Land-use and sedimentation patterns in Saint Lucia in relation to their impacts on coral reefs

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1. Introduction

Coral reefs are degraded throughout the world (Bellwood et al. 2004) and severely so in the Caribbean. In this region, coral cover – an accepted indicator of reef condition – has declined by 80% in the past 30 years (Gardner et al. 2003). Marine Protected Areas (MPAs) have emerged as the most promising management tool to conserve coral reefs (Mumby and Steneck 2008), and many have been established throughout the Caribbean over the past few decades. Many MPAs have been successful in increasing the density and biomass of coral reef fish; however, the abundance, diversity and health of corals themselves appear to be largely unaffected by spatial protection afforded to the overlying waters (Aronson and Precht 2006; Mora 2008). Instead, coral wellbeing may be influenced largely by events occurring on land rather than in the sea. Many anthropogenic activities involving the conversion of natural terrestrial ecosystems, particularly in coastal areas and around watersheds, have resulted in an increased sediment burden on reefs and other shallow-water habitats (Richmond et al. 2007). Although increased sedimentation is widely perceived to be detrimental to corals, many studies have in fact shown little or no link to coral health (McClanahan and Obura 1997; Piniak and Brown 2008). However, studies of the effect of sedimentation on corals have typically been limited to a single location, and in many cases to a single coral species. Moreover, the wide range of methods employed and responses measured make it difficult to compare studies, draw general conclusions and calculate tolerance thresholds that would be useful to managers.

With increased deforestation and land development affecting most islands of the Caribbean, there is an urgent need to quantify the effects of increased sedimentation on coral. In particular, there is a strong need for accurate measurements of long-term variations in sediment accumulation rates, and associated changes in coral reef benthic communities. There is growing appreciation for the fact that marine ecosystems cannot be managed in an ecological vacuum, and that a cross-ecosystem perspective might offer the greatest likelihood of success. Elucidating the general links between land use, sedimentation, marine protection and coral health is fundamental to this new management ethos.

The Soufriere coastal region, on the southwest coast of Saint Lucia, is an area of great ecological diversity, with well-developed coral reefs and outstanding landscapes. The area of the Pitons, just south of Soufriere, has been declared a UNESCO World Heritage Site. Coral reefs in the SMMA have been protected for over 15 years yet still suffer from land impacts. Studies have shown that corals in this area are vulnerable to increased levels of sediment (e.g. Hawkins et al. 2006), and sediment monitoring and reduction has been a management priority for the SMMA for many years. However, limited funding and expertise have severely constrained this effort. More studies are needed to quantify the link between corals and sediment and establish threshold values of sediment effects. A detailed comparison of coral condition and sediment burden between areas with very limited land development (i.e. the Piton Management Area) and nearby reefs subjected to effluents from development will enable us to quantify the link between land activities, sediment levels and coral health. The Saint Lucia government has not yet developed a national sustainable development strategy (Tulsie 2006), and outside of the strictly protected Piton Management Area, development has been proceeding rapidly and with little planning.

The main objective of this project is to identify the causes and consequences of changing sedimentation patterns for two watersheds in Saint Lucia. Specific objectives include: 1) to quantify changes in sedimentation rate over the coral reefs located in the SMMA and the CAMMA; 2) to develop a GIS-based sediment budget model for the two main watersheds influencing corals in the SMMA and CAMMA; 3) to identify, using this sediment budget model, areas and activities that contribute disproportionately to the coastal sediment yield; 4) to assess the changes in coral reef benthic communities in the past decade; 5) to investigate the influence of terrestrial sediment on current coral cover as well as change in coral cover in the past decade.

This report is organized in two main parts. The first (Increase in sediment loads over coral reefs in Saint Lucia in relation to changes in land use in upstream watersheds), aims to answer specific objectives 1-3. The second (Effect of protection and sediment stress on coral reefs in Saint Lucia) specifically addresses objectives 4 and 5. Overall findings and management recommendations are then outlined in the conclusion. Reports on workshop held as part of these projects are included as appendices.

2. Increase in sediment loads over coral reefs in Saint Lucia in relation to changes in land use in upstream watersheds

Abstract

Increased sedimentation is widely cited as an important stress for Caribbean coral reefs. However, for most locations we currently lack both accurate records of changes in sediment accumulation rate over reefs as well as a quantitative link between land use practices and downstream sediment yield. This study aims to provide this information for two watersheds in Saint Lucia. We modified a GIS-based sediment budget model originally developed in Saint John (US Virgin islands) to calculate current and past sediment yields in the two focal watersheds, and used sediment cores collected near downstream coral reefs to examine changes in sediment composition and accumulation rate over the past several decades. Our results show increases over the last decades in accumulation rates of terrigenous sediment, originating from the upstream watersheds, as well as calcareous sediment, likely arising from the decline of corals. Changes in sediment yields over time calculated with the model were similar to changes in terrigenous sediment accumulation rate on the reef, suggesting that this simple model has good potential as a predictive tool.

Introduction

Land uses that remove natural vegetation, such as agriculture and urbanization, have the potential to greatly increase erosion and sediment delivery to downstream waters (Walling 1997; Rawlins et al. 1998; Neil et al. 2002; Syvitski et al. 2005; Wilkinson and McElroy 2007). Coastal sediment yields have increased markedly following human impacts (Dearing and Jones

2003) , especially in small drainage basins and where rivers drain to the coast without dams, reservoirs or wetlands (Dearing and Jones 2003; Syvitski et al. 2005). As a consequence, increased sedimentation is becoming an important threat to many coastal ecosystems worldwide (Chansang et al. 1981; Lee et al. 2006; Fraschetti et al. 2011). This is particularly true of coral reef ecosystems, which have suffered significant declines worldwide in the past several decades (Gardner et al. 2003; Bruno and Selig 2007), in part due to increased runoff (Burke et al. 2011).

Increased sediment is widely cited as a source of stress contributing to the decline of coral reefs in the Caribbean (Hubbard 1986; Acevedo et al. 1989; Rogers 1990; Nemeth and Nowlis 2001; Torres 2001), yet there is still remarkably little quantitative information on past or present rates of sediment accumulation near reefs in this region. Sedimentation rates on coral reefs have traditionally been measured using sediment traps which do not, in this environment, accurately measure accumulation of sediment (Storlazzi et al. 2011). Accumulation rates in coastal sediment can be measured more accurately using cores and short-lived radioisotopes (SLR) such as ^{210}Pb, ^{137}Cs, ^{234}Th and ^{7}Be as date markers (Cochran et al. 1998; Patchineelam and Smoak 1999; Crusius et al. 2004; Sanders et al. 2006; Draut et al. 2009). Lead-210 is a naturally-occurring daughter product in the ^{238}U decay series, and from the atmosphere gets adsorbed to and incorporated into depositing sediment (Holmes 1998). It has a half-life of 22.3 years. Excess ^{210}Pb (i.e., in excess of equilibrium activity supported by parent isotopes) characterizes sediment deposited within the past ~100 years (Holmes 2001) and can be used to model rates of sediment accumulation and mixing (e.g., Nittrouer et al., 1979; Crusius et al., 2004). Cesium-137 was added to the environment by nuclear-weapon testing that began around 1952 and peaked in 1963. In a core with well-preserved stratigraphy, the ^{137}Cs profile is expected to mimic production, with a peak in ^{137}Cs activity associated with sediment deposited in 1963 (Livingston and Bowen 1979; Smith and Ellis 1982; Holmes 1998). Therefore, ^{137}Cs can be used directly as a dating tool, as well as provide a calibration for ^{210}Pb chronology (Noller, 2000). ^{234}Th and ^{7}Be, with their short half-lives (24.3 and 53 days, respectively), can be used to assess recent deposition or mixing (Fuller et al. 1999; Draut et al. 2009). Recently, sediment cores and short-lived radioisotopes (SLR) have been used to provide a more accurate assessment of changes in sediment accumulation rate at a few locations in the Caribbean (Brooks et al. 2007; Ryan et al. 2008), including Saint Lucia (Chapter 3).

Saint Lucia, like many islands in the eastern Caribbean, is at particularly high risk of accelerated erosion due to its topography (i.e., small and steep watersheds), high levels of rainfall typical of tropical climates (Dadson et al. 2003; Gellis et al. 2006), and rapid coastal development (Burke et al. 2011). Coral cover on reefs in this country has recently declined substantially (Schelten 2002; Hawkins et al. 2006), and increased sedimentation levels have been repeatedly identified as an important cause of coral loss (Sladek Nowlis et al. 1997; Schelten 2002; Hawkins et al. 2006). Agriculture (Cox et al. 2006) and roads (Anderson 1983; Sladek Nowlis et al. 1997) have both been identified as causes of soil loss on the island, but the relative contribution of each is unknown. Increased sedimentation rates have been reported near the island's reefs (Schelten 2002; Hawkins et al. 2006), especially following large tropical storms (Sladek Nowlis et al. 1997), yet only recently have sediment cores been used to accurately identify changes in sediment accumulation rates in the coastal zone (Bégin 2012). Analysis of one core at a site near Soufriere (southwest coast) indicated ~40% increases in total mass accumulation rate over the past ~40 years (Bégin 2012). It remains unclear whether this is a general trend near other coral reefs. Moreover, there are still limited data for Saint Lucia, or anywhere in the Caribbean region, linking directly land use practices to sediment delivery in the coastal zone.

In this study, we investigated the link between temporal variation in sediment accumulation rate over coral reefs of Saint Lucia and changes in the upland watersheds by means of a customized GIS-based model, the predictions of which we test empirically with radioisotope analysis of sediment cores. Many models estimate soil loss based on the universal soil loss equation (USLE) with little or no field data (Cox and Madramootoo 1998; López et al. 1998; Hoyos 2005; Schiettecatte et al. 2008). USLE-based models have been shown to perform poorly at predicting sediment yields (Boomer et al. 2008), which makes them of limited value to guide decisions about land use aimed at reducing sedimentation rates to the coast. In contrast, models that incorporate extensive field measurements of sediment erosion and delivery are much more accurate, although they are clearly more difficult to develop, especially in developing countries with limited resources. One such model was developed recently to estimate watershed-scale erosion and sediment yield on the island of Saint John, in the US Virgin Islands (Ramos-Scharrón and MacDonald 2007a). This GIS-based model, called STJ-EROS, was based on extensive field estimates of erosion from different types of land uses (Ramos-Scharrón and MacDonald 2007b), and provided reasonably accurate sediment yield predictions for three watersheds on Saint John. The simple structure of this model means that it can be adapted to estimate sediment yields on other, geologically similar islands in the eastern Caribbean (Ramos-Scharrón and MacDonald 2007a; Ramos-Scharrón 2009).

The specific goals of this study were 1) to modify the STJ-EROS model to estimate past and current sediment delivery from two watersheds in Saint Lucia, 2) to quantify variation over time in sediment accumulation rate on reefs downstream of those two watersheds and use these rates to calibrate the sediment budget model as needed, and 3) use the calibrated model to identify specific areas in each watershed that contribute disproportionate amounts of sediment to the coastal zone. We adapted the STJ-EROS model to the Saint Lucia landscape by deriving from the literature erosion estimates for those land uses found on Saint Lucia but not on Saint John. We used sediment cores taken near coral reefs downstream of two watersheds and SLR dating to examine changes in sediment accumulation rates over the past several decades, including sediment deposited shortly after the passage of Hurricane Tomas in 2010.

Methods

Study Area

Saint Lucia is a volcanic island located in the eastern Caribbean, at approximately 14°N and 61°W. It is relatively large (616 km^2) and has steep, rugged topography with peaks over 900 m. Our study areas on the island were chosen based on the location of two marine protected areas, the Soufriere Marine Management Area (SMMA) on the southwest coast, and the Canaries Anse La Raye Management Area (CAMMA) on the central west coast (Figure 2.1). The SMMA receives sediment from the Soufriere River, which drains the ~ 16 km^2 Soufriere watershed. The CAMMA receives input from three nearby rivers: Petite Riviere de l'Anse, Grande Riviere de l'Anse, and Riviere Galet in a combined watershed of ~20 km^2 (Figure 2.1). Mean annual rainfall at the Soufriere weather station is 180 cm (± 47.3, standard deviation) and at the Anse La

Raye station, 175 ± 32 cm (Saint Lucia Water Resources Department, based on rainfall data from 1997 to 2009).

Saint Lucia sediment budget model (SLU-EROS)

Background

SLU-EROS was built in ArcInfo 9.3 using the Model Builder tool, to calculate sediment from different sources that reach the marine environment. It was modified from STJ-EROS (Ramos-Scharrón and MacDonald 2007a; Ramos-Scharrón 2009) to reflect the differences between Saint John and Saint Lucia. We obtained a version of STJ-EROS that had been modified for the islands of Culebra and Vieques in Puerto Rico from its author (Ramos-Scharrón 2009). STJ-EROS calculates sediment erosion and delivery from three main land features: unpaved roads, streambanks/treethrow, and hillslopes. In SLU-EROS, sediment erosion and delivery from the former two elements were calculated in the same way as in STJ-EROS. The main modification for Saint Lucia was in the calculation of sediment production and delivery from hillslopes, which in STJ-EROS was limited to natural (undisturbed) hillslopes because most land area in Saint John is protected by a national park (MacDonald et al. 1997). In Saint Lucia, hillslopes were divided into six land uses: undisturbed, densely vegetated, farmed, grasslands, urban, and exposed soil.

Routines

SLU-EROS is composed of four separate routines, each created as a model in ArcInfo (Figure 2.2). It begins with the sediment delivery routine, which asks the user to select sediment delivery ratio (SDR) values for areas of high, moderate and low sediment delivery potential in the watershed. These areas have been predefined as polygons in a data layer and represent, respectively, areas draining directly to the coast, to a coastal wetland (e.g. mangroves) and to a pond with no pathway to the marine environment (Ramos-Scharrón and MacDonald 2007a). The sediment delivery ratio represents the proportion of eroded sediment that is moved to the basin outlet, rather than re-deposited along the way. The SDR is influenced by a multitude of factors and is difficult to measure, but it tends to decrease with basin size; small (15-20 km^2) watersheds, such as those in Saint Lucia, have been estimated to have SDRs between 35-100% (Walling 1983). In SLU-EROS, as in STJ-EROS, the user can choose values between 50-100% for high sediment delivery potential areas, and between 0-50% for those with moderate sediment delivery potential. Areas of low sediment delivery potential are automatically assigned an SDR of 0. This routine creates a polygon data layer that incorporates the user-defined SDRs into the sediment delivery layer; this new layer is called SDR. The SDR layer is used in subsequent routines to calculate sediment delivery to the coast based on sediment production within each polygon. Since there were no ponds or wetlands in the two watersheds of interest, the entire watershed was designated as having a high sediment delivery potential.

The Road Sediment Delivery routine calculates the production of sediment for each unpaved road segment (between two drains) based on its surface type (graded, ungraded or abandoned), slope, length and width, and rainfall. Paved roads were considered to contribute no sediment. Each road segment is associated with a drainage point, and the amount of eroded sediment delivered to the coast from each drainage point is calculated based on the SDR where the drainage point is located. This routine requires the input of watershed boundaries, roads and drains and creates a polygon data layer which stores the calculated sediment delivery value of each road segment. The Hillslope Sediment Delivery routine calculates sediment erosion within polygons of the six defined land uses (undisturbed, densely vegetated, farmed, grasslands, urban, and exposed soil) based on the erosion function (see below) and rainfall. The Streams Sediment Delivery routine calculates total annual erosion from streams, from both erodible banks as well as treethrow. Stream sediment delivery is calculated per amount of time, rather than as a function of rainfall. All calculations were done for one year and mean annual rainfall.

