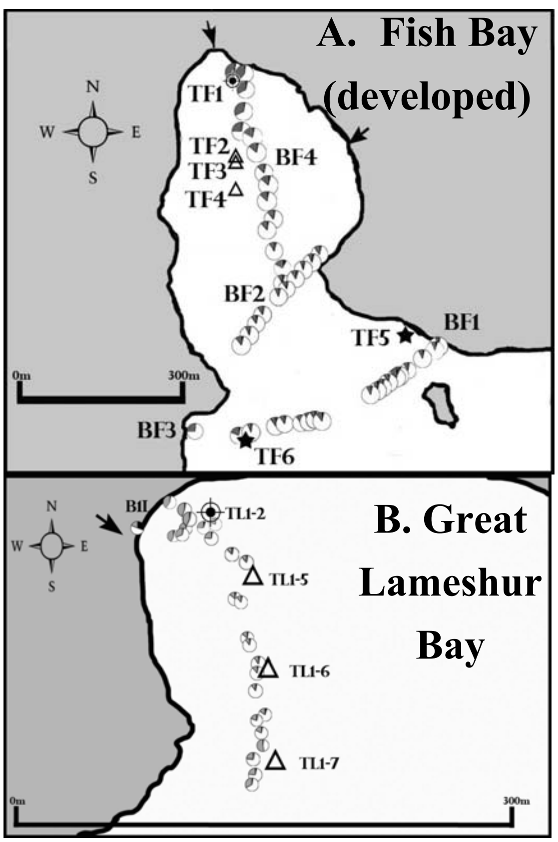


Figure 1: Map of St. John the four watersheds draining into the four study areas: Hawksnest Bay, Fish Bay, Reef Bay, and Great Lameshur Bay. Most of Fish Bay watershed is developed the other three watersheds are within the boundaries of the Virgin Islands National Park and thus considered undeveloped watersheds. The rectangles mark the locations of detailed maps (Fig. 2). Figure modified from Hubbard et al. (1987).



