SEDIMENT PRODUCTION FROM NATURAL AND DISTURBED SURFACES IN DRY TROPICAL AREAS OF LA PARGUERA-PR, 2003-2005

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ABSTRACT: Many coral reef systems within the Caribbean are at risk from land-based sources of sediment and this has prompted the U.S. Coral Reef Task Force to encourage local governments to develop erosion control strategies to mitigate their impacts. The lack of quantitative information and proper watershed assessment protocols is sometimes cited as a cause for inadequate land use decisions. This study begins to address the need for empirical data by quantifying the effects of land development on plot- and hillslope-scale sediment production rates in a tropical dry forest of southwestern Puerto Rico. Bounded plots were used to measure runoff and sediment yields from three freshly-disturbed surfaces between 2004 and 2005, while hillslope-scale sediment production rates were measured with sediment traps from eleven undisturbed hillslopes and nine unpaved road segments between 2003 and 2005. The mean sediment production rate from undisturbed hillslopes was 0.1 Megagrams per hectare per year. The mean sediment production rate from road segments and freshly-disturbed plots were 1.1 and 1.4 Mg ha^{-1} yr^{-1}, respectively. These rates show that disturbance associated to land development in a dry tropical area induces at least a ten-fold increase in sediment production rates above undisturbed conditions. The data presented here will be combined with additional data from other areas in the Caribbean to develop a comprehensive surface erosion model for dry tropical areas. The incorporation of this model into a new Geographical Information System application will allow land managers to evaluate surface erosion problems at the watershed-scale and to standardize the development of erosion control strategies.

INTRODUCTION

The decline of coral cover observed over the past several decades throughout the Caribbean Region has been associated in part to localized increases in levels of land-based anthropogenic stresses (Gardner et al., 2003). The US Coral Reef Task Force has recommended the immediate reduction of land-based pollution to lessen the threats to Caribbean reefs, and has given special attention to the effects of land development on erosion and sediment delivery (USCRTF, 2000). Excess delivery of terrigenous sediments may have detrimental effects on coral reefs (Rogers, 1990), but with the exception of only a handful of studies (e.g., Ramos-Scharrón & MacDonald, 2007a, 2007b; Warne et al., 2005), limited information is available on sediment delivery rates to the marine environment (UNEP, 1994). In Puerto Rico (PR), most previous erosion-related research has centered on the larger river basins and has focused on agricultural lands, mass

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wasting processes, or on sedimentation of water reservoirs. These studies agree that maximum sediment yield rates from the major rivers must have occurred during the peak of the agricultural era (1930s-1950s) (Warne et al., 2005), but current yields remain high due to mass wasting, remobilization of agricultural-era sediment (Clark and Wilcock, 2000), and other currently active sediment sources. However, some of the best remaining examples of nearshore reefs within the U.S. Caribbean are not in close proximity to the outlets of these major rivers, as they tend to face small coastal watersheds (< 1 km^2 to ~10 km^2) on dry-tropical climatic zones that currently are being heavily impacted by land development. These small watersheds have a low potential for mass wasting and a limited capacity for fluvial sediment storage, therefore surface erosion from disturbed lands is likely to control current sediment yield rates.

Coral reefs in the La Parguera Bay-PR have a high abundance of living coral relative to other sites on the island, but these reefs are threatened by increased sediment yields resulting from land clearing on the catchments draining into the bay (Morelock et al., 2000). Land development consists of vegetation removal and ground leveling associated to medium-scale construction sites (~10's ha) and low-standard, steep unpaved roads. Very limited background information currently exists on this type of development on a dry tropical setting, but data from nearby St. John-USVI suggests that disturbed surfaces can erode at rates that are up to four-orders of magnitude higher than undisturbed surfaces (MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2005, 2007b), and that disturbance may increase catchment-scale sediment yields up to 9 times above background levels (Ramos-Scharrón and MacDonald, 2007a).

This project addresses some unresolved issues related to erosion processes in the Caribbean by focusing on these two objectives: 1) Collect field-based measurements in La Parguera to determine the impacts of land disturbance on sediment production (i.e., surface erosion) at the plot (3 m^2) and hillslope (10's-100's m^2) scales; and 2) Compare data collected in La Parguera with measurements previously collected in St. John-USVI between 1998 and 2001.