Calculations of sediment yield

Erosion functions in the model were the same as STJ-EROS, or modified from erosion functions for those land use types not present in STJ-EROS, based on field measurements in Puerto Rico and Saint Lucia (Table 2.1). Erosion from unpaved roads and streams was calculated in the same way as STJ-EROS. In the Hillslope Sediment Delivery routine, the erosion function for undisturbed hillslopes is the same as STJ-EROS and is based on the amount of rainfall from large storms (> 6 cm during the storm event), which is the minimum amount of rainfall necessary to initiate surface erosion in undisturbed catchments in Saint John (Ramos-Scharrón and MacDonald 2007a). In Saint John, those storms represent 14% of all rainfall and therefore in the erosion function, the total rainfall is multiplied by 0.14. Data were not available in the detail necessary to calculate the amount of rainfall attributable to storms producing more than 6 cm of rainfall at our study sites, but the available data suggest that this proportion is larger than 6 % (Saint Lucia Water Resources Department, based on rainfall data from 1997 to 2009). In the absence of data suggesting otherwise, we used the same proportion as Saint John. Densely vegetated areas in Saint Lucia were assumed to produce the same as undisturbed hillslopes in Saint John. Soil erosion for grasslands, farm areas and exposed soil were calculated as a factor of erosion from undisturbed hillslopes, based on differences in sediment production between undisturbed forest and these land use types measured in Puerto Rico (Gellis et al. 2006), where soil erosion was found to be 29.95, 23.1 and 1.7 times greater for exposed soil, farmlands and grasslands, respectively, than for undisturbed forest. The farmland factor appears to be appropriate for Saint Lucia: soil erosion in an agricultural watershed in the northern part of the island was measured as being 20 times greater than in an adjacent, forested watershed (Cox et al. 2006). Urban areas, which were dominated by pavement, were considered to contribute no sediment. The sediment yields from hillslopes in each polygon were obtained by multiplying the calculated sediment production rate by the assigned SDR.

GIS layer acquisition and modification

We ran the SLU-EROS model for current conditions (2010) as well as for 1995 conditions and for a completely undisturbed watershed (no roads, and 100% undisturbed forest), to compare sediment yield estimates at different time periods. The following GIS layers were obtained from the Saint Lucia government: coastline, watershed boundaries, streams, roads and land use. Roads, streams and land use layers were modified from those obtained from the government to reflect 2010 conditions and to have all the attributes necessary for the model (Table 2), based on field surveys (November 2010 & June 2011) as well as high-resolution 2010 satellite photos (GeoEye Foundation) and 2009 aerial photos (Saint Lucia Government). A data layer of road drains was created based on 2010 field surveys, when we recorded the location of culverts, stone drains and any other drainage structure using a handheld GPS device. Data layers representing 1995 conditions were modified from government data and 1992 aerial photos (Saint Lucia Government). The same drain layer as 2010 was used. We chose to estimate yield from 1995 rather than 1992, as road construction which occurred between 1991 and 1994 would have resulted is short-term increases in sediment yield. Sediment delivery estimates for undisturbed conditions involved a modified hillslopes layer composed of only undisturbed areas and streams. The roads routine was not used in that iteration of the model.

Core collection and analysis

Sediment core sampling

Sediment cores were taken at five sites near Soufriere and four sites near Anse La Raye in 2010, at various distances from river input, and where possible at two depths (Figure 2.1). At each site, cores were obtained with a diver-operated slide-hammer corer (Aquatic Research Instruments; http://www.aquaticresearch.com) at water depths of 7-23 m. The polycarbonate core barrel had an internal diameter of 69 mm. Divers chose the exact location of the core based on availability of sediment deposits of at least one meter deep (as determined with a thin probe that was pushed in the substratum at various locations), and drove the corer as far as possible into the sediment. Recovered core lengths varied between 25 and 79 cm, depending on substratum hardness. Once collected, cores were kept upright and extruded in 1 cm increments into Whirl-Pak® plastic bags. Samples were weighed immediately to provide the "wet weight" of the sample, in order to determine pore water content (required for bulk density). Once in the laboratory, samples were freeze-dried and then separated into two subsamples by coning (Lewis and McConchie 1994). One subsample was used for SLR analyses. The other subsample was rinsed twice with distilled water to remove salts and decanted, then dried at room temperature. This subsample was further divided in three: one for terrigenous content analysis, one for size analysis, and one for archive.

Short-lived radioisotope dating

Once dried, samples were analyzed for short-lived radioisotope (^{210}Pb, ^{137}Cs, ^{234}Th, ^{7}Be) activities by gamma emission on a Canberra Gamma Ray Photon Detector. SLR analyses were conducted on the top two centimeters and bottom one centimeter for every core sampled, to identify those with the highest amount of datable material. We then focused the rest of the SLR analyses on the one core in each watershed that was the most promising in being dated accurately with SLR (Figure 2.1). The high cost of SLR analyses prevented us from dating more cores. Note that many studies have successfully characterized sedimentation history at a site based on radioisotope analyses from a single core (Cochran et al. 1998; Vaalgamaa and Korhola 2004; Lima et al. 2005; Yasuhara and Yamazaki 2005; Brooks et al. 2007; Ruiz-Fernandez et al. 2009).

The two cores analyzed for SLR were 29 cm (Soufriere) and 39 cm (Anse La Raye) long. Cores were analyzed for activities of ^{210}Pb, ^{137}Cs, ^{7}Be and ^{234}Th every 2 cm over the upper 16 cm (Soufriere) or 12 cm (Anse La Raye) and at 4 cm intervals in the deeper sections. The ^{210}Pb profile was used to calculate age and mass accumulation rate using the Constant Rate of Supply (CRS) model (Appleby and Oldfield 1978; Binford 1990). Terrigenous and calcareous mass accumulation rates were obtained by multiplying total mass accumulation rate by terrigenous and calcareous fraction (see below) in each sample. SLR analyses were conducted at Eckerd College, Saint Petersburg, FL.

Sediment composition

Terrigenous content analyses were performed on the same layers of the core as the SLR analyses, using the acid leaching method (Milliman 1974). Samples were weighed and then treated with a

10 % hydrochloric acid solution to dissolve all the carbonates. Samples were dried again and reweighed. The remaining sediments can be assumed to be terrigenous (Torres and Morelock 2002; Brooks et al. 2007). The proportion of calcareous sediment was calculated by dividing the weight lost during the hydrochloric acid treatment by the weight of the subsample prior to treatment. The proportion of terrigenous was calculated by dividing the weight of the terrigenous fraction by the weight of the subsample prior to treatment with hydrochloric acid. Total organic matter was determined by loss on ignition (LOI) of the remaining terrigenous sample at 550° C for at least 2.5 hours (Dean 1974), and then calculated as % of the entire sample.

Size analyses

Grain size analyses were performed on the same layers as SLR and terrigenous content analyses. Samples were initially wet sieved through a 63 μm screen.   The larger size (> 63 μm) fraction was further divided into sand (63 μm – 2 mm) and gravel (> 2 mm) by dry sieving. The mud size (< 63 mm) fraction was divided into silt (4 – 63 μm) and clay (< 4 μm) fractions by the pipette method (Folk 1968).

Results

Predicted sediment yields

SLU-EROS sediment yield estimates (original calculations)

SLU-EROS estimated that the 2010 sediment yield for both the Soufriere and Anse La Raye watersheds was produced largely by roads (95 % and 83 % of total sediment yield, respectively, in 2010) (Figure 2.3).   Anse La Raye, with more rivers than Soufriere, has a more important contribution from streams (15 % vs 4 %). For both watersheds, the estimated sediment yield from hillslopes was very small (1.1 % of total yield in Soufriere, 2.1% in Anse La Raye; Figure 2.3). The model estimated 2.2 times greater yields per area in the Soufriere watershed than in the Anse La Raye watershed, which is mostly driven by higher inputs from roads in Soufriere (Figure 2.3).

Estimated sediment yields for 1995 in Anse La Raye were very similar to 2010 estimates (Table 2.3, Figure 2.3). There was a smaller contribution from hillslopes in 1995 (1.19 $Mg*km^{-2}$ vs 1.48 $Mg*km^{-2}$ in 2010) when fewer farms and exposed soil areas were in the watershed (Figure 2.4) but this made little difference to the overall sediment yield (2007.4 Mg in 1995 vs 2010.4 Mg in 2010). In the Soufriere watershed, on the other hand, the predicted sediment yield in 2010 was 18.5% higher than that of 1995 (Table 2.4, Figure 2.3). The increase in yield during that time period is mostly driven by new roads and previously paved roads that have been degraded and are now unpaved (Table 2.4, Figure 2.5).

Changes in sediment accumulation rates over coral reefs

The top ~5cm of both the Anse La Raye (ALR) and the Soufriere (SOU) cores formed a visually distinct layer (Figures 2.6 & 2.7). This top layer had finer sediment (Figures 2.6d & 2.7d) and a higher proportion of terrigenous material (Figures 2.6c & 2.7c) than underlying layers, suggesting that the layer was entirely associated with recent deposition from Hurricane Tomas, which occurred three weeks prior to sampling. The SLR profiles confirmed this scenario. The large decrease in ^{210}Pb activity in the top ~3cm in both cores (Figure 2.6a and 2.7a) is likely the result of very high accumulation rates which diluted the radioisotope (Holmes 2001). ^{7}Be was detected in the top 1 cm of ALR but was not detected in SOU. Dilution from high accumulation rates associated with the hurricane in the upper core may also be responsible for the lack of detectable ^{7}Be in SOU (Figure 2.7a), and ^{234}Th levels which are only slightly higher than background in both cores (Figure 2.6a and 2.7a). Neither core showed detectable levels of ^{137}Cs, which indicates that they are either too modern to have been exposed to the ^{137}Cs peak in 1963, or that the ^{137}Cs in these sediments is below detectable levels. Mass accumulation rates (MAR) and deposition dates therefore had to be estimated with ^{210}Pb alone.

In the ALR core, ^{210}Pb background levels were not found throughout the core, resulting in a loss of CRS model accuracy; thus, age at the very deepest point sampled (39cm) tends to be unreliable (Holmes 2001). Age at the next deepest sampling point, 35 cm deep, was estimated at 75 years (~1936). Mass accumulation rates, as estimated by CRS, increased (from ~0.56 $g*cm^{-2}*year^{-1}$ to ~0.86 $g*cm^{-2}*year^{-1}$) from the bottom of the core to around 20 cm deep (late 1970s), mostly driven by an increase in terrigenous MAR (from ~0.46 $g*cm^{-2}*year^{-1}$ to ~0.60 $g*cm^{-2}*year^{-1}$). The increase in total MAR from ~20 cm to 9 cm (late 1970s to just before hurricane Tomas in 2010; from ~0.86 $g*cm^{-2}*year^{-1}$ to ~1.06 $g*cm^{-2}*year^{-1}$), however, was caused largely by an increase in calcareous MAR. Between 1990 (15 cm) and 2002 (9 cm; the most recent year where MAR can be measured without being affected by deposition from Hurricane Tomas), there was a 15% increase in total MAR, which was entirely due to increase calcareous MAR; terrigenous MAR remained stable around 0.58 $g*cm^{-2}*year^{-1}$ (Figure 2.6b). The relative proportions of calcareous and terrigenous sediment reflect these trends (Figure 2.6c). Finally, total MAR increased by a factor of 2.4 in surface layers associated with hurricane Tomas (from

1.06 g*cm^{-2}*$year^{-1}$ to 2.56 g*cm^{-2}*$year^{-1}$), due to a 3.8-fold increase in terrigenous MAR (from 0.58 g*cm^{-2}*$year^{-1}$ to 2.22 g*cm^{-2}*$year^{-1}$; Figure 2.6b).

In the SOU core, sediment at 25 cm (the second deepest sampling point) was estimated to have been deposited around 1945. There was an increase over time in overall MAR (Figure 2.7b), but in contrast to ALR, the increase in the last two decades can be ascribed to increase in terrigenous MAR. The proportion of terrigenous sediment generally increased over time throughout the core (Figure 2.7c). Total accumulation rates for SOU, as estimated from the CRS model, increased by a factor of ~3.5 (from 0.35 g*cm^{-2}*$year^{-1}$ to 0.83 g*cm^{-2}*$year^{-1}$) from 29 cm deep (~1945) to 13 cm deep (~ 1991) (Figure 2.7b). Total MAR from 11 cm (~1995) to 7 cm (between 2004 and 2010, the last data point before influence from Hurricane Tomas) increased by ~35 % (from 0.99 g*cm^{-2}*$year^{-1}$ to 1.34 g*cm^{-2}*$year^{-1}$), which was due to a ~62% increase in terrigenous MAR (from 0.5 g*cm^{-2}*$year^{-1}$ to 0.84 g*cm^{-2}*$year^{-1}$). By comparison, calcareous MAR increased by less than 1%, and the proportion of calcareous sediment declined by 25% over the same period (Figures 2.7b, c). In the surface layers, total mass accumulation rate increased by a factor of 2.2 (1.34 g*cm^{-2}*$year^{-1}$ to 2.91 g*cm^{-2}*$year^{-1}$), due almost exclusively to accumulation of terrigenous sediment (Figure 2.7b).

Comparison between SLU-EROS sediment yield estimates and core-derived sediment accumulation rates

Changes in sediment yield calculated with the SLU-EROS model and sediment accumulation rates measured from the cores between 1995 and 2010 were strikingly similar for Anse La Raye but less so for Soufriere. SLU-EROS calculated a 0.01% increase in sediment yield for Anse La

Raye from 1995 to 2010. During this period, there were essentially no modifications to the road system (Figure 2.5) but there were increases in exposed soil and farming areas in the watershed (Figure 2.4). SLR analyses of the ALR core similarly indicate no increase in terrigenous sediment accumulation from 1992 to the latest estimate prior to the 2010 hurricane (Figure 2.6b). In Soufriere, SLU-EROS estimated an increase in sediment yield of 19% from 1995 to 2010, due to increases in the road network and the degradation of previously paved roads (Figure 2.5), as few changes in other land uses occurred in this watershed over that time (Figure 2.4). Core analyses show a 62% in terrigenous sediment mass accumulation over the same period, from 1995 to the latest data available prior to Hurricane Tomas.

Current major sources of sediment yields

We used the SLU-EROS model to identify the most important anthropogenic sources of sediment in each watershed. In the Soufriere watershed, five roads segments, measuring a total length of 2.5 km, are responsible for ~50% of all current sediment yield from roads (1525 $Mg*km^{-2}$ out of 2983 $Mg*km^{-2}$) and 47% of sediment yield from all sources (1525 $Mg*km^{-2}$ out of 3219 $Mg*km^{-2}$) (Figure 2.8). In the Anse La Raye watershed, the four most important road segments in terms of sediment production have a combined length of 2.3 km and together produce 61% of all sediment yield from roads (938 $Mg*km^{-2}$ out of 1521 $Mg*km^{-2}$) and 47% of all sediment yield (938 $Mg*km^{-2}$ out of 2007 $Mg*km^{-2}$). These road segments represent only 13% (Soufriere) and 19% (Anse La Raye) of the road network in length. The most important sediment contributors in hillslopes are exposed soil areas and farmlands; however, our data suggest that their contribution may not be as important roads. For example, the quarry that was developed in Anse La Raye between 2007 and 2010 is estimated to have increased sediment yield from hillslopes by 4.04 Mg, which represents ~9 % of watershed land use contributions in 2010, but only 0.2 % of all watershed contributions.

Discussion

This study represents the first in-depth look at changes in sediment accumulation rates in the coastal zone of Saint Lucia in relation to changes in upstream watersheds. Short-lived radioisotope analyses showed a 2-3 fold increase in sedimentation rate over the past several decades, due to increases in the accumulation of both terrigenous and calcareous sediment. Our model, SLU-EROS, suggested that the overwhelming majority of terrigenous sediment produced in two watersheds currently comes from unpaved roads. Changes in land use towards farming and exposed soil did not have as important an effect on overall predicted yield of terrigenous sediment. Increases in accumulation of calcareous sediment may be caused by the loss of coral cover and break down of reef framework.

Total sediment accumulation rates estimated from short-lived radioisotope analyses were very similar for both watersheds examined. Accumulation rates estimated in this study (0.35-1.34 $g*cm^{-2}*year^{-1}$, prior to the deposition event associated with Hurricane Tomas) were consistent with another core previously analyzed in the Soufriere region (Bégin 2012) and are high for a coral reef environment. By comparisons, accumulation rates derived from cores were estimated at 0.15 $g*cm^{-2}*year^{-1}$ in Coral Bay, St John (Brooks et al. 2007), and 0.24 $g*cm^{-2}*year^{-1}$ on a fore reef in Puerto Rico (Ryan et al. 2008). Both of our cores showed slow increases in accumulation rates in the past six to eight decades and a large peak in sedimentation associated with Hurricane Tomas in 2010. There was a shift to higher levels of terrigenous sediment accumulation rates in the late 1970s/early 1980s, most likely due to development in the upstream watersheds. Our cores also show increasing levels of calcareous sediment from the early 1980s to the present, probably due to increased availability of calcareous material associated with coral mortality and erosion of the reef framework. Coral cover at sites close to these cores were located has been declining steadily over the past 15 years (see chapter 3), and possibly earlier like many other Caribbean sites (Gardner et al. 2003).