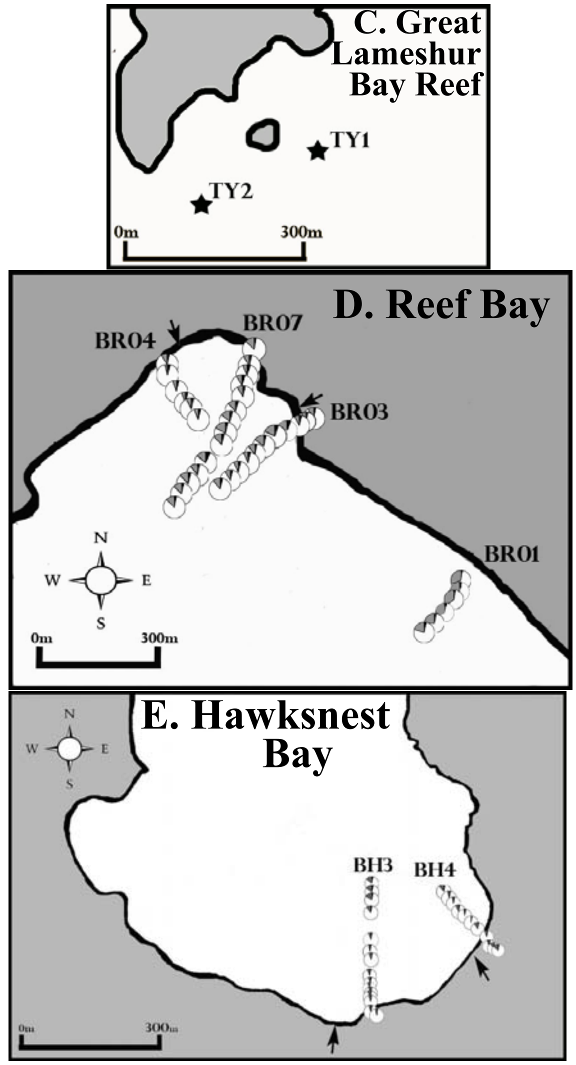


Figure 2: Maps of St. John bays showing sampling location and bay-floor bottom sediment compositions for A) Fish Bay (developed bay), B) Great Lameshur Bay, C) Yawzi Point, D) Reef Bay and E) Hawksnest Bay. Targets, triangles, and star symbols indicate the locations of sediment traps in shore, bay, and reef locations, respectively for Fish Bay (A: TF1 through TF6) and Great Lameshur Bay (B: TL1-2 through TL1-7) and Yawzi Reef (C: TY1, TY2). Pie diagrams indicate the locationsof surface bottom sampling transects in Fish (A: BF1 through BF-4), Great Lameshur (B: B1L), Reef (C: BR01, BR03, BR04, BR07) and Hawksnest (D: BH3, BH4) bays. Arrows mark the locations of guts (seasonal streams). The pie diagrams show the relative proportions of carbonate (white), terrigenous (grey) and organic matter (black) in each bottom surface sediment sample.

The variations in settling sediment (flux rates) were determined by deploying 14 sediment trap arrays (each with 4 exchangeable PVC tubes [length:diameter = 4:1]) attached to a metal stake 60 cm above the bay floor at 1-8 meters water depth in Fish and Great Lameshur Bays (Figs. 2A, 2B, 2C).

Sediment accumulation was monitored after 8 sampling periods (typically 12-14 days) between August-December of 2007. Sediment traps were collected and deployed at all locations within a six-hour time period. Sediment trap sediments were filtered, rinsed, dried and weighed to provide replicate measurements of the dry mass of sediment flux over the time deployed. Water samples were collected next to each sediment trap and at the surface when sediment traps were changed (non-storm days) and filtered through a pre-combusted glass fiber filter (GF/F Whatman) to determine the total suspended sediment. The % organic matter and carbonate were determined by Loss on Ignition (LOI) at 550^{o}C and 950^{o} C, respectively following techniques modified from Henri et al. (2001). Additionally, a subset of samples was sieved to determine the variation in mineral composition with grain size.

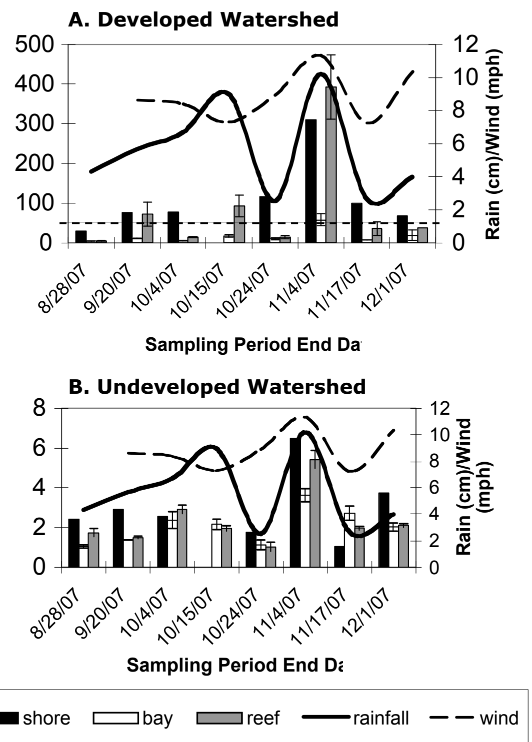


Figure 3: Variation in total sediment flux with time (Fall 2007), with total rain (cm) and mean wind speed for each sampling period in the A) developed and B) undeveloped watershed. The dashed line marks a flux rate of 50 mg cm^{-2}d^{-1} above which may be detrimental to corals.