STUDY AREA

This study took place on the small coastal watersheds draining into the La Parguera Bay (Lat: 17.9, Long: -67.1) of southwestern PR, where land erosion associated to a rapid pace of land development for urbanization threatens one of the richest coral reef systems in the Caribbean. The lithology is dominated by the Parguera limestone and mainly consists of volcaniclastic calcarenite and calcareous mudstones. Soils are shallow (<30 cm) and very cobbly. The area has a semi-arid, very dry tropical climate with an average temperature of 27 C (81F), a mean rainfall of only 77 cm yr^{-1}, and a potential evapotranspiration of 186 cm yr^{-1} (Goyal, 1988).

METHODS

Runoff plots: Runoff and sediment production from three freshly-disturbed unpaved road surfaces were measured with bounded runoff plots (~3 m^2) connected to water containers. Road slopes ranged between 9-14%. A total of 17 measurements were taken between July-2004 and May-2005, and they consisted in determining the volume of water in 130-L containers and in collecting one to two 0.5-L water samples that were analyzed for suspended sediment content.

Sediment traps: The mass of sediment produced from unpaved road segments (75-350 m^2) and undisturbed hillslopes (12 m^2-2.5 ha) was measured between August-2003 and May-2005 with 9 and 14 filter fabric sediment traps, respectively (101 measurements). Slopes ranged from 1-22%

for the unpaved roads, and 12-70% for undisturbed hillslopes. The point count method was used to determine the vegetation densities of all surfaces. All erosion measurements were matched against rainfall totals measured with a recording rain gauge.

RESULTS

A total of 183 cm of rainfall were recorded during the study period, and this is 25% higher than the expected based on the long-term local average measured at Magueyes Island (NOAA, 2002). Rainfall followed the typical wet-dry pattern of the region, but rainfall during the months of Nov-03 and May-05 was almost three times the monthly average. The large amounts of rainfall observed during the study period represented the first time in the last decade in which monthly precipitation notably exceeded potential evapotranspiration. The unpaved road segments, which had not been graded for at least 5-7 years, re-vegetated as a result of the available moisture.

Although the November-2003 monthly rainfall accounted for roughly 23% (42 cm) of the total recorded rainfall during the study period, the maximum intensity for this month (3.0 cm hr^{-1}) was exceeded during both March-2004 and May-2004 (4.0 and 3.9 cm hr^{-1}, respectively). A modified rainfall depth-intensity curve showed that 32% of the rainfall during the study period fell at intensities exceeding 2.0 cm hr^{-1}. Rainfall intensity data previously collected on a similar dry-tropical setting on St. John from 1998 to 2001 (Ramos-Scharrón and MacDonald, 2005) showed a lower intensity pattern, as only 13-22% of the rainfall was recorded at intensities exceeding 2.0 cm hr^{-1}. These analyses show that the 2003-2005 study period in La Parguera was characterized by a higher than normal rainfall pattern with high intensities.

Assuming an annual rainfall of 80 cm, the mean sediment production from undisturbed hillslopes and unpaved road segments is 0.11 and 1.1 Mg ha^{-1} yr^{-1}, respectively. This difference was statistically significant and shows that unpaved roads increased sediment production rates by one-order of magnitude above natural conditions. Average sediment production from unpaved roads showed a strong, positive, non-linear relationship with slope (Figure 1a), but a surprisingly poor correlation with rainfall. This poor correlation was caused by a decrease in sediment production rates through time. The maximum sediment production rates were recorded between Aug-2003 and October-2003 when the maximum rainfall intensity was only 2.8 cm hr^{-1}, and these erosion rates were generally higher than those associated with the high rainfall intensity periods of November-2003, March-2004, and May-2004. Given that the modified rainfall depth-intensity curves show that rainfall intensities were generally consistent throughout the entire study period, the drop in erosion rates must have been caused by a shift in the condition of the eroding surfaces. Qualitative observations suggest that the drop in erosion rates may have been caused by increased protection provided by re-vegetation of the road segments.

Sediment production—normalized by rainfall and slope— was inversely related to the vegetation cover of the road plots, road segments, and undisturbed hillslopes (Figure 1b). While the freshly-disturbed road plots had the lowest vegetation cover (1-3%), vegetation at the mid-point of the study period covered about 25-50% and 34-100% of the surface of the unpaved road segments and the undisturbed hillslopes, respectively. The lower vegetation cover of the freshly-disturbed road plots relative to that of the road segments and undisturbed hillslopes may be responsible for their higher average erosion rate (1.4 Mg ha^{-1} yr^{-1}). It is difficult to distinguish the effect of vegetation cover in reducing sediment production rates from the effects of surface coarseness, as vegetation cover is auto-correlated with the surface particle-size distribution. While the median

grain size of the surface of recently-disturbed plots was in the order of 1 mm, the median size for unpaved road segments and undisturbed hillslopes was in the order of 10-20 mm, respectively.

