# Sediment production from unpaved roads in a sub-tropical dry setting — Southwestern Puerto Rico

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## ARTICLE INFO

## ABSTRACT

The threat imposed by increased sediment loading rates ranks among the most important stressors affecting coral reef ecosystems worldwide. This study represents an effort to quantify the effects of unpaved roads on erosion rates in a dry sub-tropical area of Puerto Rico and is intended to aid in developing scientifically-based erosion mitigation strategies. Hence, the specific objectives of this study were to: (1) measure sediment production rates from unpaved roads; (2) evaluate the effect of precipitation, rainfall erosivity, slope, plot length, and vegetation cover on sediment production rates; and (3) compare measured sediment production rates to published surface erosion data from roaded and natural sites in the Eastern Caribbean. Sediment production from nine abandoned road segments with varying slopes and plot lengths were measured with sediment traps in southwestern Puerto Rico from August 2003 to September 2005.

The overall average sediment production rate was 0.84 Mg ha$^{-1}$ yr$^{-1}$, and the range of observed values was 15–50 times higher than locally-measured natural erosion rates. Only four of the nine study sites had a statistically significant correlation between sediment production and total rainfall and this is attributed to progressive changes in some of the conditions controlling erosion rates. Sediment production rates were dependent on slope raised to the 1.6th power, as well as to the product of plot length times slope$^{1.6}$. Average erosion rates were inversely but poorly related to vegetation cover.

An observed decline in sediment production rates was observed for all nine study segments, and this amounted to a statistically significant difference between observations made during the early stages of monitoring (Period 1: August 2003–April 2004) relative to those during the latter parts of the study (Period 2: May 2004–September 2005). Annual erosion rates during Period 1 amounted to 0.18 to 4.0 Mg ha$^{-1}$ yr$^{-1}$ for road segments with 1% and 22% slopes, respectively; rates during Period 2 were between 0.024 and 0.52 Mg ha$^{-1}$ yr$^{-1}$, or only 13% of those during Period 1. Differences in sediment production rates between the two periods are attributed to more intense rainfall during Period 1 and to a notably higher vegetation cover during Period 2.

Rainfall appears to play a paradoxical role in controlling surface erosion rates on abandoned road surfaces in a sub-tropical dry region. While ample rainfall is needed to generate erosion by rainsplash and overland flow, once rainfall satisfies soil moisture requirements for sustaining vegetation colonization it may also contribute to declining sediment production rates. Therefore, any model that attempts to properly address the temporal variation in erosion rates occurring on abandoned roads in a climatic setting where moisture availability is a limiting factor must not only follow the more traditional surface armoring-based approach but must also integrate the effects of re-vegetation. Such types of models will eventually become useful tools to properly assess the effects of past, current, and future land use practices on erosion rates, and to improve mitigation and land development strategies to lessen the impact on vital marine habitats.

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## 1. Introduction

### 1.1. Problem statement and objectives

Human-induced changes to vegetation cover, soils, and topography may provoke important changes on the hydrologic response of disturbed surfaces, which may in turn alter a diverse array of biogeochemical processes. Land modifications alter surface and sub-surface water flow vectors, which typically lead to increased soil erosion and sediment yield (Dunne, 1979; Walling, 1997) and induce a number of adverse on-site and off-site effects including diminished soil productivity (Lal, 1998; Eswaran et al., 2001), degraded water quality (Lal and Stewart, 1994), and increased sedimentation levels on both man-made impoundments and natural habitats (Walling and Fang, 2003; Syvitski et al., 2005). Of worldwide relevance are the

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linkages between heightened levels of sediment yields and their effects on freshwater and marine ecosystems (Waters, 1995; Bryant et al., 1998).

The threat imposed by increased land-based sediment loading rates ranks among the most important stressors affecting coral reef ecosystems worldwide (Bryant et al., 1998; Carpenter et al., 2008). Within the Caribbean region two-thirds of the 26,000 km² of reefs are at risk from at least one source of anthropogenic threat, and roughly one-third are threatened by coastal development (Burke and Maidens, 2004). Excess delivery of land-based sediments exerts a vital control on reef conditions, as high concentrations of sediment in the water column reduce the amount of light required for photosynthesis by symbiotic algae, while settling of sediment can smother existing coral or reduce the surface area suitable for new growth (Hubbard, 1986; Hodgson, 1989; Rogers, 1990; Fabricius, 2005).

Coral reefs of Puerto Rico (PR) are among the most highly threatened Caribbean reef systems (Burke and Maidens, 2004). The US Coral Reef Task Force determined that reducing the contribution from land-based sources of sediment was essential in maintaining the long-term stability of coral reefs (USCRTF, 2000). Even though most soils in PR have a high to very high vulnerability to water erosion (Reich et al., 2001) and land erosion is recognized to pose a major threat to both freshwater and marine resources (Torres and Morelock, 2002; Soler-López, 2001), limited actions are generally taken to mitigate its effects (Lugo et al., 1981).

This study represents an initial effort to quantify the effects of land development on erosion rates in La Parguera-PR (Lat: 17° 58′ N, Long: 67° 03′ W) and is intended to aid in the development of scientifically-based erosion mitigation strategies designed to address current problems and guide future development. Hence, the specific objectives of this study were to: (1) measure segment-scale sediment production rates from disturbed surfaces (i.e., unpaved roads); (2) evaluate the effect of precipitation, rainfall erosivity, slope, plot length, and vegetation cover on sediment production rates; and (3) compare the measured sediment production rates to published data from disturbed and natural sites in PR and other similar climatic regions.

## 2. Study area

The present study took place on the small coastal watersheds draining into La Parguera Bay, about 120 km southwest of the city of San Juan (Fig. 1). The landscape of La Parguera is the end result of deformation of the Upper Cretaceous La Parguera limestone into a WNW–ESE trending syncline (Almy, 1965; Volckman, 1984). The local topography is characterized by watersheds that do not exceed a few km²'s in source area and 45 m of relief. Hillslopes in the upper portions of the watershed have maximum gradients of 70% which sharply grade to tidal-controlled mudflats adjacent to the coast (Fig. 1). Soils are dominated by shallow (<30 cm), well-drained, and moderately permeable gravelly clay and clay-loam soils (Beinroth et al., 2003). Erosion processes are limited to soil creep (Lewis, 1975) and surface erosion by overland flow.

A mean annual temperature of 27 °C, an average annual rainfall of 760 mm, and a potential evapotranspiration of 1860 mm yr$^{-1}$ characterize climatic conditions in the study area (Goyal, 1988; NOAA, 2001). Mean monthly rainfall is generally below 50 mm, except during May and between August and November. A weather station within La Parguera Bay (Isla Magueyes, NCDC Coop ID #665693) has the distinction of having the hottest mean annual
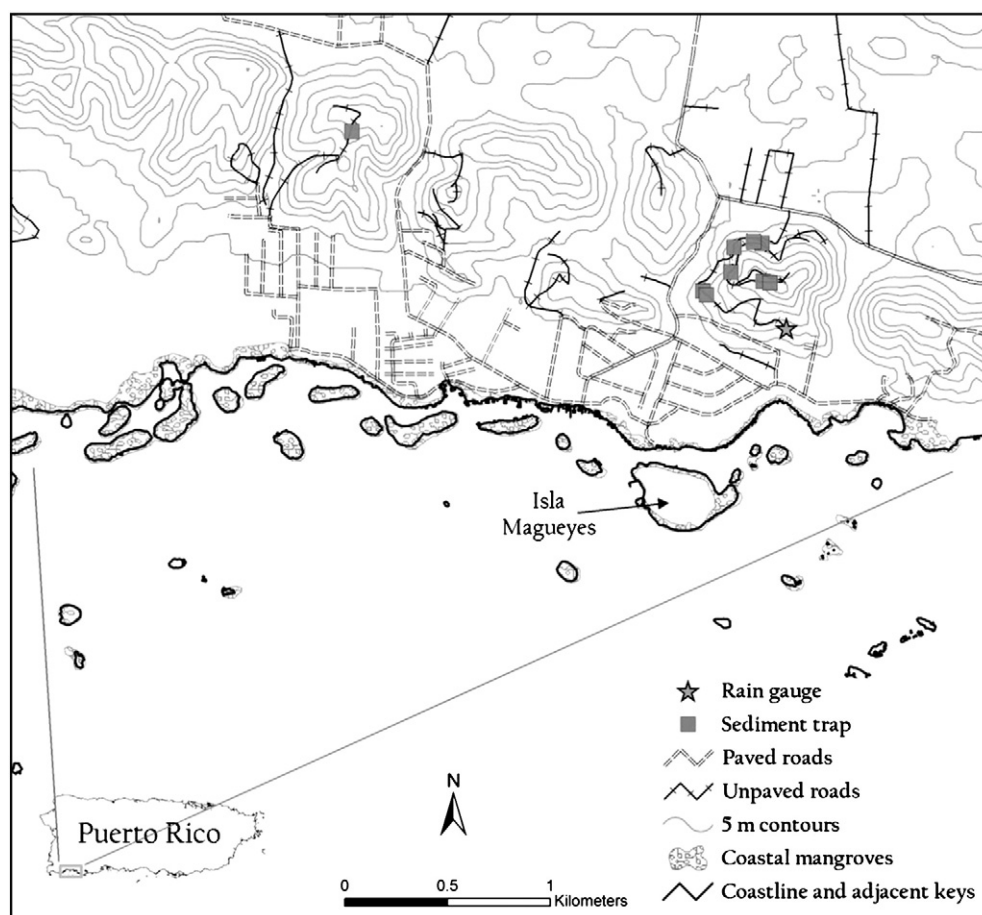