Table 1: Ratio of unsieved sediment flux below the developed watershed (Fish Bay) to unseived sediment flux below the undeveloped watershed (G. Lameshur Bay)

Sampling Period	28-Aug	20-Sep	4-Oct	15-Oct	24-Oct	4-Nov	17-Nov	1-Dec
Shore	12	26	30		66	48	94	18
Bay	4	8	2	8	8	16	3	9
Reef	3	48	5	48	14	73	18	18
Whole bay	**6**	**25**	**8**	**18**	**24**	**45**	**15**	**12**

Results

Unsieved sediment flux rates ranged from less than 1 to 400 mg cm^{-2}d^{-1} (Fig. 3). The greatest sediment flux rates occurred between 10/25/07-11/4/07 when rain and mean wind speeds were highest (Fig. 3). Total mean sediment flux rates for the shore, bay, and reef stations were significantly higher in the developed

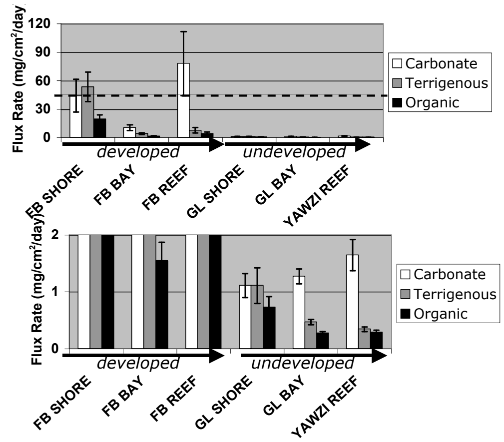


Figure 4: Mean seasonal flux rates for carbonate, terrigenous (siliceous) and organic matter were many times higher below the developed (Fish Bay) compared to the undeveloped (G. Lameshur Bay) watersheds. Arrows point from near to offshore stations. Upper and lower graphs are the same but with different vertical scales (FB: Fish Bay; GL: Great Lameshur; Yawzi Reef is in G. Lameshur Bay). The dotted line in the upper graph marks a flux rate of 50 mg cm^{-2}d^{-1} above which may be detrimental to corals.

(Fish) compared to the undeveloped bay (G. Lameshur Bay) (p values = 0.0018, 0.0003, and 0.0109 for the shore, bay and reef, respectively)(Fig. 3). Compared to the flux rate at the undeveloped stations, mean sediment flux rates were up to 73, 16, and 94 times higher on the developed reef, bay and shore stations, respectively (Table 1).

The mineralogic composition of the sediments did not appear to vary much between grain size fractions for either the bottom or sediment trap samples. Carbonate, terrigenous and organic matter was found in all grain size fractions suggesting that sieving is not an appropriate way to separate terrigenous from carbonate constituents.

Carbonate was the most abundant constituent at most sediment trap stations except those nearest the shore (Fig. 4). Mean seasonal carbonate, terrigenous, and organic flux rates were up to 110, 128 and 28 times higher, respectively at the stations below the developed compared to the undeveloped watershed (Fig. 4). However, a pattern of decreasing terrigenous with increasing carbonate sedimentation with distance offshore was evident at both locations (Fig. 4).

Distinct compositional sediment flux ratios characterized sediments collected in each of the three environments (shore, bay, reef) (Fig. 5). Although the compositional flux ratios from the developed and undeveloped stations overlap, the flux ratios from the developed bay (Fish Bay) show a much wider range of values than do those from the undeveloped bay (G. Lameshur Bay) (Fig. 5).