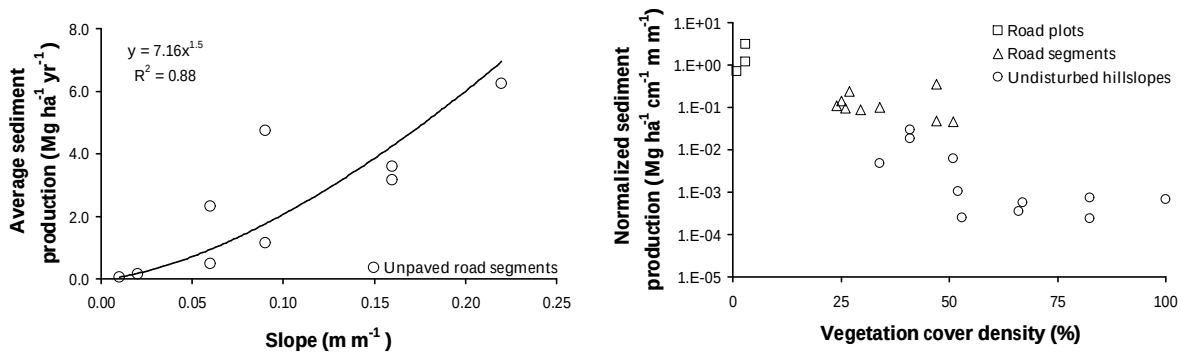

Figure 1a (left). Non-linear relationship between average road-segment slope and average annual sediment production from unpaved road segments in La Parguera. Figure 1b (right). Relationship between vegetation cover density and sediment production in La Parguera (in Mg) normalized by source area (in ha), total rainfall (in cm), and slope (in decimal or m m^{-1}).

Comparisons of the Parguera erosion data with that collected in St. John from 1998-2001 (Ramos-Scharrón and MacDonald, 2005, 2007b) show that while mean sediment production from undisturbed hillslopes on La Parguera is one-order of magnitude higher than on St. John, the unpaved roads on St. John erode at a rate that is one– to two-orders of magnitude higher than those in La Parguera (Table 1). The differences cannot be attributed to disparity in precipitation intensity, as analyses of modified rainfall depth-intensity curves show that rainfall in La Parguera (2003-2005) was slightly more intense than on St. John (1998-2001). The differences in erosion rates may be attributed to the effects of vehicular traffic. With the exception of abandoned roads, all roads on St. John were used by 10-300 vehicles per day and lacked any significant vegetation cover (Ramos-Scharrón and MacDonald, 2005), while blocked access prohibited vehicle traffic on vegetated road surfaces in La Parguera. The findings presented here support the hypotheses that sediment production from disturbed surfaces in dry tropical areas is strongly controlled by their degree of re-vegetation, and that this may be controlled by the presence or absence of vehicular traffic and the presence of enough soil moisture to support vegetation growth.

Table 1. Summary of average sediment production rates measured in La Parguera-Puerto Rico and St. John-U.S. Virgin Islands.

Sediment source	**Mean sediment production (Mg ha^{-1} yr^{-1})**
La Parguera	
Hillslopes	0.11
Road plots	1.4
Road segments	1.1
St. John	
Hillslopes	0.01
Active road segments	64-110
Abandoned road segments	12

CONCLUSIONS

Sediment production rates were measured from undisturbed and disturbed surfaces in the dry tropical environment of La Parguera in southwestern Puerto Rico between 2003 and 2005. The data showed that land disturbance for urban land development may increase sediment production rates by an order of magnitude relative to background sediment production rates. Sediment production rates from disturbed surfaces were controlled by the slope, vegetation cover density, and surface particle-size distribution. Results show a surprisingly complex relationship between rainfall and sediment production from unpaved road surfaces, with high sediment production rates at the onset of the study period followed by a sharp, one- to two-order of magnitude drop by the end of the study. This decline in sediment production from unpaved road surfaces lacking active vehicular traffic is attributed to increases in vegetation cover densities as time progressed throughout the study period. These results imply that in the absence of traffic, rainfall is still an indisputably important factor controlling sediment production as it provides the energy and means to induce erosion and sediment flux from eroding surfaces, but in this moisture-limited, semi-arid environment periods of high precipitation might also provoke a sharp reduction in sediment production by stimulating re-vegetation.

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