**Fig. 1.** Topographic map of the La Parguera study area showing the location of the rain gauge and the nine study sites.

temperature and the lowest mean annual rainfall of all long-term weather stations in PR (NOAA, 2001). Climatic conditions in the area are typical of a sub-tropical dry to very dry forest characterized by dominant deciduous vegetation with abundant thorny and spiny species, and an almost complete ground cover (Ewel and Whitmore, 1973).

La Parguera emerged as a fishing village in the first quarter of the 19th century and until the late 1960's land use was limited to low-intensity grazing, occasional wood cutting for charcoal production, and small-scale agricultural activity (Feliú, 1983). La Parguera still houses some of the most spectacular coral reef systems in PR (Goenaga and Cintrón, 1979; Morelock et al., 2001) and its marine resources represent a valuable socio-economic asset that supports an artisanal fishing culture and a profitable tourism industry (Valdez-Pizzini, 1990). The high coral cover (>20%) that typifies reefs in La Parguera contrasts with those found on other reef systems in southwestern PR (Morelock et al., 2001), and this may be due in part to historic low doses of terrestrial sediment inputs from relatively small watersheds in combination with a sub-tropical dry climatic setting (Almy and Carrión-Torres, 1963; Goenaga and Cintrón, 1979).

Land development in La Parguera followed the general trend occurring on other coastal areas of the Caribbean where over the past few decades secondary forests have been replaced by urban areas (Johnston, 1987; Valdez-Pizzini et al., 1988; Ramos-González, 2001). The onset of urban development on watersheds facing La Parguera has been cause for alarm given its close proximity to the reefs and its potential for increasing sediment loads (Morelock et al, 2001; Hertler, 2002). Sediment cores taken from La Parguera Bay reveal an almost doubling of sediment settling rates over the past 70 years, which may be attributed to land development activities (Ryan et al., 2008).

## 3. Methods

Rainfall was measured with a tipping-bucket rain gauge (Fig. 1) between Aug-03 and Mar-05 and compared to average monthly totals (NOAA, 2001). Observations were used to calculate 30-minute rainfall erosivity for individual storms (Renard et al., 1997), whereas individual storms were defined as rainfall periods isolated by one hour with no precipitation (Ramos-Scharrón and MacDonald 2005, 2007a). Data were used to determine the frequency and total rainfall contribution from different storm sizes, and to determine the relationship between storm size and erosivity.

Long-term (1959–2005) potential evapotranspiration (PET) was calculated by the Thornthwaite method (Thornthwaite, 1948) based on monthly average temperature data from Isla Magueyes (http://www.ncdc.noaa.gov/oa/ncdc.html; Accessed March 2007). Missing data was filled-in by extrapolations based on linear regression analyses with observations from a nearby weather station (Lajas Substation: NCDC Id# 665097; 10 km West of La Parguera). Monthly rainfall at Isla Magueyes was used to calculate the difference between precipitation and PET (PPN-PET).

Sediment production rates were periodically measured from nine unpaved road travelways between 31-Jul-2003 and 01-Jun-2005, with the exception of one single measurement taken on 16-Sep-05 (n = 52 measurements) (Fig. 1). Selected segments represent the range of source areas and slopes found within the study area as these factors are known to control erosion rates from unpaved roads (Fu et al., 2010). The exact date of construction is unknown, but the roads were last graded 7–10 years prior to the start of this study and are currently closed to vehicular traffic. The mean plot length and surface area of the road travelways were 40 m and 180 m$^2$, respectively, with plot lengths ranging between 17 and 77 m (75 and 345 m$^2$) (Table 1). Road segments had an average slope of 0.10 m m$^{-1}$ or 10%, with a 0.01–0. 22 m m$^{-1}$ range. The point count method was employed to characterize the proportion of surface covered by bare soil, rock fragments, or vegetation at 100 points along multiple transects spanning the road surface (Parker, 1951). Surface characterization was performed only once, roughly at the mid-point of the study period. In addition, four to five kilogram composite surface samples from five road segments were collected for textural analyses based on the dry sieving method (Bowles, 1992).

Sediment production rates were measured with filter fabric sediment fences placed immediately below a point of concentrated road drainage (Robichaud and Brown, 2002; Ramos-Scharrón, 2004) (Fig. 2). The filter fabric used had a tight-weave that did not allow water to readily flow through it, so sediment fences acted more like 50-cm high dams than filters. Measurements consisted of field-weighing the trapped material with a radial scale. One or two well-mixed samples of 1–2 kg were collected and placed in watertight bags and taken to the lab for percentage moisture content analyses (Gardner, 1986) to correct the field-measured weights to a dry mass. In cases when traps did not contain sufficient material for a field measurement, the entire contents were collected and dried in the lab following the above-referenced moisture content protocol. Measurements were taken on average once every three months. Particle-size distribution curves for 18 samples were determined by dry sieving analyses (Bowles, 1992). Sediments eroding from all road segments, with the exception of Road-A-Low-C, were represented by these samples.

The effect of precipitation was evaluated for every road segment by plotting total sediment production against matching observed precipitation. Similar analyses were conducted with 30-minute rainfall erosivity, but only for observations prior to 1-April-2005 (n = 43) due to the lack of matching rainfall intensity data during the final eight months of the study (n = 9). Daily rainfall observed at Isla Magueyes was matched to the nine sediment production observations taken after 1-April-2005. The individual effects of other independent factors such as slope, plot length, and vegetation cover were similarly evaluated by simple regression. Meanwhile, the integrated effects of all independent factors were evaluated by multivariate regression

**Table 1**
General characteristics of the nine study sites used in this study.

| Plot identification | Area (m$^2$) | Slope (m m$^{-1}$) | Area × slope (m$^2$ m m$^{-1}$) | Measurement period | Number of observations | Date of vegetation cover characterization | Vegetation cover (%) |
|---|---|---|---|---|---|---|---|
| Road-A-Low-A | 124 | 0.06 | 7.44 | 30-Sep-03 to 25-May-05 | 5 | 15-Nov-04 | 47% |
| Road-A-Low-B | 144 | 0.02 | 2.88 | 03-Oct-03 to 25-May-05 | 6 | 15-Nov-04 | 51% |
| Road-A-Low-C | 75 | 0.01 | 0.75 | 13-Oct-03 to 25-May-05 | 4 | 15-Nov-04 | 47% |
| Road-A-Mid-A | 192 | 0.16 | 30.7 | 02-Oct-03 to 01-Jun-05 | 6 | 2-Aug-04 | 34% |
| Road-A-Mid-B | 182 | 0.16 | 29.1 | 02-Oct-03 to 01-Jun-05 | 5 | 30-Jul-04 | 26% |
| Road-A-Mid-C | 142 | 0.09 | 12.8 | 09-Oct-03 to 01-Jun-05 | 6 | 30-Jul-04 | 25% |
| Road-A-Top-A | 345 | 0.06 | 20.7 | 01-Aug-03 to 01-Oct-03 | 7 | 23-Jul-04 | 29% |
| Road-A-Top-B | 108 | 0.09 | 9.72 | 31-Jul-03 to 01-Jun-05 | 7 | 26-Jul-04 | 24% |
| Road-O-Top | 312 | 0.22 | 68.6 | 14-Aug-03 to 16-Sep-05 | 6 | 10-Nov-04 | 27% |
| Mean | 180 | 0.10 | 20.3 | | | | 34% |

**Fig. 2.** An example of a sediment trap used to measure sediment production rates (Road-O-Top). Fabric floor was used to protect pre-existing road cross-drains and to facilitate the extraction of eroded material.

analyses on individual factors and all possible combinations of two-, three-, and four-way interaction terms.