Sediment yields from each watershed were calculated using a simple GIS-based model adapted from the island of Saint John. Comparisons of the changes in terrigenous sediment yield estimates from the model with terrigenous sediment accumulation rates measured in cores near downstream reefs suggest that the SLU-EROS model performed well. SLU-EROS predicted no change in sediment yield in Anse La Raye from 1995 to 2010, and our cores indeed showed a stable rate of terrigenous sediment accumulation over that period. In the Soufriere watershed, SLU-EROS accurately predicted a more substantial increase in sediment yield for the same period, although it underestimated its magnitude (19% increase in predicted yield vs 62% increase in terrigenous sediment mass accumulation rate measured on the reef). It is difficult to compare this performance to other models since model performance, if evaluated at all, is usually measured against different measures of sediment yield or accumulation (e.g. yield at catchment input, or sedimentation rate measured by sediment traps; (Ramos-Scharrón and MacDonald 2007a; Boomer et al. 2008). However the discrepancy between predictions and measured values in this study is comparable to that of other erosion models (Warren et al. 2005; Ramos-Scharrón and MacDonald 2007a).

Different changes occurred in the two watersheds over the study period. In Anse La Raye, the road network remained the same but several forested areas were converted to farms or quarries. In Soufriere, land use remained similar while new roads were developed and several previously paved roads were degraded so much that their sediment yield was considered that of an unpaved road, either as “abandoned” or “ungraded”. While it may be surprising that the conversion of forest to farming and quarries (as seen in Anse La Raye) does not increase sediment yield as much as increases in unpaved roads (as seen in Soufriere), this result was found for both model-predicted yields and core-measured accumulation rates. It should be remembered that roads on steep slopes are predicted to produce more sediment (Table 2.1) than those on more gentle inclines, and many roads in these watersheds are quite steep. By contrast, farms and quarries are likely to be on relatively flat ground and slope was not used in the erosion functions associated with these land uses. The stable rate of terrestrial sediment accumulation downstream of the Anse La Raye watershed (Table 2.3, Figure 2.3) during a time where increased watershed area was developed into farms and quarries (Figure 2.4) supports the idea that little sediment produced from those land uses was carried to the coastal zone. However, this result should not be taken to mean that increased deforestation for farms and quarries has no effect on sediment yield. It is possible that these land uses produced little sediment under normal rain conditions but have the potential, even if they are occur on relatively flat land, to produce much higher sediment yield than undisturbed areas during large storms. It could also be that the new quarries in Anse La Raye, which were developed around 2007, are too recent for their effect to have been detected in our sediment core before the large accumulation associated with Hurricane Thomas.

The fact that SLU-EROS predicts changes in sediment yield relatively accurately in both Anse La Raye and Soufriere gives confidence in its potential as a predictive tool. However, the model still has several weaknesses. Most obviously, field measurements of erosion rates in Saint Lucia would be preferable over estimates derived from other islands. The hillslope erosion functions used in this chapter do not take account of slope, and better field data on erosion rates of all landscapes at various slopes may allow the incorporation of a slope variable for hillslopes, which would improve accuracy. The Sediment Delivery Ratio used in this model is a simplification of sediment re-deposition and storage in the watershed (Walling 1983; Ramos-Scharrón and MacDonald 2007a). All paved areas (urban areas and paved roads) are estimated to contribute no sediment, when in fact these impervious surfaces can alter flow patterns (Lee et al. 2006) and increase the risk of landslide (Larsen and Parks 1997; Holcombe and Anderson 2010). The effect of large storms is also difficult to predict as the model cannot account for landslides that are often associated with those storms. Besides increasing sediment yield during storms, landslides can significantly alter land cover and the sediment yield from the watershed for months afterwards. These limitations must be remembered when using the model and interpreting its results; for example, it may be worthwhile to examine the effects of roads and land use in separate analyses to avoid downplaying the potential contribution of land use to overall yield, which may only be evident during large storm events. However, our initial results show that the model is promising, and its simplicity may allow its application to other watersheds and other islands. The accuracy of the model can be tested further in coming years, as land use and roads change and additional sediment accumulation data become available.

In evaluating the accuracy of SLU-EROS, we compared sediment yields calculated from the model to sediment accumulation rates measured on reefs near river mouths. We assumed that the relative proportion of the sediment yield accumulating near reefs would be consistent, so that a two-fold increase in yield would be recorded as a two-fold increase in accumulation rate. However, this may not necessarily be the case. Changes energy levels and current patterns may all affect where sediment is ultimately deposited in the coastal zone (Brooks et al. 2007), resulting in some discrepancy between sediment yield and sediment accumulation rate at one site. However, in the absence of data to quantify the link between yield and deposition, accumulation rates from these cores are the best estimates available, and a good starting point evaluate the accuracy of SLU-EROS.

Our study shows that there have been marked increases in sedimentation accumulation rates over coral reefs at two sites in Saint Lucia over the past several decades. Increased sediment loads have been an on-going threat to coral reefs in Saint Lucia and corals in and out of MPAs have declined in the past 15 years (see chapter 3 of this report). Reducing sediment loads to reefs has been an important management concern in the country. We believe that SLU-EROS can serve in its current form as a helpful, if perhaps crude, predictor of sediment yields under various roads and land use scenarios. For example, it can identify specific landscape features or road segments that are the most likely major contributors to sediment yields, thereby facilitating priority ranking for remedial action. Further research, including field estimates of various landscapes in Saint Lucia, will continue to improve it as a useful management tool.

Table 2.1. Sediment production functions for unpaved roads, streams and hillslopes in SLU-EROS. Distances are in m, area is in m^2, time is in years, slope is a decimal, and rainfall is in centimeters. Resulting sediment production is in Mg. Erosion functions for roads, streams, undisturbed hillslopes and densely vegetated hillslopes are based on Ramos-Scharron and MacDonald (2007a), and those for farms, grasslands and exposed soils are calculated as a ratio of erosion in those land uses compared to undisturbed forest (Gellis et al. 2006). Variables that are derived from GIS layers are in italics.

Sediment source	Sediment production function
Graded roads	[-0.432+4.73*(*slope*$^{1.5}$)*rainfall]**length***width**1.204/1000
Ungraded roads	[-0.432+1.88*(*slope*$^{1.5}$)*rainfall]**length***width**1.136/1000
Abandoned roads	0.071**slope**rainfall**length***width**1.0034/1000
Streambanks	10*2**channel length with erodible banks***bank height**years/1000
Treethrow	0.17**channel length**years/1000
Undisturbed	0.000064*14% rainfall**area**1.0136/1000
Densely vegetated	0.000064*14% rainfall**area**1.0136/1000
Farmland	23.1 *(0.000064*14% rainfall**area**1.0136/1000)
Grasslands	1.71 *(0.000064*14% rainfall**area**1.0136/1000)
Exposed soil	29.95 *(0.000064*14% rainfall**area**1.0136/1000)
Urban areas	0

Table 2.2. List of GIS data layers necessary to run the SLU-EROS model, along with feature type, list of attributes needed and routine in which is it used.

Layer	Feature Type	Attributes	Routine
Sediment delivery potential	Polygon	Delivery potential (High, moderate, low)	Sediment delivery
Watershed	Polygon	Area	Sediment delivery, roads, streams, hillslopes
Roads	Line	Length, width, slope, drain ID, surface type (graded, ungraded, abandoned)	Roads
Drains	Point	Drain ID	Roads
Land use	Polygon	Land use (undisturbed, densely vegetated, farmland, grassland, exposed soil, urban), area	Hillslopes
Streams	Line	Length, bank height	Streams

Table 2.3. Sediment yields estimated by SLU-EROS for the Anse La Raye watershed in 1995 and in 2010, and percent change between the two time periods.

Routine	Category	1995		2010		1995-2010 change
		Watershed yield ($Mg*year^{-1}$)	Area yield ($Mg*km^{-2}*yr^{-1}$)	Watershed yield ($Mg*year^{-1}$)	Area yield ($Mg*km^{-2}*yr^{-1}$)	(%)
Roads	Total	1670.50	85.62	1659.60	85.06	-0.7
	graded	403.94	20.70	403.94	20.70	0.0
	ungraded	1248.49	63.99	1237.65	63.44	-0.9
	abandoned	18.04	0.92	18.04	0.92	0.0
Hillslopes	Total	28.95	1.48	42.80	2.19	47.8
	Undisturbed	12.40	0.64	12.26	0.63	-1.1
	Densely vegetated	9.46	0.48	9.12	0.47	-3.6
	Grasslands	1.68	0.09	1.52	0.08	-9.5
	Farming	5.17	0.26	15.58	0.80	201.4
	Exposed	0.26	0.01	4.30	0.22	1553.8
Streams	Total	307.96	15.78	307.96	15.78	0.0
Total		2007.41	102.89	2010.36	103.04	0.1

Table 2.4. Sediment yields estimated by SLU-EROS for the Soufriere watershed in 1995 and in 2010, and percent change between the two time periods.

Routine	Category	1995		2010		1995-2010
		Watershed yield ($Mg*year^{-1}$)	Area yield ($Mg*km^{-2}*yr^{-1}$)	Watershed yield ($Mg*year^{-1}$)	Area yield ($Mg*km^{-2}*yr^{-1}$)	Change (%)
Roads	Total	2483.00	160.92	2983.20	193.34	20.1
	graded	40.87	2.65	40.87	2.65	0.0
	ungraded	2439.15	158.08	2880.42	186.68	18.1
	abandoned	2.99	0.19	61.90	4.01	1968.4
Hillslopes	Total	49.64	3.22	51.90	3.36	4.6
	Undisturbed	3.04	0.20	3.04	0.20	0.0
	Densely vegetated	11.84	0.77	11.30	0.73	-4.6
	Grasslands	2.93	0.19	3.65	0.24	24.6
	Farming	31.83	2.06	33.90	2.20	6.5
	Exposed	0.00	0.00	0.00	0.00	0.0
Streams	Total	183.50	11.89	183.50	11.89	0.0
Total		2716.14	176.03	3218.60	208.59	18.5

Figure 2.1. Map of Saint Lucia, showing Anse La Raye and Soufriere watersheds, major rivers (thick black lines) and core sites (black dots). The cores analyzed for short-lived radioisotopes are identified with arrows.

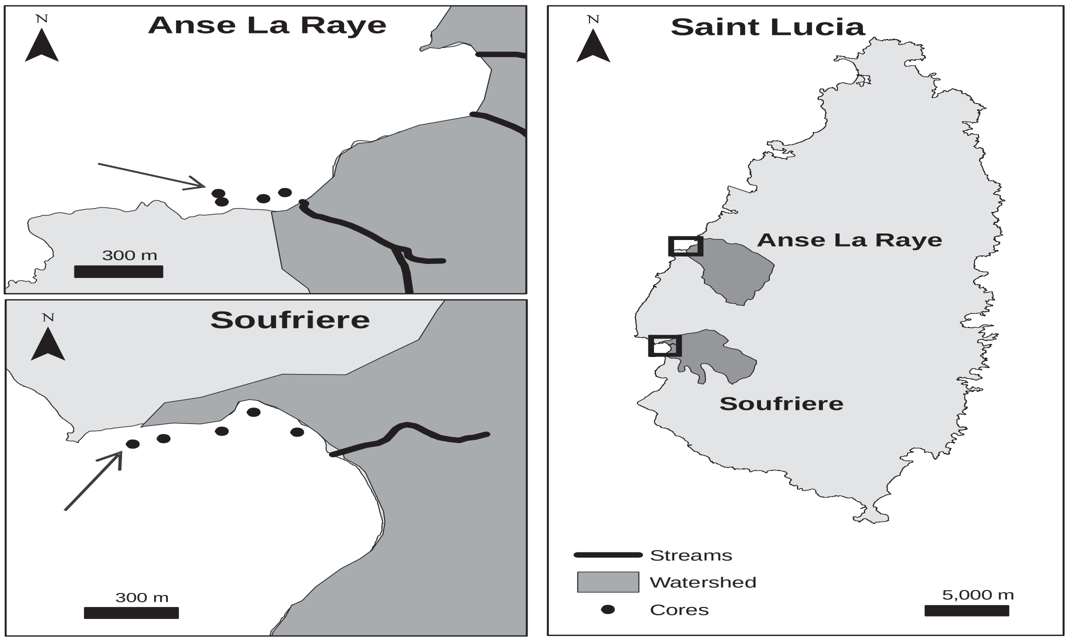


Figure 2.2. Flowchart of the SLU-EROS model.

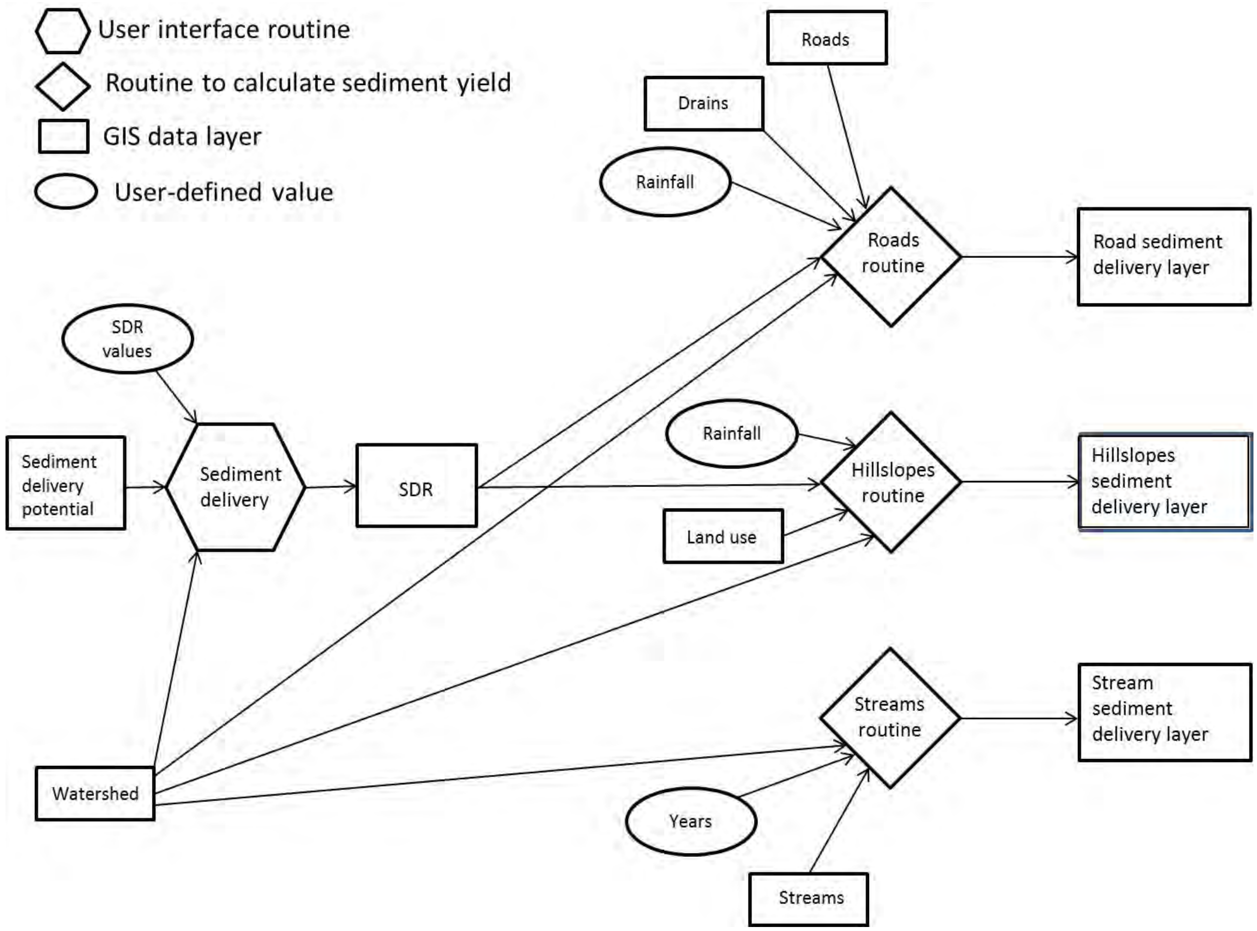


Figure 2.3. Sediment yields from different land uses calculated by SLU-EROS for two watersheds in Saint Lucia, eastern Caribbean, for undisturbed watersheds, and conditions in 1995 and 2010. Note the smaller Y-axis scale for Anse La Raye than Soufriere.