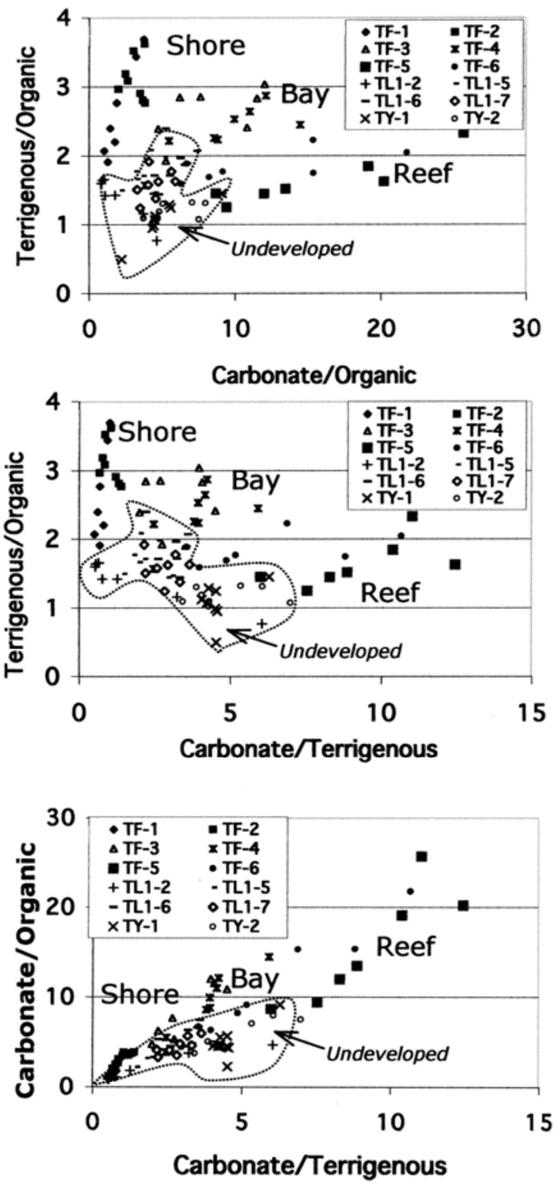


Figure 5: Distribution of compositional flux rate ratios for each sediment trap during each of 7 sampling periods indicated in Figure 3. The distribution shows distinct ratios for the reef, bay and shore environments, but a wider range of values for the developed compared to the undeveloped (within dotted lines) stations.

Like the sediment trap samples, the bay-floor bottom sediments (upper 3 cm) were comprised predominantly of carbonate, followed in abundance by terrigenous and organic matter (Fig. 6).The relative % carbonate and the ratio of carbonate to terrigenous (C_i/T) material in the bottom sediments increased with distance from the shore to the reef in both Fish and Great Lameshur Bays but not in Reef or Hawksnest Bays (Fig. 6). The percentage organic matter differed between the three sediment reservoirs (suspended: 36%-68%; trapped: 6%-23% and bottom: 2% to 4%) (Fig. 7). Mean total suspended sediment

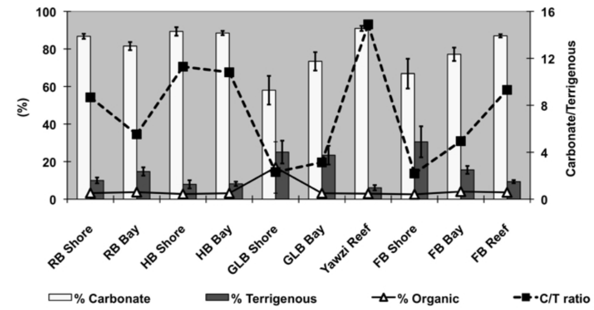


Figure 6: Composition of bottom samples (in %). The solid line marks organic matter % and the dashed line marks Carbonate/Terrigenous ratios (Ci/T). (RB: Reef Bay; HB: Hawksnest Bay; LB: Great Lameshur Bay; FB: Fish Bay).

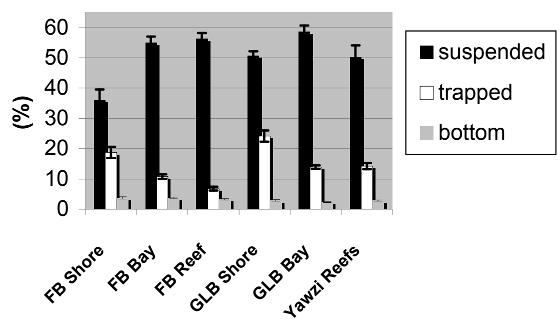


Figure 7: Mean % organic matter in three sediment reservoirs (suspended, trapped & bottom) (FB: Fish Bay; GLB: Great Lameshur Bay).