## 4. Results

### 4.1. Precipitation and PET

A total of 2205 mm of rainfall was recorded between Aug-03 and Sep-05 (Table 2). This total excludes Jun-05 due to vandalism of the rain gauge and lack of data from the Isla Magueyes station. Overall the monitoring period represented a relatively wet period that exceeded average conditions by 28%. Monthly precipitation generally followed the average seasonal trends (Fig. 3). The maximum monthly rainfall recorded in Nov-03 (417 mm) was only the sixth time in 46 years that total rainfall during a particular month has exceeded 400 mm at Isla Magueyes. Rainfall in 2004 was rather unusual in that observations generally exceeded average values during the drier months (Jan–Jul) but were consistently lower during the typically wetter months (Aug–Dec). Overall, rainfall in 2004 was 50 mm short of the long-term average.

A total of 271 individual storms were recorded from Aug-03 through Mar-05 by the automated rain gauge. Fifty-eight percent of these rainfall events individually carried less than 2.5 mm and these were responsible for only 8% of the total registered rainfall (1540 mm) (Fig. 4). Meanwhile, the 18 storms exceeding 20 mm represented 6.6% of the total number of events but 48% of the rainfall.

**Table 2**
Summary of monthly precipitation data collected in La Parguera during the study period.

| Month–year | Observed precipitation (mm) | Maximum 1-h intensities (mm h$^{-1}$) | EI-30 min (MJ ha$^{-1}$ mm h$^{-1}$) | EI-30 min per unit rainfall (MJ ha$^{-1}$ mm h$^{-1}$ per mm rainfall) |
|---|---|---|---|---|
| Aug-03 | 67.82 | 24.1 | 313 | 4.6 |
| Sep-03 | 77.70 | 27.7 | 400 | 5.2 |
| Oct-03 | 111.50 | 17.0 | 357 | 3.2 |
| Nov-03 | 416.60 | 30.5 | 2,828 | 6.8 |
| Dec-03 | 94.50 | 19.8 | 373 | 4.0 |
| Jan-04 | 55.90 | 3.30 | 113 | 2.0 |
| Feb-04 | 54.60 | 10.9 | 142 | 2.6 |
| Mar-04 | 98.30 | 39.9 | 764 | 7.8 |
| Apr-04 | 25.10 | 7.11 | 31 | 1.2 |
| May-04 | 155.70 | 39.4 | 1,230 | 7.9 |
| Jun-04 | 4.60 | 1.02 | 0.83 | 0.18 |
| Jul-04 | 107.20 | 23.9 | 746 | 7.0 |
| Aug-04 | 30.00 | 8.38 | 61 | 2.0 |
| Sep-04 | 64.80 | 5.33 | 63 | 0.97 |
| Oct-04 | 86.40 | 17.3 | 245 | 2.8 |
| Nov-04 | 17.00 | 5.59 | 20 | 1.2 |
| Dec-04 | 10.40 | 2.29 | 5.2 | 0.50 |
| Jan-05 | 51.30 | 15.7 | 124 | 2.4 |
| Feb-05 | 7.40 | 1.78 | 2.1 | 0.29 |
| Mar-05 | 0.50 | 0.25 | 0.02 | 0.05 |
| Apr-05[*] | 114.00 | | | |
| May-05[*] | 287.80 | | | |
| Jun-05 | no data | | | |
| Jul-05[*] | 70.90 | | | |
| Aug-05[*] | 103.90 | | | |
| Sep-05[*] | 90.70 | | | |
| Sum | 2205 | | 7820 | |

[*] Data from Isla Magueyes weather station.

One-hour rainfall intensities reached a maximum of 39 mm h$^{-1}$ during May-04. One-hour rainfall intensities exceeded 25 mm h$^{-1}$ six times between Aug-03 and Mar-05. Thirty-minute erosivity during the period of rainfall intensity monitoring totaled 7,820 MJ ha$^{-1}$ mm h$^{-1}$ for an overall average of 5.1 MJ ha$^{-1}$ mm h$^{-1}$ per mm of rainfall. Larger storms were responsible for most of the rainfall erosivity as storms exceeding 25 mm were responsible for 71% of total (Fig. 4). Storm precipitation showed a strong non-linear correlation with 30-minute erosivity (Fig. 5), further enforcing the important role that large events have in providing energy for erosion relative to smaller storms. Five of the eight events exceeding 45 mm occurred between Oct-03 and Nov-03, while the remaining three were registered between Mar-04 and Jul-04.

Average monthly PET ranges between 102 mm for the relatively milder temperatures typical for the month of January to a high of
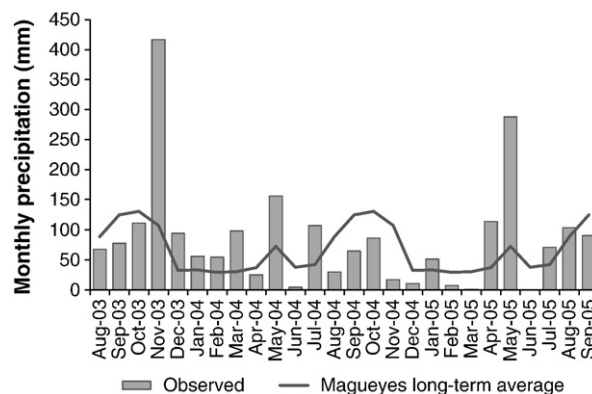


**Fig. 3.** Monthly precipitation at La Parguera during the study period (columns). Gray line shows the long-term average rainfall from the Isla Magueyes weather station (NOAA, 2001).
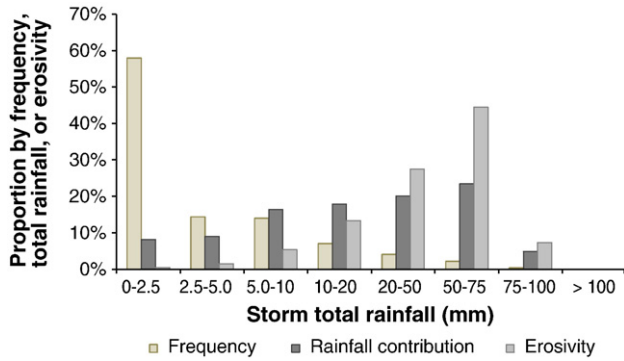
**Fig. 4.** Frequency distribution for varying sized storms observed during the study period (August 2003 to March 2005). Graph also shows the proportion of total rainfall and erosivity contributed by different sized storms (n = 271 rain storms).

**Table 3**
Long-term average monthly potential evapotranspiration (PET), precipitation, and precipitation minus potential evapotranspiration for the Isla Magueyes weather station.

| Month | Average PET (1959–2005) [mm] | Average precipitation (1971–2000)[*] [mm] | Average precipitation – PET [mm] |
|---|---|---|---|
| January | 102 | 33 | −69 |
| February | 107 | 29 | −78 |
| March | 120 | 30 | −90 |
| April | 142 | 37 | −105 |
| May | 166 | 73 | −93 |
| June | 188 | 38 | −150 |
| July | 187 | 42 | −145 |
| August | 182 | 89 | −93 |
| September | 173 | 125 | −48 |
| October | 157 | 131 | −26 |
| November | 131 | 101 | −30 |
| December | 110 | 33 | −77 |
| Total | 1765 | 761 | −1004 |

[*] From NOAA (2001).

188 mm during the peak of the summer in June (Table 3). Annual average PET is 1770 mm and this is just over 1000 mm higher than the mean annual rainfall of 760 mm. Average monthly PET surpasses average precipitation for every month of the year. October is the month when average precipitation most closely approaches PET, but the difference is still in the order of 26 mm.

Differences between monthly precipitation and PET (PPN-PET) ranged from −212 mm (Jun-97) to 426 mm (Oct-85), with an overall average of −83 mm. The PPN-PET timeline shows a tendency for negative values suggesting consistently dry conditions interrupted by brief periods of relatively wetter conditions typically lasting no longer than three months (Fig. 6). The study period represents the first time since Oct-90 in which precipitation exceeded PET by more than 100 mm. While monthly precipitation only barely matched PET ten times since 1993 (Fig. 6), precipitation exceeded PET twice during the study, and was within 50 mm of matching PET a total of five times. Calendar year 2004 signified a return to dry conditions.