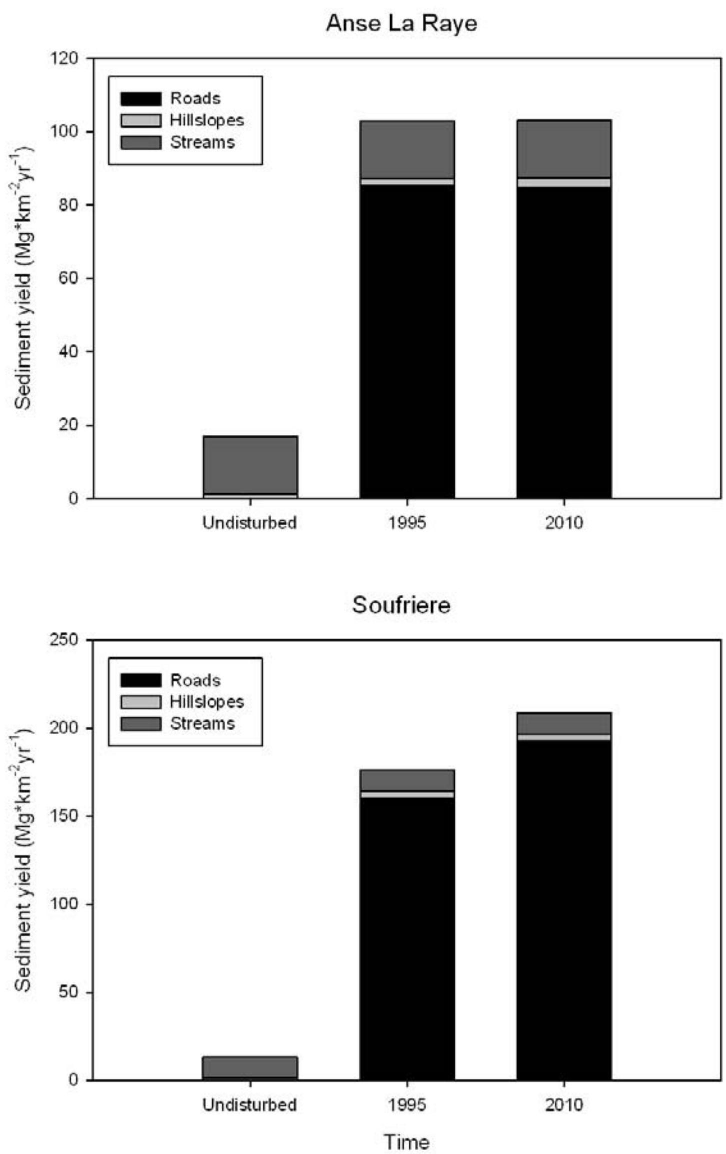


Figure 2.4. Maps of Anse La Raye (top panels) and Soufriere (bottom panels) watersheds in Saint Lucia, eastern Caribbean, in 1995 (left panels) and 2010 (right panels), showing land cover/land use in each time period.

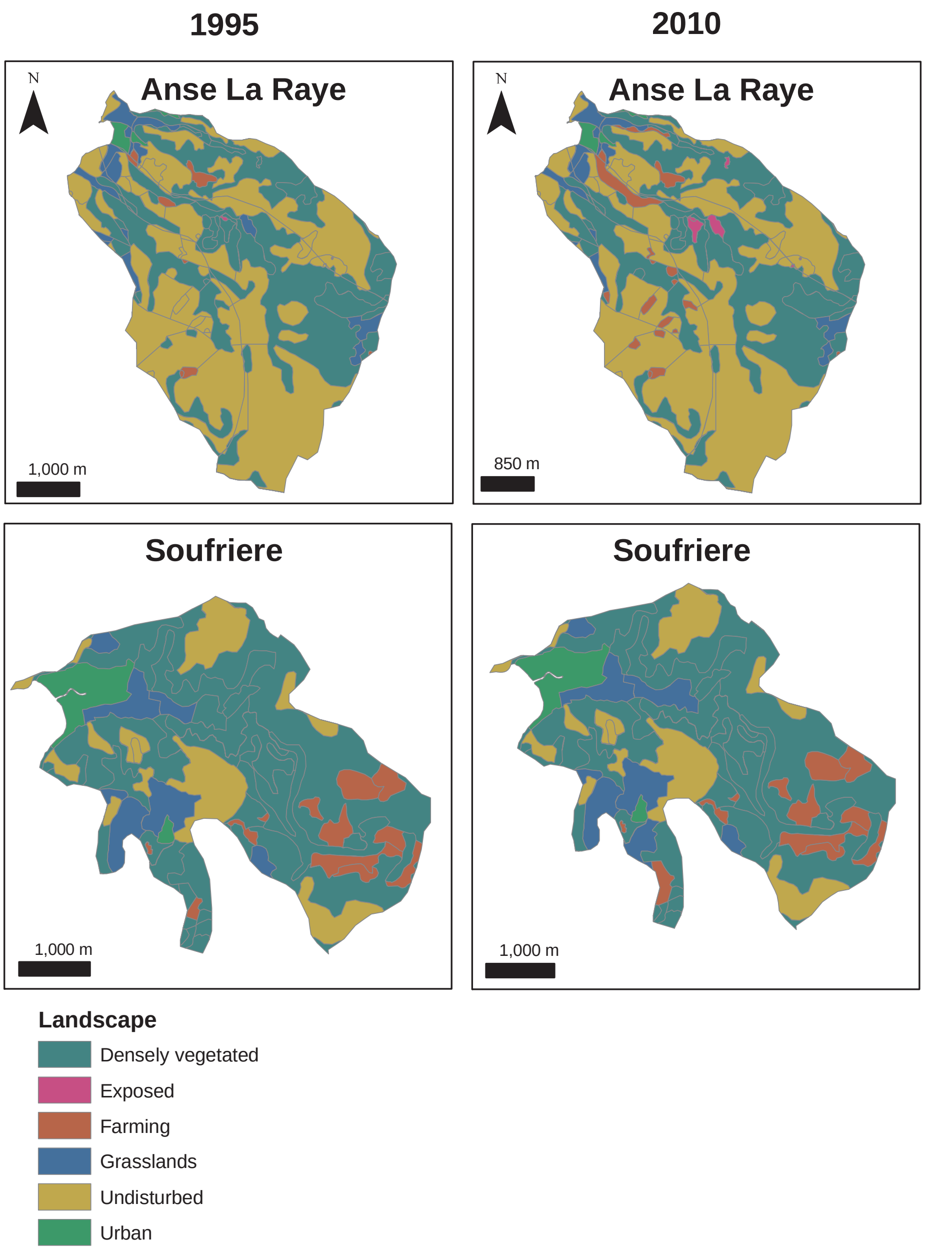


Figure 2.5. Maps of Anse La Raye (top panels) and Soufriere (bottom panels) watersheds in Saint Lucia, eastern Caribbean, in 1995 (left panels) and 2010 (right panels), showing the extent of the road network and road surface types in each time period.

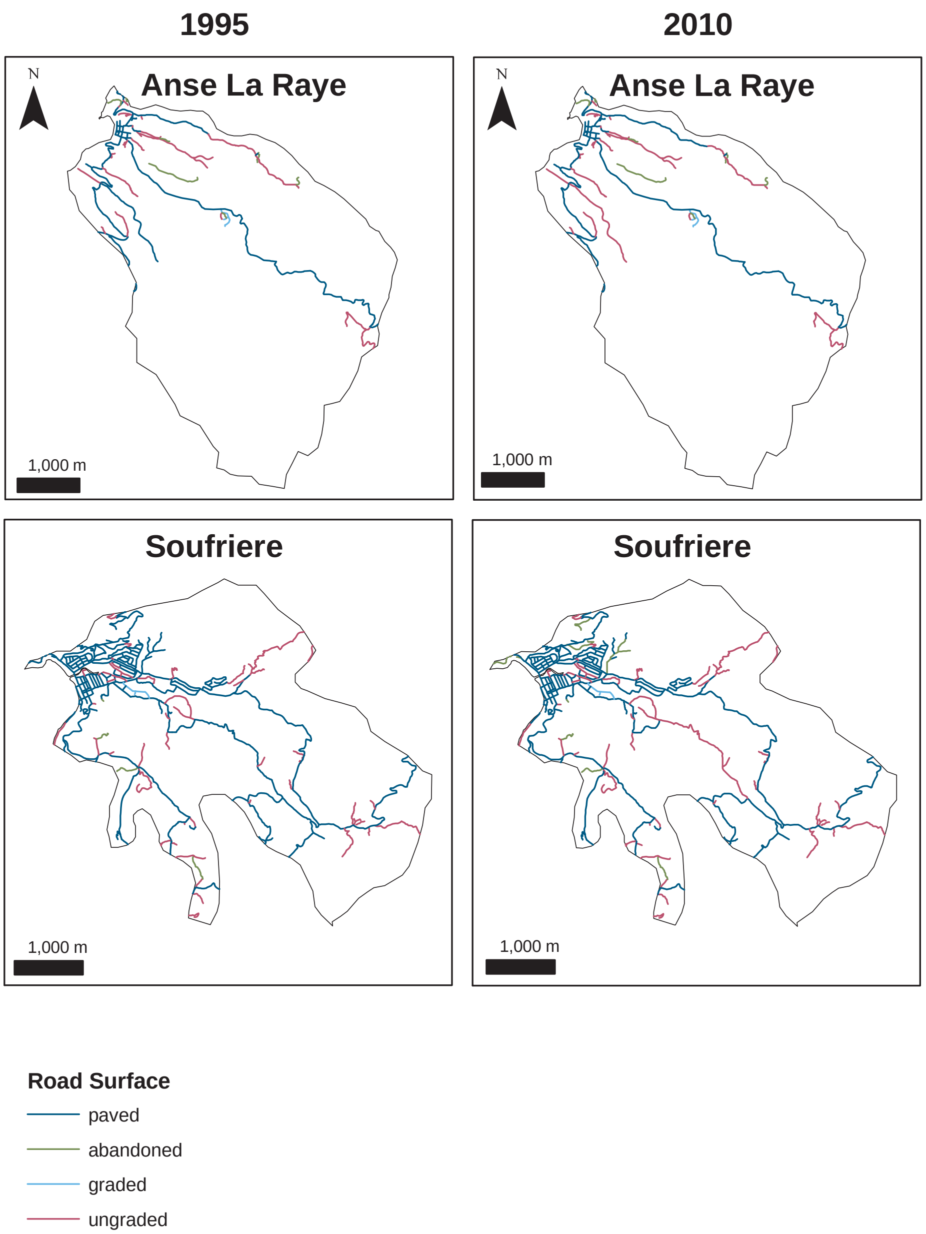


Figure 2.6. Results of analysis of the Anse La Raye core, Saint Lucia, eastern Caribbean. (a) Activity of three radioisotopes, (b) mass accumulation rates (estimated by CRS model) of total sediment, calcareous fraction and terrigenous fraction , (c) proportion of carbonates, terrigenous material, total organic content (TOC), (d) proportion of mud (grain size < 63μm) and (e) approximate year deposited, in relation to depth along the core. Depth = 0 represents the top (surface) of the core. The photograph to the left of panel (a) shows the core, scaled to match the depth axis. Year deposited is estimated based on the CRS model, and years with high uncertainty are marked with an asterisk. The location of the coring site is shown in Figure 2.1.

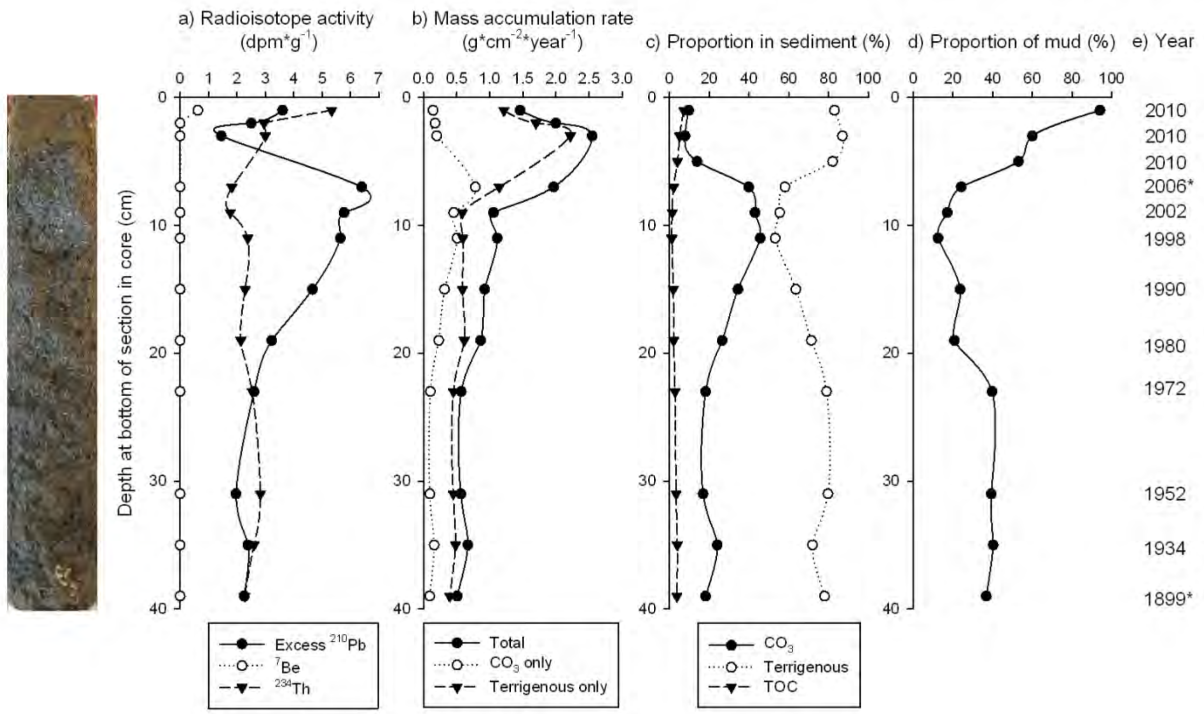


Figure 2.7. Results of analysis of the Soufriere core, Saint Lucia, eastern Caribbean. (a) Activity of three radioisotopes, (b) mass accumulation rates (estimated by CRS model) of total sediment, calcareous fraction and terrigenous fraction , (c) proportion of carbonates, terrigenous material, total organic content (TOC), (d) proportion of mud (grain size < 63μm) and (e) approximate year deposited, in relation to depth along the core. Depth = 0 represents the top (surface) of the core. The photograph to the left of panel (a) shows the core, scaled to match the depth axis. Year deposited is estimated based on the CRS model, and years with high uncertainty are marked with an asterisk. The location of the coring site is shown in Figure 2.1.