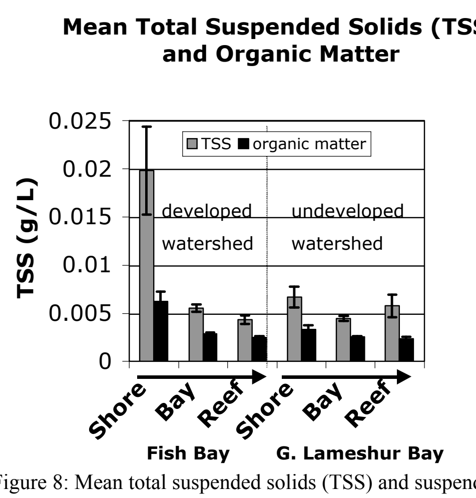


Figure 8: Mean total suspended solids (TSS) and suspended organic matter for shore, bay and reef locations below the developed and undeveloped watersheds. Arrows point from near to offshore stations. TSS and suspended organic matter were significantly higher at the shore below the developed watershed.

for the season ranged from 0.004 to 0.02 g/L and was significantly higher at the developed compared to the undeveloped shore and bay stations (p values = 0.0114 and 0.0151, respectively) (Fig. 8). The concentration of suspended organic matter was significantly higher in the developed compared to the undeveloped bays (p = 0.0005).

Discussion

What can account for an up to 73-fold higher total flux and an up to 128-fold higher terrigenous flux on the Fish Bay compared to the Great Lameshur Bay (Yawzi) reefs? This difference is too large to be explained by the fact that the area of the Fish Bay watershed is three times the area of the Great Lameshur watershed. The Fish and Great Lameshur Bay watersheds have similar mean slopes, soil types, and vegetative cover. The bays are of generally similar geometry, orientation, and exposure to swells, tides and currents. The fact that the composition of the sediments in the traps is primarily carbonate suggests that the traps are likely collecting sediments that have been resuspended by waves and currents in addition to terrigenous sediments delivered directly in suspension from terrestrial runoff. There is greater availability of terrigenous sediment in Fish Bay (developed) compared to Great Lameshur Bay (undeveloped). We are conducting further studies to evaluate the sediment availability to resuspension and have deployed current meters to quantify the specific relationship between current velocity and sediment flux into the traps.

These data clearly show that the corals at Fish Bay reef are under significantly greater sediment stress than the corals at Great Lameshur (Yawzi) reef. The total sediment flux rates at Great Lameshur Bay reef were consistent with rates previously recorded for reefs that were not subjected to human activities (<1-10 mg $cm^{-2}d^{-1}$: Rogers, 1990). However, the sediment flux rates on the Fish Bay reef were high enough to be potentially dangerous to the reefs. Pastorak and Bilyard (1985) suggested that flux rates of 10-50 mg $cm^{-2}d^{-1}$ and > 50 mg $cm^{-2}d^{-1}$ could cause "moderate to severe" and "severe to catastrophic" sediment stress, respectively. Sediment flux rates on Fish Bay reefs were higher than 50 mg $cm^{-2}d^{-1}$ during three of the 8 sampling periods and above 300 mg $cm^{-2}d^{-1}$ during one. These high flux rates (>100 mg $cm^{-2}d^{-1}$) have been shown to kill exposed coral tissue within a few days (Riegl and Branch 1995) or reduce photosynthetic yields (Philipp and Fabricius 2003). Studies suggest that organic sediment may be particularly harmful to corals (Fabricius 2005). The reef below the developed watershed had organic flux rates up to 28 times higher than the reef below the undeveloped watershed.

Though bay-to-bay flux rate differences were quite dramatic, compositional differences between fluxing sediments were more subtle and were revealed by examining within-bay and bay-to-bay differences in the relative ratios of constituent flux rates.

Comparisons of both quantity and compositions of the suspended and bay floor bottom sediments did not reveal striking differences between the developed and the undeveloped locations. Our preliminary comparisons show that the composition of bottom sediments has not systematically changed (within 5% relative %) since the Hubbard et al. (1987) sediment survey despite intensive development in the area. Continued research through the 2008 season is underway as well as textural and geochemical analyses of the 2007 sediments.

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