### 4.2. Sediment production

Sediment production rates generally showed a poor correlation with total rainfall. Only four of the study sites had a statistically significant correlation between sediment production and total rainfall (Table 4). The average correlation coefficient for road segments with a statistically significant correlation with precipitation was 0.82, while the average value for those lacking a significant correlation was only 0.05. Correlation values between sediment production and total erosivity showed very similar results in that only three out of nine sites yielded statistically significant regressions (p-values<0.05) and high correlation coefficients (Table 4). The 'Road-A-Mid-A' segment
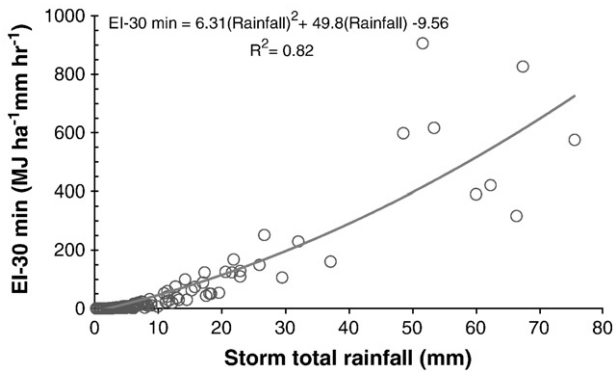
had a very high coefficient of determination but a p-value of 0.069 that was just above the 0.05 significance level.

Even though sediment production was significantly correlated with precipitation for only four of the study sites, data were still normalized by precipitation to estimate erosion rates and to assess the relative effects of slope, plot length, and vegetation cover. The average sediment production rate for the nine study sites was 0.00011 kg m$^{-2}$ per mm of rainfall, or 0.84 Mg ha$^{-1}$ yr$^{-1}$ if we assume an annual rainfall rate of 760 mm yr$^{-1}$.

Erosion rates showed to be related to road steepness. While sediment production rates from a road segment with a 1% slope averaged $5.8 \times 10^{-6}$ kg m$^{-2}$ per mm of rainfall, a road segment with a 22% slope eroded at a rate that was almost two orders of magnitude higher at $3.9 \times 10^{-4}$ kg m$^{-2}$ mm$^{-1}$. Regression analyses show that normalized sediment production was related to slope to the 1.6th power ($R^2 = 0.92$; p = 0.0011) (Fig. 7a). Similarly, regression of erosion rates normalized by erosivity yielded a strongly significant correlation ($R^2 = 0.81$ ; p = 0.0009) with slope to the 1.4th power. Plot length proved to be significantly but rather poorly correlated with sediment production ($R^2 = 0.42$; p = 0.057), but a much stronger relationship was evident between sediment production normalized by rainfall and the plot length-slope (LS$^{1.6}$) product (Fig. 7b) ($R^2 = 0.87$; p = 0.0003).

The average vegetation cover density was 34% with values for individual road segments ranging between 24% and 51%. Average



**Fig. 5.** Relationship between observed rainfall for individual storms against 30-minute rainfall erosivity (EI-30 min) (n = 271 storms).
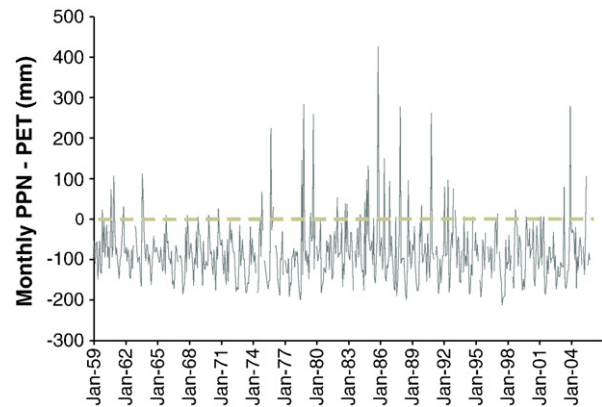


**Fig. 6.** Precipitation (PPN) minus potential evapotranspiration (PET) for the Isla Magueyes weather station (January 1959–September 2005). Horizontal dashed line represents no difference between estimated PET and monthly PPN. Gaps in data correspond to months for which insufficient rainfall data was available to provide an accurate representation of monthly rainfall.

**Table 4**
Coefficient of determination ($R^2$), p-values, and slope coefficients for the relationship between sediment production (kg m$^{-2}$) with total rainfall (mm) and erosivity (MJ ha$^{-1}$ mm h$^{-1}$) for the nine study sites. Significant relationships are shown in bold.

| Plot identification | Versus total rainfall | | | Versus erosivity | | |
|---|---|---|---|---|---|---|
| | Coefficient of determination ($R^2$) | p-value | Slope coefficient (kg m$^{-2}$ mm$^{-1}$) | Coefficient of determination ($R^2$) | p-value | Slope coefficient (kg m$^{-2}$ MJ$^{-1}$ ha mm$^{-1}$ h) |
| Road-A-Low-A | 0.25 | 0.395 | 1.70E-05 | 0.52 | 0.28 | 4.90E-06 |
| Road-A-Low-B | **0.85** | **0.0086** | **1.20E-05** | **0.94** | **0.0063** | **2.30E-06** |
| Road-A-Low-C | **0.93** | **0.033** | **1.00E-05** | **0.99** | **0.041** | **1.80E-06** |
| Road-A-Mid-A | **0.8** | **0.0068** | **4.20E-04** | 0.92 | 0.069 | 8.00E-05 |
| Road-A-Mid-B | 0.06 | 0.69 | −3.10E-05 | 0.31 | 0.44 | −3.30E-05 |
| Road-A-Mid-C | **0.68** | **0.04** | **1.80E-04** | **0.92** | **0.010** | **3.70E-05** |
| Road-A-Top-A | 0.023 | 0.74 | −1.00E-05 | 0.01 | 0.82 | −1.40E-06 |
| Road-A-Top-B | 0.0011 | 0.94 | 2.40E-06 | 0.03 | 0.72 | 2.50E-06 |
| Road-O-Top | 0.18 | 0.40 | 2.90E-04 | 0.56 | 0.14 | 1.10E-04 |
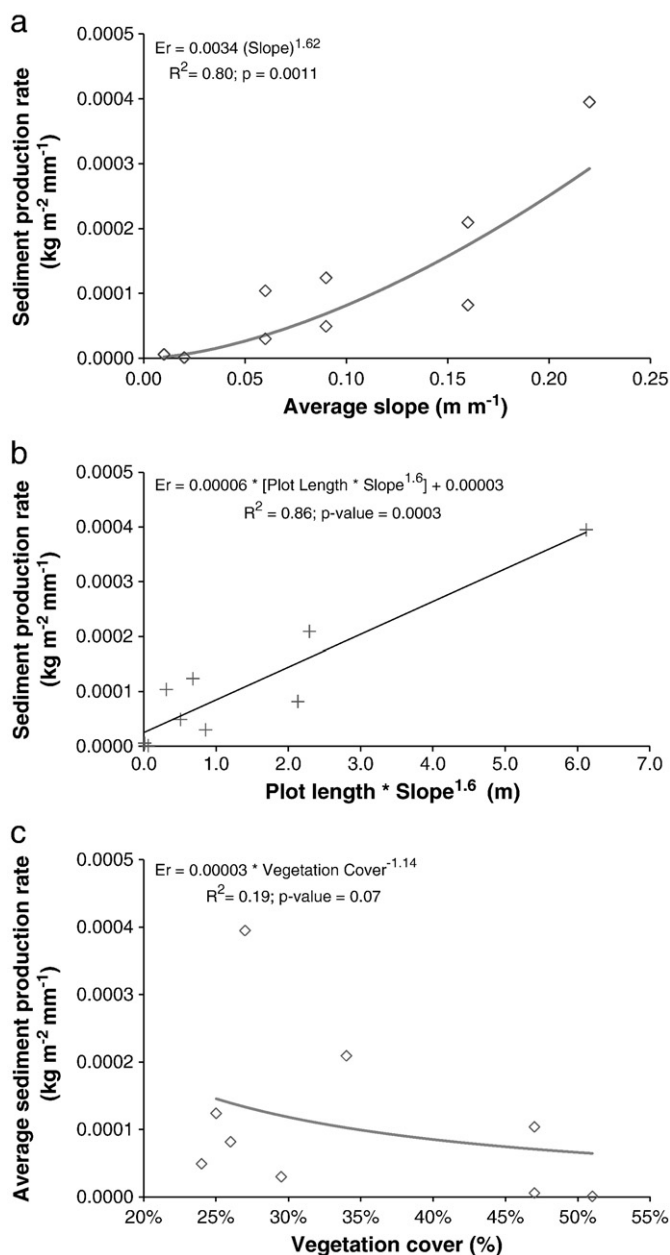


**Fig. 7.** a. Relationship between average sediment production ($E_r$) and average slope for the nine monitored unpaved roads. b. Relationship between average sediment production ($E_r$) and the Length*Slope$^{1.6}$ product for the nine monitored unpaved roads. c. Relationship between average sediment production ($E_r$) and vegetation cover for the nine monitored unpaved roads.

normalized erosion rates showed a weak, inverse, non-linear correlation with vegetation cover density ($R^2 = 0.19$; p-value = 0.07) (Fig. 7c). Correlation with erosion rates normalized by slope and erosivity yielded similar results. The weakness of this relationship is attributed to the fact that vegetation cover was assessed only once and therefore did not account for the observed trend of increased vegetation cover. Nevertheless, vegetation cover density was still included among the various significant interaction terms selected by stepwise multiple linear regression analyses (Table 5).