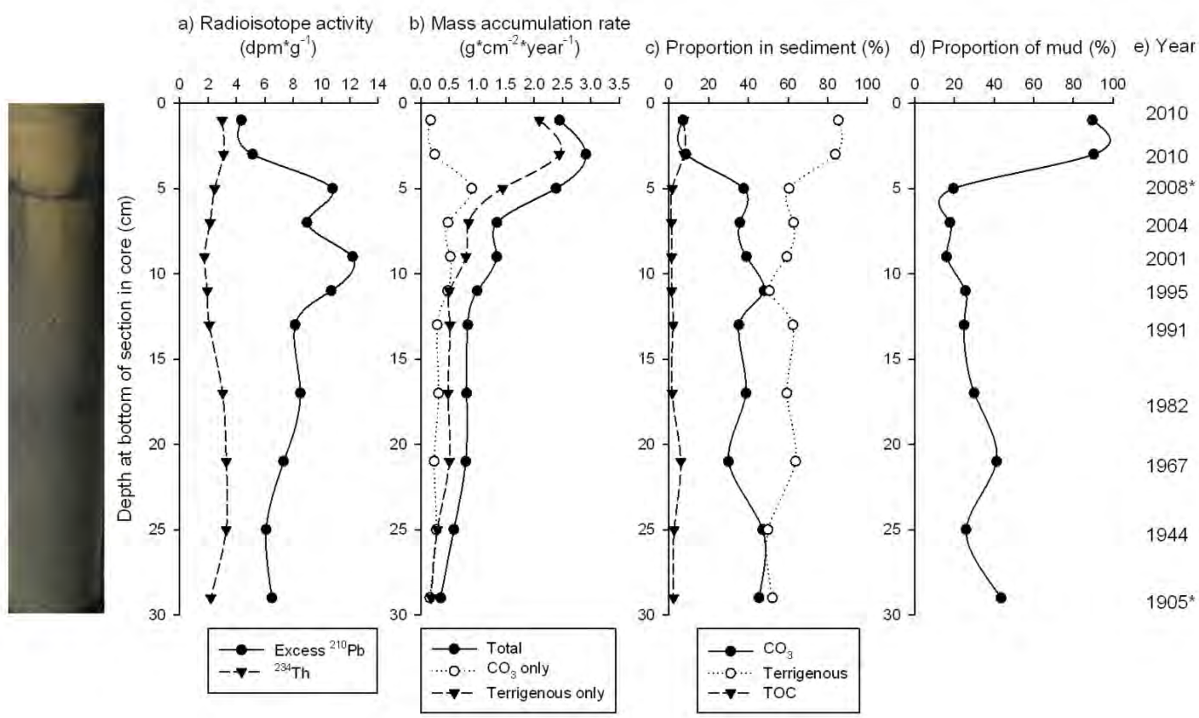
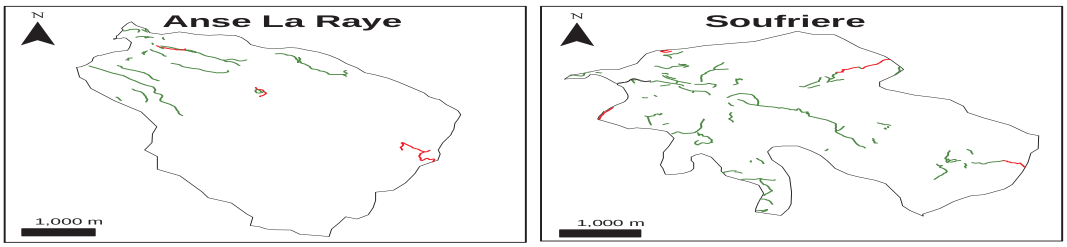


Figure 2.8. Maps of (a) Anse La Raye and (b) Soufriere watersheds in Saint Lucia, eastern Caribbean, showing all unpaved roads in 2010. The road segments highlighted in red together contribute 50% (Soufriere) and 61% of Anse La Raye of sediment yield from roads, based on SLU-EROS.



3. Effect of protection and sediment stress on coral reefs in Saint Lucia

Abstract

The extent to which Marine Protected Areas benefit corals is contentious. On one hand, MPAs could enhance coral growth and survival through increases in herbivory within their borders; on the other, they are unlikely to prevent disturbances, such as terrestrial runoff, that originate outside their boundaries. We examined the effect of spatial protection and terrestrial sediment on the benthic composition of coral reefs in Saint Lucia. In 2011, we resurveyed 21 reefs that had been surveyed in 2001 and analyzed current benthic assemblages as well as changes in benthic cover in the past decade in relation to protection status (in or out of marine protected areas), terrestrial sediment influence (measured as the proportion of terrigenous material in reef-associated sediment). We included depth (5 and 15 m) as an additional factor. Benthic cover of all biotic components has changed significantly in the past decade, including a decline in coral and increase in macroalgae. Protection status was not a significant predictor of either current benthic cover or changes in the past decade, for any of the benthic components, whereas terrigenous content of sediment and depth were both significantly related to several components. Sites with a higher proportion of terrigenous sediment were associated with lower current coral cover, higher macroalgal cover and greater coral declines. Our results suggest that terrestrial sediment is an important factor in the degradation of coral reefs in Saint Lucia and that conservation efforts on the island need to incorporate measures to reduce runoff from land.

Introduction

In the past few decades, multiple threats have contributed to large declines in coral cover worldwide (Bruno and Selig 2007). This phenomenon has been especially dramatic in the Caribbean (Gardner et al. 2003), where the decline in coral has been associated on many reefs with an increase in macroalgae (Hughes 1994). Driving factors for this shift include direct impacts on coral from hurricanes, disease, bleaching and runoff, as well as the indirect impacts of the release of top-down control of macroalgae from overfishing of fish herbivores and mass mortality of the grazing black-spined sea urchin *Diadema antillarum* (Aronson and Precht 2006; Sotka and Hay 2009). A high cover of macroalgae reduces the space available for coral recruitment and the relative herbivory pressure per unit area, which may result in a positive feedback loop that helps maintain macroalgal dominance. The stability of the macroalgae-dominated state has been debated (Mumby 2009b), yet it is clear that a higher biomass of herbivores, which exert a stronger control on macroalgae, is beneficial to corals (Williams and Polunin 2001; Hawkins and Roberts 2004; Mumby 2009a). In this context, marine protected areas (MPAs), within which all extractive activities are banned, should have positive effects on coral through increases in herbivorous fish populations (Côté et al. 2001; Roberts et al. 2001; Kaunda-Arara and Rose 2004; Francini-Filho and de Moura 2008; Guarderas et al.).

Nevertheless, whether protected or not, corals remain vulnerable to factors originating outside reserves such as runoff, storms, disease and increased water temperatures (Jameson et al. 2002). While the latter three threats are virtually impossible to manage directly, runoff may be more easily controlled. The benefits to reef health of reducing runoff may be considerable given that sediment has been shown to decrease light available for photosynthesis, inhibit recruitment, reduce growth and cause stress and mortality to a wide variety of corals (Dodge et al. 1974; Rogers 1983; Hodgson 1990; Babcock and Davies 1991; Piniak and Brown 2008). Controlling runoff, particularly upland of marine protected areas, may be a sound management strategy to enhance coral cover, or at least reduce significantly its rate of loss.

In this study, we examine the effects of marine protection and terrestrial sediment on the benthic composition of coral reefs. This work focused on the coral reefs of Saint Lucia which, as a small volcanic island, is at high risk of accelerated erosion owing to its small, steep watersheds with high precipitation rates (Milliman and Syvitski 1992; Dearing and Jones 2003). A series of small no-take MPAs, known as the Soufriere Marine Management Area (SMMA), was created in 1995 on the west coast of the island. These MPAs have a high level of compliance (Roberts et al. 2001), and within six years of establishment, total biomass of fishes had quadrupled inside the reserves and tripled outside the reserves, with the greatest increase observed for herbivores (Hawkins et al. 2006). However, the initial benefits of the SMMA did not extend to coral, which decreased in cover by 35-46% over this period, owing to disease (in 1997), bleaching (in 1998), hurricane damage (in 1999) and chronic sedimentation stress from the Soufriere River (Nugues 2002; Schelten 2002; Nugues and Roberts 2003). Another no-take MPA – the Canaries-Anse-La-Raye Marine Management Area (CAMMA), was created in 2001, 10 km north of the SMMA. The long-term effect (> 6 years) of the SMMA and the CAMMA on coral has not yet been documented.

We specifically asked whether (1) current benthic composition on Saint Lucian reefs and (2) the changes, both absolute and relative, observed in the cover of major benthic groups over the last 10 years vary in relation to protection and terrestrial influence. To answer these questions, we revisited in 2011 multiple sites located in and out of MPAs, which were surveyed a decade ago (Schelten 2002). To evaluate terrestrial sediment stress, we sampled surface reef sediment and measured the proportion of terrigenous (non-calcareous) material in this sediment. Surface sediment composition has been shown to reflect input of terrestrial sediment in a variety of settings (Subba Rao 1958; Maxwell and Swinchat 1970; Orpin et al. 2004; Perry and Taylor 2004; Badran and Al Zibdah 2005), including coral reefs in the eastern Caribbean (Bégin 2012).

Methods

Study area

Coral reef surveys and sediment sampling were carried out on the west coast of Saint Lucia (Fig. 3.1). Saint Lucia has a steep terrain and depth increases quickly with distance from shore. Fringing reefs are the typical reef formation around the island, and the only type of coral reef surveyed in this study. Twelve of the survey sites were located inside effective marine protected areas, either within the Soufriere Marine Management Area (SMMA) or the Canaries-Anse-La-Raye Marine Management Area (CAMMA).

Early surveys of benthic cover (2001)

Benthic cover at 27 sites along a 16-km stretch of coast was estimated in 2001 using 8–16 1-m^2 quadrats, placed at computer-generated 1-5 m intervals along the reef at each of two depths, 5 and 15 m (Schelten 2002). Divers estimated visually the percent cover (%) of coral (all species combined), sponges, macroalgae (thick and/or leathery, > 1 cm in height), turf algae (diminutive filaments, < 1 cm in height), crustose coralline algae and filamentous cyanobacteria (Schelten 2002).

Current surveys of benthic composition (2011)

In May and June 2011, benthic composition was re-assessed at 21 of the sites surveyed in 2001 and at one additional site (Fig. 3.1). Benthic surveys were conducted at 5 and 15 m depth at 18 of the sites, and at only one depth at four sites where reef development was minimal or absent at the other depth. At each site, scuba divers deployed three 30 m transects haphazardly on the reef, parallel to shore. Transects were at least 10 m apart. Every two meters on each transect, four contiguous photographs were taken from a distance of 0.75 m above the reef. The four photographs together (totaling 0.82 m x 1.22 m) formed a one-meter quadrat; there was a total of 15 such quadrats per transect. Percent cover of benthic organisms was quantified using the software CPCe version 3.6 (Kohler and Gill 2006). Ten random points were overlaid onto each photograph (forty points per 1 m^2 quadrat) and the organism directly under the point was identified. The benthic types recorded were the same as Schelten (2002): hard coral, macroalgae, turf algae, sponges, crustose coralline algae, filamentous cyanobacteria. Percent cover was calculated for each replicate unit as the number of random points identified as a given benthic type divided by the total number of points scored. Transects were the replicate unit for the analysis of current benthic cover, whereas quadrats were used as the replicate unit in the comparisons between 2001 and 2011 since no transects were used in the 2001 surveys.

Sediment composition

Three replicate samples of sediment (~ 100 ml) were collected from the surface layer of sediment (to a substrate depth of 5 cm) in a soft-bottom area immediately adjacent (maximum 5 m away) to each transect at each site surveyed in 2011. Such fore-reef environments tend to have better preservation of sediment compared to back reefs or channels because of lower rates of transport and biogenic re-working (Perry 1996).

In the laboratory, each sample was rinsed twice with distilled water to remove salts and decanted, then dried at room temperature. Each dry sample was separated into two subsamples by coning (Lewis and McConchie 1994), one for archiving and the other for composition analysis. Samples were weighed and then treated with a 10 % hydrochloric acid solution to dissolve carbonates. Following four rinses with deionized water, samples were dried again and reweighed. The remaining sediments can be assumed to be terrigenous (Torres and Morelock 2002; Brooks et al. 2007). The proportion of terrigenous sediment was calculated by dividing the weight of the terrigenous fraction by the weight of the subsample prior to treatment with hydrochloric acid. Organic content was determined by loss on ignition (LOI) after at least 2.5

hours at 550°C (Dean 1974), and was low (< 5 %) in all samples. Organic content was therefore not considered in subsequent analyses.

Statistical analyses

Determinants of current benthic composition

We used mixed-effects models and a correlation structure to evaluate variation in the cover of major benthic groups at the 22 sites surveyed in 2011 in relation to three (fixed) effects: sediment composition, depth (5 vs 15 m) and protection status (protected vs unprotected). We included depth as a fixed effect as it was expected to influence community composition (Sheppard 1982; Chiappone et al. 2001) and we were interested in its possible interactions with sediment composition and protection status. We also included region (Anse La Raye vs Soufriere) as a random effect. Site could not be included as a random effect in the mixed-effects models because data on terrigenous content of sediment were only available at the site rather than at the transect level. Therefore a compound symmetry correlation structure was also tested by comparing models with one of two correlation terms, i.e. either site within region or region only. Compound symmetry correlation can be used instead of random effects to account for a lack of independent samples caused by correlations among variables across different scales (Zuur et al. 2009), and tests for correlation in the residuals. The analyses were carried out using models with normal errors and constant variance following arcsine transformation of the dependent variable, which is the best method for analysing percentage cover data (Crawley 2007).

For each dependent variable (percent cover of coral, macroalgae, sponges, turf algae, coralline algae, filamentous cyanobacteria), we followed the protocol outlined in Zuur et al. (2009) for model selection. First, the optimum random-effects structure was selected by comparing generalized least square (GLS) models that included no random structure to mixed-effect models with random intercept, using the most complex fixed effects (3-way interaction between the proportion of terrigenous sediment, depth and protection status). Models were compared using Akaike's Information Criterion (AIC). AIC values represent the trade-off between model fit and model complexity, where the lowest value represents the best trade-off. The model that had the lowest AIC value was then used to select the most appropriate correlation structure. Random structure was re-tested using the optimum correlation structure. Random and correlation structures were chosen based on minimum AIC scores using the restricted maximum likelihood (REML) estimation method. Finally, the optimum model (with respect to random and correlation structure) was used to select the fixed structure (terrigenous content, depth and protection status), where terms that were not significant were successively removed until all variables remaining significantly improved model fit.   Fixed structure selection was carried out using maximum likelihood (ML). Final models were computed using REML. Homogeneity was assessed by graphical methods (Zuur et al. 2009). Because we observed no heterogeneity in the residuals, we did not test for model improvements by including variance parameters. All analyses were conducted in R 2.13.1.

Determinants of long-term changes in benthic composition

We calculated the changes in cover of major benthic groups between 2001 and 2011 in relation to protection status and sediment composition. Changes in benthic cover at these sites from 1996 to 2002 have been reported previously (Schelten 2002; Hawkins et al. 2006). We chose to focus on the decade 2001-2011 to cover a period after the 1998 bleaching event and the passage of Hurricane Lenny in 1999, both of which caused extensive mortality on the reefs of Saint Lucia (Schelten 2002). Moreover, this time period covers the first decade since the establishment of the CAMMA.

We first evaluated absolute changes in benthic cover of each major group over the last decade using repeated-measures ANOVAs, with sites as the subjects and year as the within-subject factor. Because quadrats used in reef surveys were not permanent and their exact location changed with each survey, site was used as the unit of repeated measurement in these analyses, with site-level benthic cover obtained by averaging across all quadrats (irrespective of transect for 2011).

We then estimated the importance of terrigenous content of sediment, protection status and depth for the annual rate of (relative) change in benthic cover of each major benthic group using mixed-effects models as described above. For this analysis, changes in benthic cover were calculated relative to the original survey (i.e. ($100*[Cover_{end} – Cover_{start}]/Cover_{start}$)/year), similar to Gardner et al. 2003) to control for varying initial cover, and expressed as annual rates in terms of percentages. In these mixed-effects models, the only random factor was region. The site effect was not accounted for in a compound symmetry correlation since data were only available at the site level.

Relationship between protection and sediment composition

We performed a t-test to compare the proportions of terrigenous sediment in and out of MPAs. The dependent variable was arcsine-transformed prior to the analysis, which was carried out in PASW Statistics 18.

Results

Determinants of current benthic composition

Protection status was not a significant predictor of current benthic cover in any of our models (Table 3.1). However, there were significant relationships between the cover of four of the six major benthic components considered and either sediment composition or depth or both. In all cases the best model was a generalized least-square with region/site correlation terms (Table 3.1). Current coral cover was best explained by sediment composition and depth, with higher coral cover when terrigenous content was lower (Figure 3.2a) and at shallower depth (Figure 3.3a). Macroalgal cover increased with terrigenous content (Figure 3.2b) and depth (Figure 3.3b), with a significant negative interaction between those factors (Table 3.1). Cover of sponge and filamentous cyanobacteria were both best explained by depth only. Both were more abundant at 15 m than at 5 m (Figure 3.3c&d). The cover of coralline algae and turf algae did not vary with either protection, sediment composition or depth.

Long-term changes in benthic composition

The patterns of absolute change in cover of benthic components from 2001 to 2011 were similar at 5 m and 15 m depth, although initial cover and magnitude of change varied (Figure 3.4). There were significant differences in the cover of all major benthic groups shown in Figure 3.4 between 2001 and 2011, except for crustose coralline algae at 5 m and sponge and cyanobacteria at 15 m (Tables 3.2 and 3.3). Most notably, mean coral cover decreased by 7–13% (in absolute terms) and turf algae by 9–25%. Macroalgal cover increased by 5–9% over a decade.