Sediment production rates – normalized by area, slope, and rainfall or erosivity – showed a consistent decline as time progressed during the study period (Fig. 8a and b) to levels that were on average only one-tenth of the rates measured at the onset of the study. In order to evaluate the cause of declining erosion rates, the data was sorted into two periods. Period 1 consists of all data collected from Aug-03 through Apr-04 and Period 2 refers to observations made from May-04 through Sep-05. The average normalized sediment production rate for Period 1 (n = 19) was 0.024 kg m$^{-2}$ cm$^{-1}$ m m$^{-1}$, or almost a full order of magnitude higher than the 0.0031 kg m$^{-2}$ cm$^{-1}$ m m$^{-1}$ for Period 2 (n = 33). These differences are statistically significant (T-Test, p-value = 0.03) [Table 6]. Erosion rates normalized by erosivity showed a similar one-order difference in sediment production rates between Periods 1 and 2.

The progressive decline in erosion rates aids to explain the general weakness of the correlation between sediment production and rainfall (or erosivity) for individual road segments (Table 4). Visual inspection of the relationships between sediment production and rainfall shows that the strength of the correlation depends on the timing and magnitude of measurements. Only road segments for which the maximum total rainfall value corresponds to a trap measurement collected during Period 1 (when erosion rates were still high) end up displaying strong relationships due to the influence of these points in defining correlation parameters.

Stepwise, multiple regression analyses based on independent factors and all possible combinations of two- to four-way interaction terms showed that some factors containing *Period* as a binary categorical variable proved to be statistically significant (Table 5). *Period* was included in three out of four significant regression parameters when all independent variables and possible interactions were regressed against sediment production. Plot length, slope, and rainfall are the other factors included as significant regression parameters. Meanwhile, only a pair of two-way interaction terms proved significant when regressed against sediment production when erosivity substituted rainfall, and *Period* is included in one of those two.

Rainfall erosivity patterns during Periods 1 and 2 were compared against each other to better understand the observed declines in sediment production rates. It should be noted that while rainfall intensity data was collected for the entirety of Period 1, it was only collected until 30-Mar-05 during Period 2. There were 136 storms

**Table 5**
Summary results of stepwise multiple regression analyses between sediment production in kg m$^{-2}$ and various independent factors and their interaction terms. Independent factors included rainfall [$R$; in mm], erosivity [$E$; in MJ ha$^{-1}$ mm h$^{-1}$], plot length [$L$; in meters], slope [$S$; as a decimal], vegetation cover density [$V$; in percent], and period [$P$; binary categorical variable representing Period 1 (value = 1) and Period 2 (value = 0)].

| | Factors with statistical significance (p<0.05) | | | | | | |
| Independent factors | Single | Two-way | Three-way | Four-way | Sample size | R$^2$ | p-value |
|---|---|---|---|---|---|---|---|
| $R$, $L$, $S^{1.6}$, $V$, and all 2-, 3-, 4-way interaction terms | – | – | $R*S^{1.6}*V$ | – | 52 | 0.42 | <0.0001 |
| $E$, $L$, $S^{1.6}$, $V$, and all 2-, 3-, 4-way interaction terms | $S^{1.4}$ | – | $E*S^{1.4}*V$ | $E*L*S^{1.4}*V$ | 43 | 0.71 | <0.0001 |
| $R$, $L$, $S^{1.4}$, $P$, and all 2-, 3-, and 4-way interaction terms | – | $R*S^{1.6}$, $S^{1.6}*P$ | $R*L*S^{1.6}$ | $R*L*S^{1.6}*P$ | 52 | 0.74 | <0.0001 |
| $E$, $L$, $S^{1.4}$, $P$, and all 2-, 3-, and 4-way interaction terms | – | $E*S^{1.4}$, $S^{1.4}*P$ | – | – | 43 | 0.79 | <0.0001 |
| $R$, $L$, $S^{1.6}$, and all 2- and 3-way interaction terms [only using Period 1 data] | – | – | $R*S^{1.6}*L$ | NA | 19 | 0.77 | <0.0001 |
| $R$, $L$, $S$, and all 2- and 3-way interaction terms [only using Period 2 data] | $R$ | – | – | NA | 33 | 0.24 | 0.0034 |
| $E$, $L$, $S^{1.6}$, and all 2- and 3-way interaction terms [only using Period 1 data] | $S^{1.6}$ | – | $E*S^{1.6}*L$ | NA | 19 | 0.81 | <0.0001 |
| $E$, $L$, $S^{1.4}$, and all 2- and 3-way interaction terms [only using Period 2 data] | $E$ | – | None | NA | 24 | 0.82 | <0.0001 |

carrying 1002 mm during Period 1, for an average of 7.4 mm per storm (Table 6). Total 30-minute erosivity for this period was 5320 MJ ha$^{-1}$ mm h$^{-1}$ for an overall average of 5.3 MJ ha$^{-1}$ mm h$^{-1}$ per mm of rainfall. Total observed rainfall during the 135 individual storms in Period 2 was 536 mm (Table 6). The overall average rainfall per event during Period 2 was 3.9 mm or only slightly more than half of that for Period 1, which indicates that Period 2 had a relatively higher frequency of smaller events. Total 30-minute erosivity for the latter period was 2500 MJ ha$^{-1}$ mm h$^{-1}$ for an average of 4.7 MJ ha$^{-1}$ mm h$^{-1}$ per mm of rainfall, or only 12% lower than Period 1.

Further analyses show important differences in the temporal distribution of rainfall patterns between the two periods. The amount of erosivity contributed by events smaller than 10 mm was very similar for both periods, but total erosivity derived from 10–50 mm storms in Period 1 was 3.6 times higher than for Period 2 (2508 and 686 MJ ha$^{-1}$ mm h$^{-1}$, respectively) [Fig. 9]. In addition, 10–50 mm storms were responsible for 47% of the erosivity that occurred during Period 1, while similar magnitude storms represented only 27% of the erosivity during Period 2. Period 1 also contained five storms exceeding 50 mm in total rainfall, while Period 2 only registered two events exceeding 50 mm, and these two were responsible for 61% of total erosivity. What is most important for the purposes of explaining the declining sediment production rates is that while erosivity during Period 1 was well-distributed throughout the period, the two storms responsible for most of the erosivity during Period 2 occurred in May-04 and Jul-04 or during its early stages. Therefore, the lack of high erosivity values following Aug-04 may be in part responsible for lower erosion rates during the latter stages of the study.

Differences in vegetation cover density also might have contributed to the observed decline in sediment production. Visual comparisons of vegetation cover between the initial stages of Period 1 against those during Period 2 (Fig. 10a and b) demonstrate a substantial increase in cover density as time progressed through the study period. This cover represents the early colonization stages of shrubland vegetation characterized by low-lying grasses and herbaceous plants. Unfortunately, vegetation cover assessments were collected only once and during the initial to mid-stages of Period 2 (Table 1).

### 4.3. Particle-size distribution analyses

The surface texture of the five unpaved road segments from which samples were collected was dominated by gravel and coarse rock fragments. The average percent of gravel and coarser-sized particles (>2.0 mm) on the surface of these road segments was 71%, while sand (0.065–2.0 mm) and silt- and clay-sized materials (<0.065 mm) only represented 24% and 5%, respectively (Table 7). The median particle size ($D_{50}$) was 3.0 mm or fine gravel, and the 16th ($D_{16}$) and 84th ($D_{84}$) percentiles were 0.18 mm and 15 mm, respectively. The particle-size distribution data corroborate visual observations of surfaces being armored by coarse particles. Particles larger than 12.5 mm, which may be expected to resist the effects of rainsplash erosion, represent on average about 40% of the surface material. Due to the limited sample size no analyses was attempted to evaluate the role of texture on sediment production.

In contrast, material collected in sediment traps was dominated by sand-sized particles. The mass-weighed average percent of sand in sediment trap samples was 71%, while gravel and the silt-clay fraction
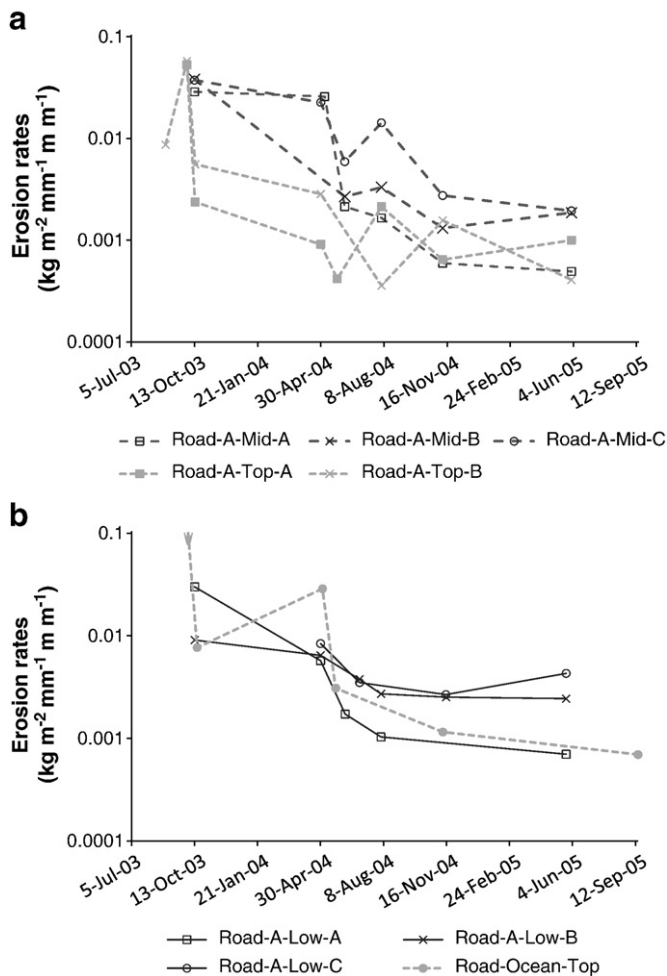


**Fig. 8.** a. Time trends in sediment production rates (E$_r$) – normalized by source area, precipitation, and slope – for five of the nine monitored unpaved roads. b. Time trends in sediment production rates (Er) – normalized by source area, precipitation, and slope – for four of the nine monitored unpaved roads.

**Table 6**
Summary of rainfall, erosivity, and sediment production data for Period 1 (August 2003–April 2004) and Period 2 (May 2004–March 2005).

| | Dates | Number of storms | Total rainfall (mm) | Average rainfall per storm (mm) | Total erosivity (MJ ha$^{-1}$ mm h$^{-1}$) | Erosivity per unit rainfall (MJ ha$^{-1}$ mm h$^{-1}$ mm$^{-1}$) | Erosion rate normalized by rainfall (kg m$^{-2}$ m m$^{-1}$ mm$^{-1}$) | Erosion rate normalized by erosivity (kg m$^{-2}$ MJ$^{-1}$ ha mm$^{-1}$ h) |
|---|---|---|---|---|---|---|---|---|
| Period 1 | 1-Aug-03 to 30-Apr-04 | 136 | 1002 | 7.37 | 5,322 | 5.3 | 0.0024 | 0.0052 |
| Period 2 | 1-May-04 to 31-Mar-05 | 135 | 536 | 3.97 | 2,498 | 4.7 | 0.00031 | 0.00052 |

represented 22% and 7%, respectively (Table 7). The median size (D$_{50}$) of the eroded material was 0.3 mm or medium sand. Sand content varied from 55% to just above 80% on individual sediment traps, while gravel ranged between 6% and 46%. The silt-clay fraction also showed a broad range from 1% to almost 40%. In comparison with surface texture, eroded material was enriched with sand, while the finer silt- and clay-sizes eroded at a proportion similar to that at which they are represented on the surface. Due to the limited number of samples no further analyses was done to evaluate the relationship between factors controlling erosion and the texture of the eroded material.

## 5. Discussion

### 5.1. Annual erosion rates and comparisons with previous studies

The overall average sediment production rate – normalized by area, rainfall, and slope – from the nine disturbed study sites was 0.0010 kg m$^{-2}$ mm$^{-1}$ m m$^{-1}$. Based upon a 760 mm yr$^{-1}$ rainfall rate this average erosion rate yields annual erosion estimates ranging over two orders of magnitude from 0.036 to 3.9 Mg ha$^{-1}$ yr$^{-1}$ for roads with 1% and 22% slopes, respectively.

Sediment production rates from currently undisturbed hillslopes covered by secondary forests were also measured in La Parguera between Aug-03 and Jun-05 (Ramos-Scharrón, 2006). Observed rates averaged 0.00033 Mg ha$^{-1}$ mm$^{-1}$ m m$^{-1}$ (Ramos-Scharrón, 2007), and this translates into annual erosion rates of 0.0025 to 0.055 Mg ha$^{-1}$ yr$^{-1}$ for 1% and 22% slopes, respectively (Fig. 11). Therefore, results demonstrate that sediment production rates on roaded surfaces in La Parguera are 15–50 times higher than analogous undisturbed surfaces.

Observed sediment production rates during the initial nine months of the study period (Period 1) were 0.024 Mg ha$^{-1}$ mm$^{-1}$ m m$^{-1}$, or almost an order of magnitude higher than the 0.0031 Mg ha$^{-1}$ mm$^{-1}$ m m$^{-1}$ average measured during the remaining 13–16 months

(Period 2). If we assume both a linear relationship between erosion and slope and an annual rainfall rate of 760 mm yr$^{-1}$, it is possible to extrapolate these measurements into annual rates. Annual rates based on Period 1 data equal 0.18 and 4.0 Mg ha$^{-1}$ yr$^{-1}$ for surfaces with 1% and 22% slopes, respectively (Fig. 11). Annual rates for homologous surfaces based on Period 2 rates are 0.024 to 0.52 Mg ha$^{-1}$ yr$^{-1}$, or only 13% of those for Period 1. These sediment production rates are within the low to moderate range of worldwide road erosion values reported in the literature (0.03–1000 Mg ha$^{-1}$ yr$^{-1}$; summarized by Ramos-Scharrón and MacDonald, 2005) and this is attributed to lack of traffic, abundant vegetation cover, and armored condition.

Additional erosion measurements on freshly-disturbed surfaces were collected at La Parguera between Jul-06 and Jun-07 from 3 m$^2$ erosion plots. Observed erosion rates ranged from 3.2 to 41 Mg ha$^{-1}$ yr$^{-1}$ (Ramos-Scharrón and Rodríguez-Benítez, 2008), and these are 10–18 times higher than those measured during Period 1 of this study (Fig. 11). The higher erosion rates of the follow-up study are in part due to a lower vegetation cover and a higher content of easily erodible fine sediment on the freshly-disturbed surfaces relative to the progressively vegetated and highly armored surfaces that typified the study described by this article.

Previous work on erosion from unpaved roads has been conducted on the nearby island of St. John, U.S. Virgin Islands (Ramos-Scharrón, 2004). Erosion rates from unpaved roads on St. John were found to be controlled in part by the frequency of road maintenance (i.e., blading). Road maintenance was therefore classified into three categories: graded at least once every two years, ungraded for more than two years, and abandoned for 15 years (Ramos-Scharrón and MacDonald, 2007b). Annual erosion rates for graded and ungraded roads with 1% and 22% slopes on St. John were between 5 and 140 times higher than those observed during Period 1 in La Parguera and up to three-orders of magnitude higher than Period 2 (Fig. 11). While some of this disparity can be attributed to higher rainfall rates on St. John, a 51% difference in annual rainfall alone cannot explain such great discrepancy. Most of the difference may be then credited to the effects of vehicle traffic and maintenance activities on St. John in limiting vegetation growth and supplying material to prolong unarmored road surface conditions (MacDonald et al., 2001; Ramos-Scharrón and MacDonald, 2005).