Variation in annual rate of relative change in coral cover over the last decade was best explained by a generalized least-square model, with depth and proportion of terrigenous sediment as fixed factors (Table 3.1). Protection status was not a significant factor. The annual rate of coral loss was higher at sites that were deeper (Figure 3.3e) and at sites with a higher proportion of terrigenous sediment (Figure 3.2c). There was no effect of protection or sediment composition on the rate of change of any other benthic component analyzed.

Relationship between protection and sediment composition

The proportion of terrigenous sediment was similar within and out of MPAs (mean ± standard deviation; unprotected: 71.4 ± 23.0 %; protected: 54.3 ± 23.8 %; $t = 1.248$, $df = 46$, $P = 0.22$).

Discussion

This study shows significant shifts in coral reef community composition in Saint Lucia in the last decade, and highlights strong links between the terrigenous content of reef-associated sediment –

a proxy of terrestrial influence on reefs – and both the rate of coral decline and current coral cover. The layer of sediment collected in this study (i.e., the top ~5cm) represents approximately 5 years of accumulation at sites with high sediment load (Bégin 2012) and even longer at sites with slower accumulation. It therefore reflects the nature of the sediment deposited at a site over a significant portion of the last decade. Importantly, protection status appeared to have no impact on benthic assemblages, perhaps because sediment composition was similar in and out of protected areas. The MPAs of Saint Lucia, while successful at protecting fishes, have not had a similar effect on corals (see also (Hawkins et al. 2006).

The cover of coral and macroalgae in 2011 varied significantly with the proportion of terrigenous content in reef sediment. This relationship was negative for coral, which is consistent with the known detrimental effects of sediment on coral (Dodge et al. 1974; Rogers 1983; Rogers 1990; Fabricius et al. 2005), and with a large-scale study showing a strong spatial association between low coral cover and high terrestrial influence on reefs (Bégin 2012). On the other hand, there was a positive relationship between the cover of macroalgae and terrigenous content of sediment. These results contrast with a previous study conducted throughout the eastern Caribbean, in which macroalgal abundance was negatively correlated with levels of terrigenous sediment (Bégin 2012). The discrepancy may be caused by differences between the two studies in the algal dominant species. In both cases, the two most abundant taxa were *Lobophora variegata* and *Dictyota* spp. In the present study, the overall mean macroalgal cover was 5.8 ± 7 % (mean ± standard deviation), with the majority of cover provided by *L. variegata* (5.0 ± 9.5 %) and only a small proportion by *Dictyota* spp. (0.3 ± 0.6 %). By contrast, in the eastern Caribbean study, the mean macroalgal cover was substantially higher (19.3 ± 12.2 %), with the cover of *Dictyota* spp. (13.2 ±10.3 %) exceeding greatly that of *L. variegata* (2.7 ± 4.8 %). The contrasting results could be explained if *L. variegata* has a higher tolerance to high sedimentation than *Dictyota* spp. To our knowledge, the responses of these macroalgae to sediment load and composition have never been directly investigated, and more research is needed to fully understand these results.

The current cover of several benthic components (coral, macroalgae, sponges, filamentous cyanobacteria) varied significantly with depth in a manner consistent with known patterns of depth zonation on coral reefs and in many other ecosystems (Sheppard 1982; Chiappone et al. 2001; Harborne et al. 2006; Kahng and Kelley 2007; Pandolfi and Budd 2008). There was a significant interaction between depth and terrigenous sediment in explaining spatial variation in the cover of macroalgae. Macroalgal cover increased more rapidly with increasing terrigenous fraction in sediment at 5 m than at 15 m, though this was driven mostly by high cover of macroalgae at two shallow sites (Anse Chastanet and Malgretout, 25.9 % and 34 % cover, respectively). The annual rate of decline in coral cover from 2001-2011 was greater at 15 m (mean: 6.2 $\%*year^{-1}$, standard deviation: 1.9) than at 5 m (mean: 3.6 $\%*year^{-1}$, standard deviation: 2.8), although the reason for this difference is not clear.

There was a sharp decline in coral cover between 2001 and 2011, which mirrored a similar change recorded between 1995 and 2001 (Hawkins et al. 2006). The reduction in coral cover over that earlier period was attributed to sedimentation, disease, bleaching and a hurricane (Nugues 2002; Schelten 2002). Multiple stressors have also acted on Saint Lucian reefs in the past decade. Two hurricanes have affected Saint Lucia (Dean in 2007 and Tomas in 2010), generating significant rainfall and storm surge but limited swell (Anonymous 2010; Anonymous 2011), which suggests that they likely impacted corals mainly through increased sedimentation rather than direct breakage. There was also a substantial bleaching event throughout the Caribbean in 2005 (Eakin et al. 2010) but this resulted in little coral mortality and no change in coral cover in Saint Lucia (Wilkinson and Souter 2008). In contrast, we found that the decline in coral in the past decade was significantly related to the proportion of terrigenous sediment at a site, suggesting that terrestrial sediment is a particularly important factor in driving this change at this location.

The cover of all benthic components other than coral also changed significantly between 2001 and 2011, but unlike coral, these changes were not clearly associated with sedimentation. Of particular interest is the increase in macroalgae, which occurred across all sites, regardless of depth, terrestrial influence or protection status. Although the cover of macroalgae remains low (~7–15%) in absolute terms (see also (Bruno et al. 2009)), this increase is of concern as both *Dictyota* spp and *L. variegata*, the most common species at our sites, have been shown to inhibit coral growth, increase mortality (Jompa and McCook 2002; Box and Mumby 2007) and reduce coral fecundity (Foster et al. 2008). Shifts in benthic dominance towards lower coral cover and increased macroalgal cover have been reported on many other Caribbean reefs (Hughes 1994; Shulman and Robertson 1996), including some in remote areas that have little human influence (McClanahan and Muthiga 1998), signaling that these changes are not only or necessarily caused by local anthropogenic factors.

In conclusion, spatial protection in Saint Lucia has not affected either current benthic assemblages or changes in the biotic composition of coral reefs over the past decade. The creation of MPAs on this island has led to rapid increases in fish biomass, and in particular of herbivorous fishes (Hawkins et al. 2006). Yet, the cover of macroalgae has continued to increase both in and out of the reserves in the past 10 years, while coral cover has declined steadily. These results suggest that factors other than herbivory are controlling variation in coral cover, and that the current management of this ecosystem in Saint Lucia is not adequate to successfully conserve corals. Our study shows that the influence of terrestrial sediment is one factor that is linked to coral success in Saint Lucia. Sediment accumulation rates on reefs in Saint Lucia are high and have been increasing in the past several decades (Chapter 2, Bégin 2012), and this terrestrial influence is acting both within and beyond protected boundaries. We suggest that efforts to conserve coral in Saint Lucia should focus on this localized threat.

Table 3.1 Parameter estimates, standard errors (SE), and significance statistics of optimum mixed-effects models explaining variation in percent cover of coral, macroalgae, sponge and filamentous cyanobacteria in 2011, and annual rate of change in coral cover (2001 – 2011) on fringing reefs at 22 sites in Saint Lucia. Cover data were arcsine transformed. Annual rate of change in coral cover was calculated relative to initial cover (see Methods).

Dependent variable	Parameter	Estimate	SE	t	P
Coral	Intercept	0.396	0.030	12.92	<0.0001
	% terrigenous	-0.0016	0.0004	-3.81	0.0002
	depth	-0.032	0.016	-2.014	0.0470
Macroalgae	Intercept	0.121	0.040	3.04	0.0029
	% terrigenous	0.0015	0.0006	2.56	0.0107
	Depth	0.149	0.051	2.91	0.0042
	% terrigenous*depth	-0.002	0.0008	-2.41	0.0176
Sponge	Intercept	0.201	0.013	14.89	<0.0001
	Depth	0.061	0.012	5.17	<0.0001
Filamentous cyanobacteria	Intercept	0.122	0.026	4.74	<0.0001
	Depth	0.052	0.012	4.49	<0.0001
Change in coral cover	Intercept	-2.005	0.886	-2.26	0.0297
	% terrigenous	-0.032	0.013	-2.45	0.0191
	depth	-2.142	0.648	-3.31	0.0022

Table 3.2 Results of repeated-measures ANOVAs comparing the cover of major benthic components at 5 m depth on coral reefs of Saint Lucia between 2001 and 2011, with mean change in absolute percent cover for each group. * denotes significant changes.

Benthic component	**Mean change in absolute cover (%)**	$\mathbf{F_{1,18}}$	**P**
Coral	-6.8	14.49	0.002*
Sponge	+2.3	13.196	0.002*
Turf algae	-26.4	25.12	<0.0001*
Macroalgae	+5.0	6.49	0.02*
Cyanobacteria	-4.7	5.56	0.03*
Crustose coralline algae	-2.0	1.62	0.22

Table 3.3 Results of repeated-measures ANOVAs comparing the cover of major benthic components at 15 m depth on coral reefs of Saint Lucia between 2001 and 2011, with mean change in absolute percent cover for each group. * denotes significant changes.

Benthic component	**Mean change in absolute cover (%)**	$\mathbf{F_{1,18}}$	**P**
Coral	-12.4	67.20	<0.0001*
Sponge	+1.5	0.99	0.33
Turf algae	-9.3	11.50	0.003*
Macroalgae	+8.7	9.94	0.006*
Cyanobacteria	-1.7	2.44	0.14
Crustose coralline algae	-4.3	30.91	<0.0001*

Fig 3.1. Location of sampling sites in Saint Lucia. Grey areas represent the no-take marine protected areas of the Soufriere Marine Management Area (SMMA), and the hashed ones those of the Canaries-Anse-La-Raye Marine Management Area (CAMMA). The location of the two management areas is shown on the middle-right panel. All sites were surveyed at both 5 m and 15 m, except sites # 1 and 6 (5m only), and 5 and 19 (15 m only). Site # 16 was surveyed in 2011 only; all others were surveyed in both 2001 and 2011.

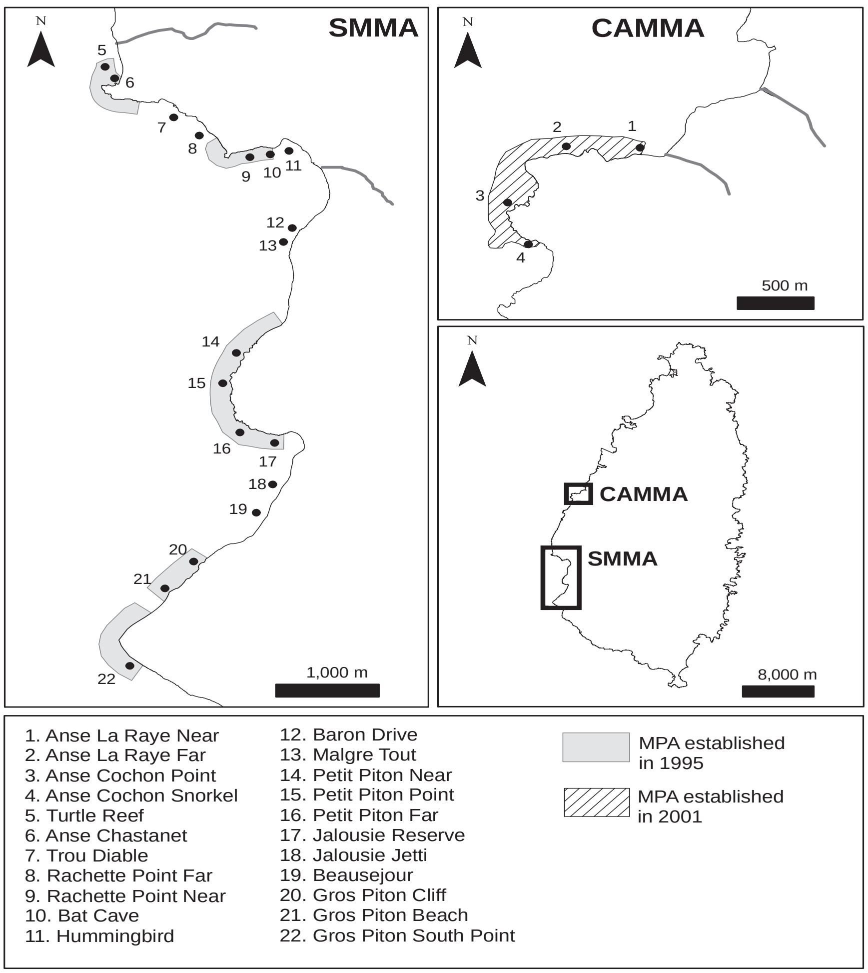


Figure 3.2. Cover of (a) coral, (b) macroalgae in 2011 (arcsine %), and (c) annual rate of relative change in cover of coral from 2001-2011 (see Methods for equation), in relation to terrigenous content of reef sediment.

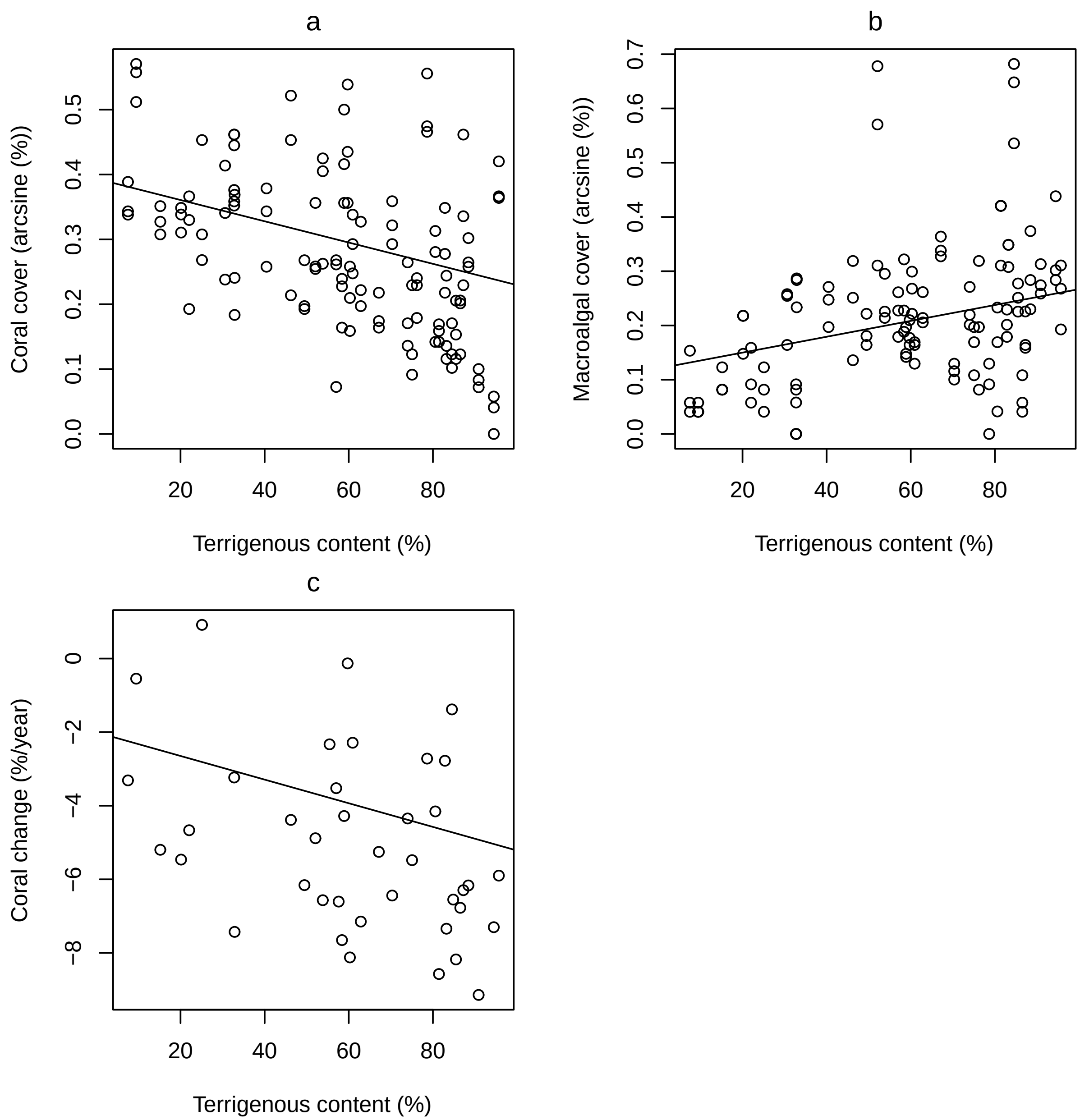


Figure 3.3. Cover of (a) coral, (b) macroalgae, (c) sponge and (d) filamentous cyanobacteria in 2011 (arcsine %), and (e) annual rate of relative change in cover of coral from 2001-2011 (see Methods for equation), at depths of 5 and 15 m.