Average erosion rates from abandoned roads with 1–22% slopes on St. John ranged from 0.9 to 20 Mg ha$^{-1}$ yr$^{-1}$, respectively (Ramos-Scharrón and MacDonald, 2005) (Fig. 11). These rates are 5 times higher than those observed for Period 1 in La Parguera, and 38 times higher than those observed for Period 2. Even when accounting for the 51% higher annual rainfall rate, erosion rates from abandoned roads on St. John would still be 3–25 times higher (0.6–13 Mg ha$^{-1}$ yr$^{-1}$) than those observed during both measurement periods in La Parguera. It should be noted that measured rates in St. John contain a period of prolonged rainfall associated to a tropical storm (Hurricane Lenny, Nov-99) that included a one hour period with an intensity of 47 mm h$^{-1}$, and induced erosion rates that were 5000 percent higher than during the rest of the study period (Ramos-Scharrón and MacDonald, 2005). No analogous rainfall event to that one occurred on La Parguera during the 2003–2005 monitoring period. Therefore, if the abandoned road erosion measurements taken in St. John during this storm are discarded, average
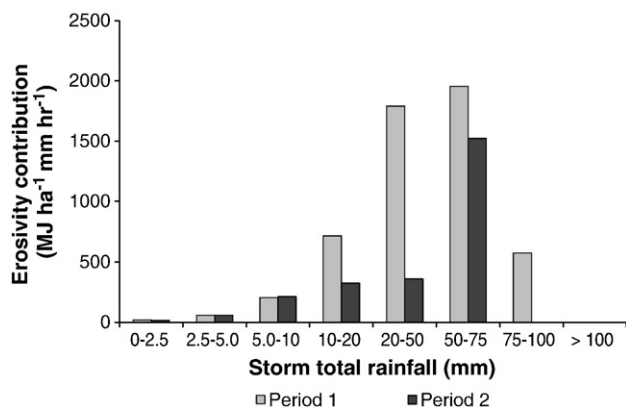
**Fig. 9.** Total rainfall erosivity contribution for storms of various sizes. Period 1 incorporates data collected between 1-Aug-03 and 30-Apr-04, while Period 2 contains data from May-04 through Mar-05. No erosivity estimates were calculated for Apr-05 to Sep-05 due to the lack of the required rainfall intensity data.

a

b



**Fig. 10.** a. Picture of Road-A-Top-A during the initial portions of the study (Period 1). b. Picture of Road-A-Top-A during the latter portions of the study (Period 2).

sediment production rates drop by a full order of magnitude to 0.07–1.5 Mg ha$^{-1}$ yr$^{-1}$, and these are within the range of values measured for abandoned roads in La Parguera.

**Table 7**
Mass-weighed mean particle sizes and percentages for road-segment surface and sediment trap samples.

| Plot Id | D16 (mm) | D50 (mm) | D84 (mm) | Silt and clay (%) | Sand (%) | Gravel (%) |
|---|---|---|---|---|---|---|
| *Road surface* | | | | | | |
| R-A-Mid-A | 0.10 | 15 | 18 | 7.8 | 19 | 73 |
| R-A-Mid-B | 0.08 | 2.8 | 16 | 9.1 | 27 | 64 |
| R-A-Mid-C | 0.12 | 2.1 | 15 | 5.4 | 24 | 71 |
| R-A-Top-A | 0.70 | 3.0 | 13 | 2.1 | 16 | 82 |
| R-A-Top-B | 0.20 | 1.8 | 15 | 2.8 | 35 | 62 |
| Average | 0.18 | 3.0 | 15 | 5.0 | 24 | 71 |
| | | | | | | |
| *Sediment traps* | | | | | | |
| R-A-Low-A | 0.04 | 0.07 | 0.50 | 39 | 55 | 6.0 |
| R-A-Low-B | 0.09 | 0.50 | 1.30 | 0.9 | 80 | 19 |
| R-A-Mid-A | 0.08 | 0.23 | 1.00 | 2.7 | 82 | 16 |
| R-A-Mid-B | 0.14 | 0.85 | 1.30 | 0.4 | 53 | 46 |
| R-A-Mid-C | 0.10 | 0.51 | 2.45 | 1.8 | 69 | 29 |
| R-A-Top-A | 0.09 | 0.38 | 2.29 | 9.3 | 64 | 27 |
| R-A-Top-B | 0.08 | 0.27 | 1.94 | 19 | 54 | 26 |
| R-Ocean-Top | 0.07 | 0.22 | 1.45 | 4.8 | 78 | 17 |
| Average | 0.07 | 0.30 | 1.70 | 7.0 | 71 | 22 |

### 5.2. Factors controlling erosion rates

Observed sediment production rates in La Parguera show a general decline as time progressed throughout the study (Fig. 8a and b) and
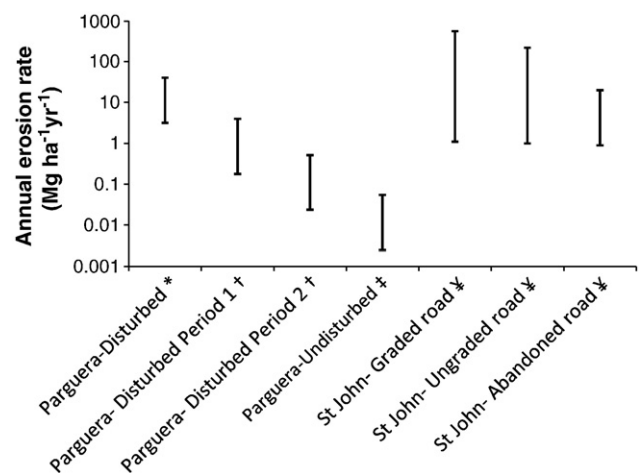


**Fig. 11.** Sediment production rates measured as part of this study in La Parguera as compared to a follow-up study in La Parguera and previous studies in St. John-US Virgin Islands. [* represents Ramos-Scharrón and Rodríguez-Benítez, 2008; † refers to this study; ‡ is for Ramos-Scharrón, 2007; and ¥ stands for Ramos-Scharrón and MacDonald, 2005].

this is interpreted as an indicator of changes in the relationship between erosion and its controlling factors. Lower sediment production rates during the latter stages of the study were associated to lower rainfall intensities (i.e., lower erosivity per unit cm of rainfall — see Table 6), which implies a reduced efficiency of rainfall in generating sediment relative to the initial phases of the monitoring period. The lack of rainfall intensity data to match measurements taken after Mar-05, preclude a more assertive statement about its role in controlling the observed erosion rates.

Changes in vegetation cover also might have played a role in declining sediment production. Although temporally-distributed quantitative data on vegetation cover are lacking in this study, field observations suggest that low-lying grasses and herbaceous plants could have played a dominant role in not only affecting sediment production rates, but also in the quantitative relationships between sediment production and other factors controlling erosion. Among some of the reasons why vegetation interferes with erosion processes are that vegetation provides a protective cover from the effects of rainsplash (Smith and Wischmeier, 1962; Casermeiro et al., 2004), and improves soil organic content which promotes rainfall interception (Walsh and Voigt, 1977).

Vegetation may also alter hydraulic properties of the eroding surface and thus interfere with infiltration and overland flow dynamics. Well-vegetated hillslopes rarely generate overland flow by excess precipitation due to high infiltration capacities (Prosser et al., 1995; Mohammad and Adam, 2010). The addition of vegetation to a barren and highly compact surface such as an unpaved road, may improve infiltration rates by increasing the number, size, and connectivity of macro-pores, and by increasing the area covered by highly permeable vegetated patches (Lavee et al., 1995; Vásquez-Méndez et al., 2010).

Changes in infiltration are likely to induce alterations in the frequency and magnitude of overland flow and thus erosion rates. Overland flow rates are directly proportional to the product of precipitation excess times source area (Ramos-Scharrón and MacDonald, 2005):

$$Q_i(t) = [P(t) - I(t)]A \qquad (1)$$

where $Q_i(t)$ is flow rate, $P(t)$ is precipitation intensity, $I(t)$ is infiltration rate, and $A$ is source area. It follows from Eq. (1) that any increase in infiltration rate requires higher precipitation rates or a larger source area to generate the same amount of runoff. This can have important implications on erosion rates because flow depth is a key factor controlling the shear stress applied by flowing water ($\tau$), and erosion rate ($E_r$) is dependent on the difference between the applied shear stress ($\tau$) and that required to mobilize sediment ($\tau_c$):

$$\tau = \rho_w g h s \qquad (2)$$

$$E_r \propto k(\tau - \tau_c)^n \qquad (3)$$

where $\rho_w$ is the density of water, $g$ is the acceleration due to gravity, $h$ is the depth of flow, $s$ is the water surface slope (Julien, 1995), $k$ is an index of the erodibility of the sediment, and $n$ is an exponent between 1 and 2 (Kirkby, 1980).

Eq. (1) shows that when controlling for precipitation, a systematic increase in infiltration rates by, for example, an increase in vegetation cover is likely to change the relationship between source area and flow depth. Since flow depth is an important factor controlling the shear stress of overland flow (Eq. (2)), it follows that an increase in infiltration rates can also alter the relationship between source area (or plot length) and erosion rates. Vegetation cover can also alter erosion rates by serving as a recipient for most of the shear stress that otherwise would be applied by flowing water to barren surfaces (Prosser et al., 1995).