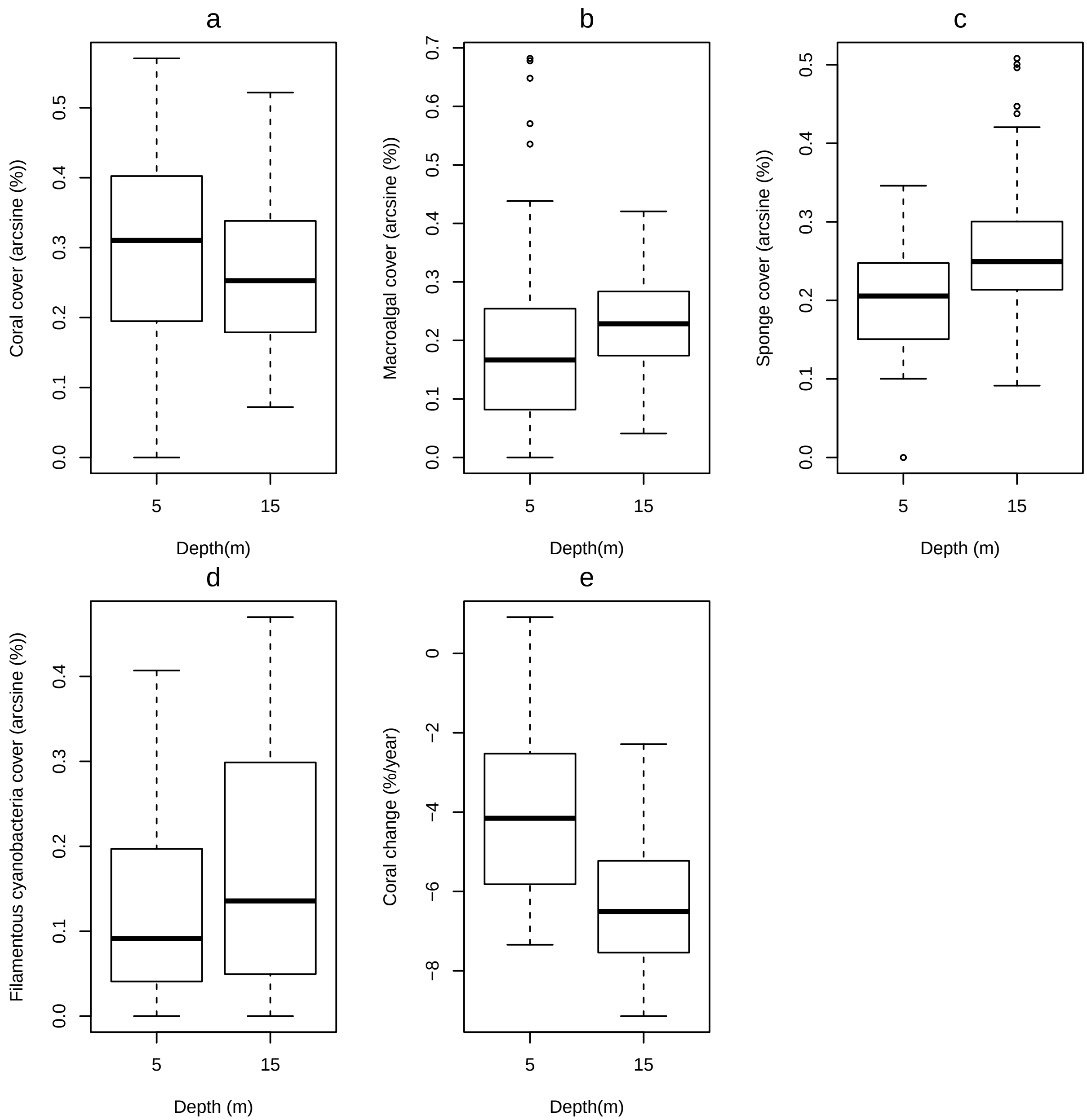
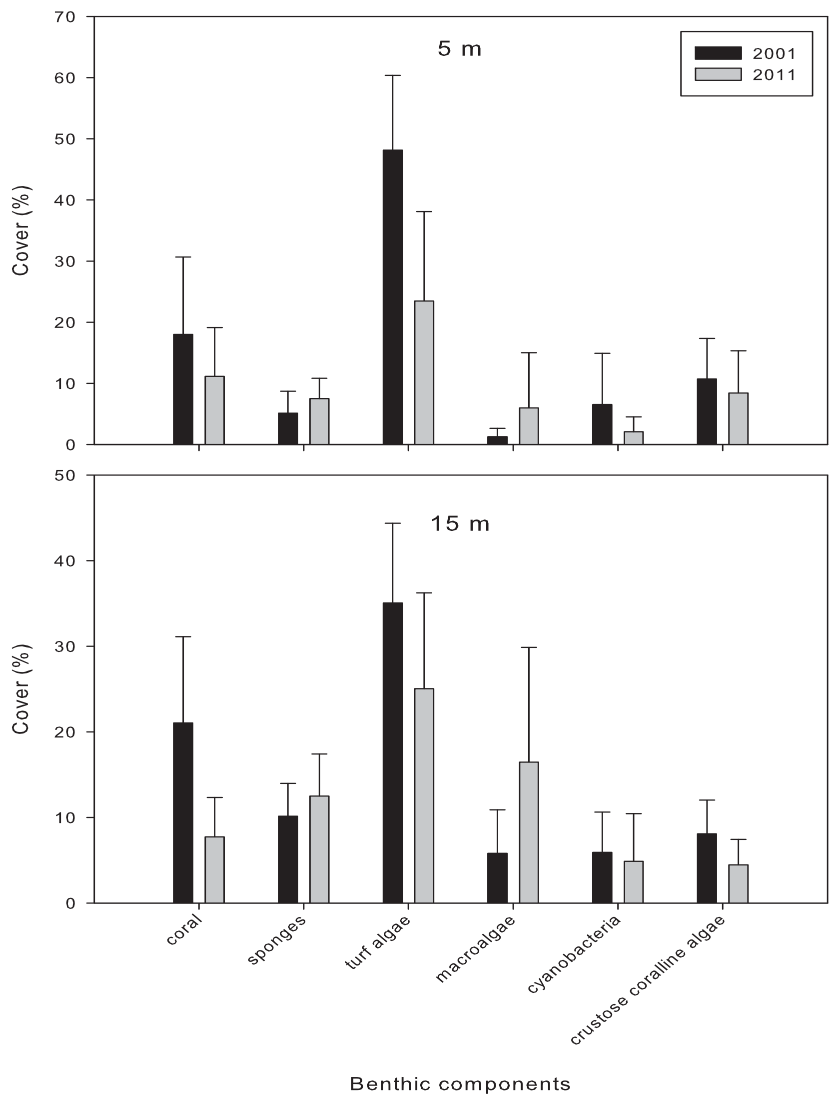


Figure 3.4. Mean cover of major benthic groups that were surveyed at depths of 5 m and 15 m in 2001 and 2011. Bars represent standard deviation. N = 19 sites.



4. Conclusions and Management Recommendations

4.1. Summary and general conclusions

The studies presented in this report show substantial increases in the accumulation of terrigenous sediment on coral reefs in both Soufriere Marine Management Area (SMMA) and the Canaries-Anse-La-Raye Management Area (CAMMA) over the past several decades and continued to declines in coral cover on those reefs in the past ten years.

Total sediment accumulation rate, prior to the effect of Hurricane Tomas, had at least doubled on reefs downstream of the Soufriere and Anse La Raye watersheds in the past 6-7 several decades. The increase was due to both an increase in the amount of terrigenous sediment (from the upstream watershed) and calcareous sediment (from the breakdown of the reef structure). The acute rainfall event and landslides associated with Hurricane Tomas (November 2010) resulted in ~5cm of terrigenous sediment deposition on reefs in both regions. Further sampling is needed to understand how much sediment from this deposition even will be retained on the reef and how much will be transported away from the reef by currents.

The sediment budget model used here (a modification from a model originally developed for Saint John, USVI) appears to perform reasonably well for the Anse La Raye and Soufriere watersheds, based on comparisons with downstream cores. This model, SLU-EROS, estimates that current sediment yields are six (Anse La Raye) and 16 (Soufriere) times greater than in undisturbed watersheds. It identifies unpaved roads as the most important source of sediment for both watersheds. Specifically, a small number of steep road segments in each watershed are responsible for a large proportion of the sediment load. While the model estimates that combined contributions from hillslopes (including farms and exposed soil) are less important than those from unpaved roads, this should not be taken to mean that deforestation of the watershed has no impact on sediment runoff. Limitations of the model must be remembered, in particular the difficulty in estimating sediment yield from large storm events which lead to large landslides. Further research is needed to better understand the relative contribution from roads and hillslopes under various rainfall scenarios. In the meantime, we recommend interpreting the results of the model separately for hillslopes and roads (see specifics for Soufriere and Anse La Raye below), and applying the precautionary principle by limiting further land use changes that reduce forested areas in each watershed.

There were significant declines in coral cover between 2001 and 2011, which followed a similar trend to that recorded from 1995 to 2001 (Schelten 2002; Hawkins et al. 2006). Current coral cover (2011) and decline over the past decade varied independently of protection status; reefs within the SMMA and CAMMA did not have more coral, or less substantial declines, than non-protected reefs. In contrast, both current coral cover and 2001-2011 coral decline were significantly related to the proportion of terrigenous sediment at a site. This confirms that terrestrial sediment runoff is an important driving factor for coral reef communities in Saint Lucia, and suggests that efforts to reduce sediment runoff must be increased for adequate conservation of coral communities within the marine parks.

4.2. Recommendations: Anse La Raye watershed

Sediment yield in both watersheds was caused largely by a few road segments. In the Anse La Raye watershed four road segments with a combined length of 2.3 km (19% of the watershed road network) produced 47% or all watershed sediment yield. Paving those road segments should be a priority in a sediment reduction program. These four road segments include a segment of the western part of the road to River Rock Waterfall, and two segments of the road leading from Anse La Raye to Durandeau, and a service road to the quarry off this latter road (Figure 2.8). Sediment production per area is highest in the two large quarries off the road to Durandeau which were created around 2007 (Figure 2.4, top right panel), followed by farms, which have increased in area in the past 15 years. Efforts to reduce sediment yield from hillslopes should focus on these zones.

4.3. Recommendations: Soufriere watershed

In the Soufriere watershed, five roads segments (total length of 2.5 km) are responsible for ~50% of all current sediment yields from roads. Those roads include the degraded south portion of Baron Drive (along Soufriere Bay), two segments to the west of the highway, north of Soufriere (Colombette area), a segment off Cresslands rd, and one segment in Fond Saint Jacques (Figure 2.8). There are no significant areas of exposed soil in the Soufriere watershed. The land use that contributes the most sediment here is farming, and farming area has remained roughly constant in the last 15 years.

4.4. Lessons learned

This project originally set out to use sediment trap data to evaluate changes in sedimentation over the past decade. However, sediment cores are a more suitable method for this task and we changed our methods accordingly. All sediment core analyses were conducted at Eckerd College (Florida) and it was therefore not possible to directly train collaborators in Saint Lucia on these methods. Short-lived radioisotope analyses require specialized equipment, but other sediment analyses presented in this report (e.g. proportion of terrigenous sediment) are relatively simple and inexpensive, and they can be used to assess changes in the input of terrigenous sediment over time.

SLU-EROS is a relatively easy model to use as a tool to predict coastal sediment yield under various land use scenarios. The model can now be used, for example, to identify key priorities in efforts to reduce sediment load given a finite budget. It could also be used to estimate sediment yield with planned changes in the road network and/or land use. However, we must remember the limitations of this model. SLU-EROS was derived from a model developed for another island, and many assumptions had to be made in the adaptation. Additional research in Saint Lucia would be helpful to obtain accurate erosion rates for various land uses on this island. More field work would also help provide additional ground-truthing of GIS layers and allow the GIS data to remain accurate as the watersheds change (e.g. after Hurricane Tomas).

The work described in this report highlights that a substantial portion of the road network in two watersheds studied is either unpaved or has severely degraded pavement. Many of the degraded roads are currently marked as paved in the available GIS data on roads. Discussions in the workshops held as part of this project highlighted that sediment piles caused by landslides or work to clear landslides (e.g. following Hurricane Tomas) may remain next to streams for extended periods of time. Sediment in such close proximity to stream are likely to be transported to the coast, and sediment plumes were indeed observed after most rain events for several months after Hurricane Tomas (e.g. front page photo, from Soufriere). It should be a priority to remove such piles of sediment. Similarly, while road and building construction inevitably requires exposing soil for some time, the period during which sediment is exposed should be as short as possible.

This report suggests that in order to avoid potentially underestimating the sediment contribution of deforested hillslopes, SLU-EROS results may be best interpreted by considering estimated contribution from roads and from hillslopes separately. Similarly, potential decisions on road construction or repair, or on modifying land uses in the watershed, may be taken largely independently of one another. This is perhaps easy to do under the current government structure as jurisdiction for roads and various land-uses lies in different departments. However, ultimately there needs to be a concerted effort between all the governing bodies and stakeholders to achieve working solutions to this important issue.

5. Acknowledgements

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6. Appendix A: Report on the workshop on changes in land use and increased coastal sedimentation in Saint Lucia, held on May 31, 2011 at the Saint Lucia Department of Fisheries, Pointe Seraphine, Castries, Saint Lucia

6.1. Workshop Participants

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6.2. Presentation

A 30 minute presentation was done to highlight the background and findings presented in the second chapter of this report (Increase in sediment loads over coral reefs in Saint Lucia in relation to changes in land use in upstream watersheds).

6.3. Discussion

Following the presentation, workshop attendants were invited to give their input on the results presented, on priorities in land development and marine conservation, and in suggested priorities for sediment reduction. Thoughts and suggestions are highlighted below.

6.3.1 Questions

- How close to the reef were the core samples taken?
    - Answer: Within few meters of the reef. It varied with the location of 'reef cement.' The method was similar to geologists use, and was based on where good core samples are most likely to be. All samples were within 10m of reef and were 40-70cm deep.
- In 1977, wouldn't there be fewer unpaved roads?
    - Answer: Many that were paved then, are no longer paved
- What do you consider unpaved roads?
    - Answer: Roads that were either never paved, or that are so degraded that they have lost most of their pavement
- There should be a category of partially paved roads
    - Answer: That would be an improvement for future versions of the model.
- Could it be also that the road is paved but the drains are not?
    - Answer: Yes, that could be a factor not considered in the model. Paved roads that have unpaved drains are recorded as paved roads.
- I noticed that with the recent flooding events from Thomas, areas without vegetation cover undergo sedimentation, and then it goes across paved roads. Could it be that the actual source is areas other than the road?
    - Answer: Yes. Paved roads may increase movement of the sediment to the coast. The model in its current state does not take this into account.
- Wouldn't hillsides contribute much more sediment if the data were collected after hurricane Thomas, regardless of the conditions of the roads?
    - Answer: Yes. Hurricane Thomas created multiple landslide and substantially changed hillslopes, especially in the Soufriere watershed. Extensive fieldwork or analysis of aerial photos will be necessary to assess this change. I hope to get some satellite photographs to address this, when they are available.
- Does sediment from hillslopes contribute to the road sediment measurement?
    - Answer: No. Sediment considered from roads is from road erosion alone.
- Does the model consider the reactions between various factors, such as roads interacting with hillslopes?
    - Answer: No. The model is simpler, in order to make it more usable. It includes the contributions of various land uses such as farms, grasslands, undisturbed and

exposed, but not quantify the transport of materials between areas. It uses instead a sediment delivery ratio, the proportion of sediment produced in the watershed that reaches the coast.

- How do you know the difference between sediment from roads and sediments from hills in the sample?
    - Answer: These estimates are based on field measurements done in St. John, USVI. Without extensive field measurements in Saint Lucia, they are the best estimates we can use. There is no way of identifying where in the watershed the terrigenous sediment accumulating on the reefs originally comes from.
- How old is this model?
    - Answer: It was published in 2004.
- The Historical Footnotes of the Archeology Society research agency did video on the highways recently, and may be able to provide more information. Try looking for the Folk Research Center or the Archeology and Historical Society to obtain data on road construction.
    - Answer: Thank you for the suggestion (*Follow up: When we contacted these organization we could not find anybody who could provide data on road construction and development)

6.3.2. General input on the model and improvements needed

- Additional information and factors could be included.
- It would be useful to go back to the model after some results are collected to confirm if the results are consistent with the model.
- Reporting roads as unpaved or paved may be misleading. Unpaved roads should be re-labeled low-maintenance or degraded.
    - Answer: This had been done throughout this report.
- Constructions should be considered as factors as well.
    - Answer: construction areas would generally be considered in the "exposed soil" category
- The amount of traffic to a road might have a large impact on its erodibility
    - Answer: This concern is at least partly addressed by classifying roads as graded, ungraded and abandoned
- Identification of key features next to the roads should be added into the model. For example, whether there is a quarry or areas that absorb sediment.
    - Answer: this would indeed increase the accuracy of the model, but at the expense of its simplicity. Incorporating detailed routing of sediment in the watershed is very difficult.
- I'm relieved it's not forestry that makes the biggest problem!
    - Answer: The results presented here seem to be supported by the sediment cores taken downstream of the Anse La Raye and Soufriere watersheds. However more work is needed to better understand the relative contribution of roads and hillslopes. The best approach at the moment may be to consider roads and hillslopes somewhat separately. The model can identify which road segments are

responsible for most of the sediment, and restoration efforts can focus on those roads. And independent effort can be made (by other agencies) to ensure minimal deforestation of the watershed.

- What is the contribution urban areas?
    - In this particular model, impervious surfaces are considered to contribute nothing at all, even though there may be small erodible zones within urban areas. Impervious surfaces may also affect sediment transport to the coast but this cannot be easily incorporated into the model.

6.3.3. What are realistic changes that can be made to reduce sediment yield? How can the model help formulate policies?

- Fix the roads
- Find out whether agriculture or greenhouses produce more sediment.
- Improve drainage, and fit sedimentation in the master plan for land use. There is one sediment trap that has not been cleared for more than 5yrs. Water and sediment just spills over it. We need to identify where to put sediment traps and also have them maintained. The government could approach private sector groups that would benefit from sediment traps or other changes, and see if they will take responsibility for maintaining the traps.
- All of the possible suggestions are already written down in policy and laws, but they are not acted on. There are already government reports in place.
- Political will is what is needed to make things happen
- Regarding the sediment trap idea, the department of fisheries was pushing for that in key areas, but from an engineering point of view, sediment traps are ineffective with the large volume of water from hurricanes.
- Sediment traps may be effective between hurricanes
- Measures must be taken on the land itself, not just sediment traps. Sometimes sediment is cleared from roads and just left on the side. We must move it away from areas of sediment flow.
- There is a lack of integrated management. Within one department, there is a lack of knowledge of environmental impact. Within one agency there should be more disciplines to provide resources. Four departments need to sit down and take the lead to determine what the priorities of other agencies should be: Department of Communications and Works, Department of Agriculture and Fisheries, Department of Tourism and Department of Physical Planning.
- The Department of Fisheries can take the lead, or the SMMA board. It would be good to do a presentation to the board of directors of SMMA.
- You should take the information to smallest man out there so he realizes that what happens in the ocean will come back to him. The farmer or shack owner must understand the impacts of his actions. Government agencies probably already know.
- It is the job of the ministries to take information to the local population
- The “Range to Reef” link is important.

- I'm concerned that your results give the impression that just fixing roads fixes the problem. I always thought hillside degradation was a bigger contributor. Could you run the model considering vegetated vs exposed land or other factors?
    - Answer: Yes. You could look at watershed without roads at all to compare land use, or interpret the results from roads and hillslopes separately.
- Is it possible that the weighting of roads can be changed in the model? Another variable which considers silt traps and other things that interact with sediment along the way can be incorporated. The question is what is the best way to do so.
    - Answer: The model as it is construction does not allow the weighing of particular road segments based on drainage or sediment traps. However the importance of particular roads can be inferred from the results and with additional knowledge (such as the existence of sediment traps).
- Students are welcome in Saint Lucia. I would like to see more of this kind of work in Saint Lucia, because it can inform management and policy making. Keep in touch and keep linkages with other students interested in carrying on your work. Monitoring without student work is not as easy with government agencies alone. We don't have the same access to funding sources and other resources.
- Please communicate with the department of fisheries to distribute the final results.

7. Appendix B: Report on the workshop on using SLU-EROS: held on June 3, 2011 at the Department of Education Office, Soufriere, Saint Lucia.

7.1. Invited participants (list developed by Ms. Nadia Cazaubon, Public Relations Officer at the Soufriere Marine Management Association)

Name	Agency	Email
Mr. Newton Eristhee	Soufriere Marine Management Association	neristhee@smma.org.lc
Ms. Nadia Cazaubon	Soufriere Marine Management Association	cazaubon@smma.org.lc
Mrs. Marion Francis-Henry	Chief Physical Planning Officer Ministry of Physical Development, Environment and Housing Chief Surveyor, Ministry of Physical Development, Environment and Housing	physicalplanningstlucia@gosl.gov.lc
Ms. Laverne Walker	Coastal Zone Coordinator Ministry of Physical Development, Environment and Housing American Drywall Bldg Castries	lwalker2006@gmail.com
Mrs. Sarah George.	Chief Fisheries Officer, Ministry of Agriculture, Lands, Fisheries and Forestry Pointe Seraphine Castries	sarah.george@maff.egov.lc
Mr. Michael Bobb	Chief Forestry Officer Ministry of Agriculture, Lands, Fisheries and Forestry Stanislaus James Bldg Castries	michaelbobb_2000@yahoo.com
	Water Resources Management Agency Ministry of Agriculture, Lands, Forestry and Fisheries Castries	

	Chief Agriculture Extension Officer, Ministry of Agriculture, Lands, Fisheries and Forestry Castries	
Mr. Dominique Alexander	General Manager Soufriere Regional Development Foundation NIC Bldg, Bay Street Soufriere	srdf@candw.lc
Mr. Kensley Promesse	Civil Engineer In Charge of South Ministry of Communications, Works, Transport and Public Utilities Blackbay, Vieux-Fort	kpromesse@hotmail.com
Mr. Michael Eugene	Water and Sewerage Company Soufriere Office Fond Benier Soufriere	Fax No. 758-457-1044
Mr. Vincent Sweeney (based at CEHI in Castries)	Regional Coordinator Integrated Watershed and Coastal Area Management (IWCAM)	vincent.sweeney@unep.org

7.2. Workshop participants present on June 3

Name	Affiliation	Email
Sonia Cazaubon	Soufriere Marine Management Association, Saint Lucia	cazaubon@smma.org.lc
Newton Eristhee	Soufriere Marine Management Association, Saint Lucia	neristhee@smma.org.lc
Jean-Marie Shernika	Ministry of Communications, Works, Transport and Public Utilities, Saint Lucia	crazysexycool_05@hotmail.com
St John Antal	Department of Forestry, Saint Lucia	antalsj5@yahoo.com
Odetta James	Department of Forestry, Saint Lucia	odettal@gmail.com

Anthony T. Robinson	Ministry of Health Saint Lucia	
Chantale Bégin	Department of Biology Simon Fraser University, Canada	chantale_begin@sfu.ca
Jessica Schultz	Department of Biology Simon Fraser University, Canada	schultz5@interchange.ubc.ca

7.3. Presentation

A short presentation was done to summarize the results presented in the second chapter of this report (Increase in sediment loads over coral reefs in Saint Lucia in relation to changes in land use in upstream watersheds), followed by a demonstration of how SLU-EROS can be used.

7.4. SLU-EROS: Instructions

1) The model was developed in ArcGIS 9.3. A copy of it can be obtained from Chantale Bégin (chantale_begin@sfu.ca). The ArcInfo license is required to run the entire model. Arc Map is the main component of the program, in which the model is run.
2) Files should be saved on the C: drive directly because different computers have different pathways. If one saves to "My Documents", it can be hard to restore pathways after files have been moved from one computer to another. The folder that contains the model, map and GIS layers is titled SLU-EROS
3) Open existing map called SLU_EROS (or start new one). Layers are listed on the left.
4) To zoom and move around the map:
   a) Right click to on a layer and choose "zoom to layer"
   b) Click the 'zoom' button (magnifier), and then click on the area of interest.
   c) Use the Hand tool to move the map around. The Arrow selects an area.
5) Layers needed to run the model are the following (list of attributes needed are in Table 2.2):
   a) Roads ("slope" attribute was derived from the Digital Elevation Model obtained from the Department of Physical Planning)
   b) Drains
   c) Streams
   d) Land use
   e) Watersheds (each watershed as a separate layer, e.g. Soufriere and Anse La Raye)
   f) Sediment delivery potential
6) Which layers are displayed on the map can be changed by checking (or unchecking) the box to the left of the layer's name; properties of the layer's display can be changed by right-clicking on the layer name and selecting "properties"
7) Attributes of each layer can be shown by right-clicking on the name of the layer and clicking on "Open Attribute Table".

8) DNR Garmin is a toolbar freely available to download on the web (at http://www.dnr.state.mn.us/mis/gis/tools/arcview/extensions/DNRGarmin/DNRGarmin.html) to import data from a GPS into ArcGIS and vice versa. This program was used to create the Drain Layer. NOTE: A new version of DNRGarmin (to be named DNRGPS) is in production. Estimated release date: January 2012.
9) This model was created as toolbox, called the SLU-EROS toolbox. Click on the "+" sign to the left of the SLU-EROS toolbox to open the five routines: *1_SedimentDelivery*, *2_RoadSedDel*, *3_Hillslopes*, *4_Streams* and *5_Hillslope_merge*. Details of each routine can be seen and modified by right-clicking the routine and choosing "Edit". Tools can easily be added and modified within Model Builder. Double-click on the routine to run it. The user will be prompted to input parameters where needed.
10) The Sediment delivery routine prompts the user to enter the selected value for
    a) "LoPotSDR", which is the value of Sediment Delivery Ratio chosen for areas of low sediment delivery potential. This value can range between 0 and 0.5. Note that all of the Anse La Raye and Soufriere watersheds are currently designated at "high sediment delivery potential" and therefore, this value has no influence on the outcome in this situation.
    b) "HiPotSDR", which is the value of Sediment Delivery Ratio chosen for areas of high sediment delivery potential. This value can range between 0.5 and 1. We used a value of 0.75 in the analysis presented in chapter 2.
    c) "Watershed"; the user selects which watershed to use
11) The Sediment delivery routine produces a shapefile called "SDR.shp", is saved in C:\SLU_EROS\EROS_Results\SDR.shp. This file will be used in the roads and hillslopes routines.
12) The Roads routine (*2_RoadSedDel*) can only be executed in the ArcInfo license of ArcMap as it uses the "join fields" tool which is not available in the other licenses types (ArcView or ArcEditor). This routine prompts the user to select the watershed of interest, and enter a rainfall value (in centimeters). All our calculations presented in chapter 2 of this report were done on an annual basis, and therefore we used the mean annual rainfall for this parameter (175 cm in Anse La Raye; 180 cm in Soufriere) Results from the Roads routine are stored in a shapefile called "RoadsFinalTotal.shp", saved in C:\SLU_EROS\EROS_Results\RoadsFinalTotal.shp. Once the model is run for one watershed, this file should be renamed (and moved, if desired), if the model is to be run again (to avoid producing two files with the same name). Sediment yields from individual road segments (in Mg) can be found in the "SedDel_Mg" column of the attribute table. Road segments can be re-ordered in order of their sediment yield contribution by double-clicking on the "SedDel_Mg" column, to identify the segments that contribute the most sediment. Total sediment yield from roads can be obtained by right-clicking on the "SedDel_Mg" column and clicking "Statistics", then looking at the sum of all roads.
13) The Hillslopes routine (*3_Hillslopes*) also asks the user to select a watershed and enter the amount of rainfall to use in the calculations. Results from this routine are stored in six separate shapefiles (one for each land use), in the folder C:\SLU_EROS\EROS_Results. These shapefiles can be merged by running the merge routine *5_Hillslope_merge*, which produces one shapefile containing all land uses in the watershed, called "Hillslope_final_Merged.shp" in

C:\SLU_EROS\EROS_Results\Hillslope_final_Merged.shp. Note that the *5_Hillslope_merge* routine does not require the input of any parameters. As with the roads routine, once the model is run for one watershed, the files should be renamed (and moved, if desired), if the model is to be run again (to avoid producing two files with the same name). Sediment yields (in Mg) can be found in the "SedDel_Mg" column of the attribute table of "Hillslope_final_Merged.shp".

14) The Streams routine (*4_Streams*) asks the user to specify the watershed to use, as well as the number of years to use in the calculations. We always performed calculations based on one year. Results from this routine are saved in the streamstm_total.shp file in C:\SLU_EROS\EROS_Results\streamstm_total.shp. As with previous routines, once the model is run for one watershed, the file should be renamed (and moved, if desired), if the model is to be run again (to avoid producing two files with the same name). Sediment yields (in Mg) can be found in the "seg_total" column of the attribute table of "streamstm_total.shp".
15) Result files can be added to a map as a layer, and properties of that layer can be changed, for example to highlight areas that create the most sediment (under layer properties → symbology).
16) Results can be exported from the shapefiles into Excel or other programs, by right-clicking 'data' → export data.
17) Input layers can be modified as desired to reflect changing conditions in the watersheds, or to calculate sediment yield under various hypothetical scenarios.

ArcCatalog should always be used to move GIS data rather than Windows Explorer, to ensure that all necessary files are transferred

7.5. Comments and discussion from workshop participants

- What about natural barriers to sediment?
    - Answer: Not all sediment gets delivered to the coastal zone. Some of it gets redeposited, and SLU-EROS handles that issue by using a Sediment Delivery Ratio (proportion of eroded sediment that reaches the coast).
- Were the same calculations as St John used in this model? Will this give accurate estimates for Saint Lucia?
    - Answer: It would be best to have field measurements of erosion from Saint Lucia for all these parameters, but in the absence of that, these are the best data available.
- I find it strange that there are no data for Saint Lucia
    - Answer: A lot of the data incorporated in this model (e.g. roads, land use, rainfall) were already available in Saint Lucia and used in the model after ground truthing. However, there are no accurate estimates of erosion rates in Saint Lucia at the scale required to run this model. The aim of today's workshop is to show how the model works, what can be accomplished with it, and how to modify it. As more data become available the model can continue to be refined further.

- So you just download GPS coordinates into ArcMap? That will save me a lot of time.
    - Answer: Yes, DNR Garmin is a very useful program for that.
- How do you incorporate sediment core data into model?
    - Answer: Sediment core data are not directly incorporated into the model. Rather they are used to evaluate the accuracy of the model. Additional core data will be useful to continue refining the model.
- Do you remove the sediment traps regularly?
    - Answer: We did not use sediment traps in this study because of various biases and inaccuracies associated with their use in a coral reef environment. We instead estimated sedimentation rate using short-lived radioisotope dating on cores.
- Can you use past aerial photographs for the historical layers and compare them?
    - Answer: Yes. We used 1992 aerial photos for that purpose, however those photographs were not georeferenced. As technology improves and becomes more available, aerial photos will become an increasingly useful tool for this work. 2004 and 2009 aerial photos (available from the Department of Physical Planning, along with 1992 photos) were geo-referenced and had much greater resolution. Satellite photos are available from the GeoEye Foundation and are also useful.
- Do you see any ways for the Department of Communications or Forestry or Planning to use the model?
    - Answer: absolutely. This was developed to be used on the island and the model will be made available to those who would like to use it.
- We are missing participants that should listen to this, e.g. from the Department of Fisheries, Department of Planning, and Department of National Emergency. It is important that all departments understand this so that when there are storms or other natural disasters, we can plan ahead. It would be good to do a video conference or Skype with other key departments that would benefit.
- When the road is private property, there are certain requirements that need to be met, but then beyond that, there is nothing the government can do for the problem

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