Addition of a vegetative cover can also interfere with overland flow by increasing surface roughness which promotes infiltration on

highly permeable patches (Lavee et al., 1995), increases depressional storage (Huang and Bradford, 1990), and reduces flow velocities (Siepel et al., 2002). Flow velocity exerts an important control on the shear stress applied by water flowing over a surface, and even though a reduction in velocity is likely complemented by deeper flows, the net effect of roughness is to reduce shear stress (Siepel et al., 2002). Although flow velocity is not explicitly included in shear stress equations such as Eq. (2), its effect is implied by the inclusion of slope. Therefore, alterations to surface roughness caused by growth of a vegetative cover are likely to change the relationship between slope and the tractive forces applied by flowing water, and thus alter the relation between slope and erosion.

Previous studies have used the product of plot length (or source area) times slope raised to an exponent between 1 and 2 ($LS^n$) as a surrogate value for the tractive forces applied by overland flow. These studies have proven $LS^n$ as an important factor controlling erosion rates from unpaved roads (e.g., Anderson and MacDonald, 1998; Luce and Black, 1999; Ramos-Scharrón and MacDonald, 2005). Similarly, plot summary data collected from La Parguera over the entire monitoring period (n = 9 plots) show strong relationships between sediment production and both $Slope^n$ and the $LS^n$ product (Fig. 7a and b). An important difference in these relationships is evident when this data is discriminated between Period 1 and Period 2. Whereas Period 1 shows similar or even stronger correlations between $Slope^n$ and $LS^n$ with sediment production than those based on the entire monitoring period, correlations significantly weaken for data collected during Period 2 (Figs. 7a,b and 12a,b). Summary data and simple regression
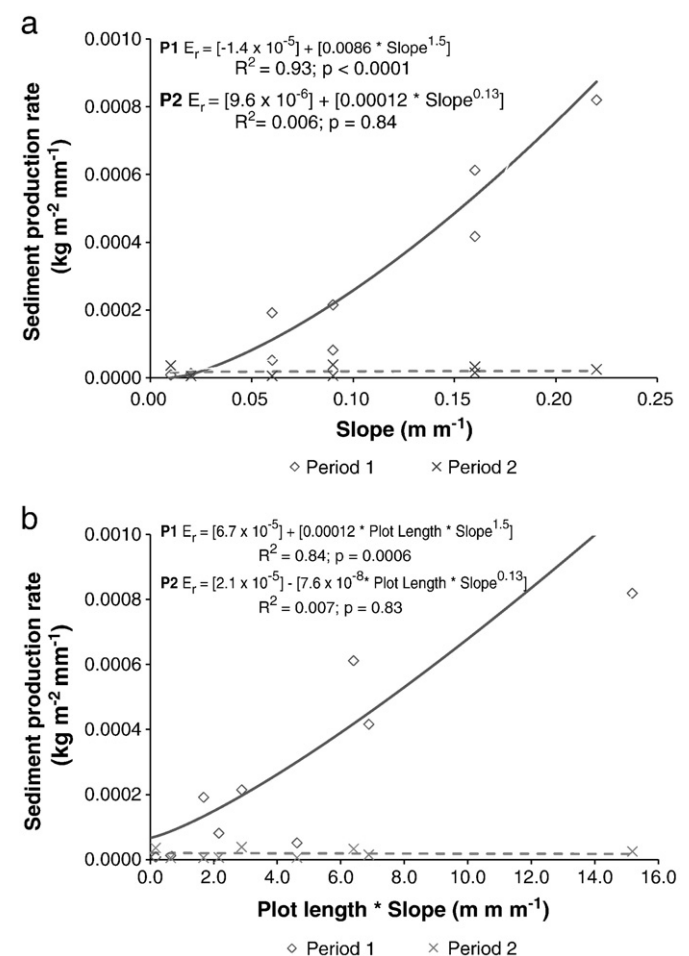


Fig. 12. a. Relationship between average sediment production rates – normalized by source area and rainfall – and slope for Period 1 and Period 2. b. Relationship between average sediment production rates – normalized by source area and rainfall – and the Area*Slope factor for Period 1 and Period 2.

analyses imply that the magnitude and relative proportion of the reduction in sediment production rates between the two study periods is larger for roads with high $Slope^n$ and $LS^n$ values than for shorter or more gently sloping roads.

These results become evident with multiple regression analyses using the entire dataset ($n = 52$). While three-way interaction terms that incorporate rainfall (or erosivity), plot length, and slope are strongly significant and yield high correlation coefficients for Period 1, only rainfall (or erosivity) show to be significant for Period 2 (Table 5). These findings suggest the need to incorporate multiple interaction terms that include rainfall, erosivity, slope, plot length, and presumably vegetation cover in any attempt to develop empirical models to predict erosion rates from abandoned disturbed surfaces.

These findings are interpreted to suggest that stable surface hydraulic conditions characterized Period 1 and this allowed a constancy in the relationships between erosion rates and both $Slope^n$ and $LS^n$. Meanwhile, Period 2 was characterized by the growth of vegetation which might have continuously altered the hydraulic properties of the eroding surfaces and lead to inconsistent relationships between sediment production with both $Slope^n$ and $LS^n$. The collapse of $LS^n$ as a significant factor controlling unpaved road erosion rates as vegetation cover increases has also been observed in the Oregon Coast Range area of the U.S. (Luce and Black, 2001a). The notable difference in rainfall intensity and erosivity between the initial stages of Period 2 relative to its latter stages might have also contributed to the poor correlations.

### 5.3. Time trends in sediment production rates

A declining trend in sediment production rates following disturbance of unpaved road surfaces is evident when the current dataset is matched by a follow-up study in the La Parguera area. Erosion rates from freshly-disturbed, unvegetated, and unarmored surfaces (Ramos-Scharrón and Rodríguez-Benítez, 2008) are higher than those from the abandoned road segments in this study, and these rates in turn are higher than those from undisturbed hillslopes (Ramos-Scharrón, 2007) (Fig. 11). This is very similar to data trends presented in several previous studies which show peak rates occurring immediately following mechanical disturbance by construction or maintenance activities (i.e., blading) and a subsequent transition to natural background rates (e.g., Megahan, 1974; Luce and Black, 2001b). High erodibility typical of the initial period following disturbance is due to the lack of vegetation or stone cover to protect surfaces from rainsplash and overland flow (Megahan and Kidd, 1972; Megahan et al., 1986; Ziegler et al., 2001).

Although the application of existing variable erodibility models (e.g., Megahan, 1974) can mimic the general declining monthly trends in sediment production rates observed at La Parguera (Fig. 8a and b), these models only address reductions in erosion rates based exclusively on the loss of easily erodible material as a proxy for sediment availability or surface armoring. However, these model structures lack explicit parameters to adequately characterize changes in erosion rates that result from varying rainfall erosivity or changes in vegetation cover. Although vegetation cover and variations in rainfall erosivity might not be as important as other factors in controlling erosion rates from active roads, data described here indicates that these two factors may play a primary role on abandoned road surfaces.

About 7–10 years had elapsed since the nine monitored road segments had been last disturbed by regrading. In addition, all sites were either intentionally blocked from vehicle access with gates and boulders or unintentionally by unrepaired gullying on access roads. Therefore, the lack of any recent maintenance or traffic activity led to the qualitative characterization of the nine monitored segments as abandoned roads with a moderately armored surface and poor vegetation cover.

Locally-collected precipitation data and potential evapotranspiration estimates based on the Thornthwaite method suggest a general moisture deficit during the last ten years prior to the start of the monitoring period (Fig. 6). The poor re-establishment of a vegetation cover at the beginning of this study is attributed to the lack of sufficient moisture to allow germination and sustain new vegetation. The average annual rainfall between 1993 and 2002 was 660 mm yr$^{-1}$ or 13% lower than the long-term average. Vegetation began to colonize the abandoned road surfaces only after the Nov-03 storms, which brought 417 mm of precipitation.

The lack of vehicular traffic, maintenance activities, or any other type of mechanical disturbance should allow for the re-establishment of vegetation once roads are abandoned (Foltz et al., 2009). However, the moisture deficit that typifies conditions throughout most of the year in La Parguera (Table 3; Fig. 6), and in any other in semi-arid and dry sub-tropical setting, appears to be a limiting factor that precludes early succession on disturbed surfaces. Under the conditions observed in La Parguera, rainfall plays a paradoxical role in controlling erosion rates on abandoned roads. While ample rainfall is needed to generate the peak erosion rates following disturbance, once rainfall provides sufficient soil moisture to allow vegetation recovery then it may also contribute to declining sediment production rates. Therefore, any approach that intends to properly model the decline in erosion rates occurring on abandoned roads where moisture availability is a limiting factor must explicitly incorporate algorithms to address the effects of both surface armoring and re-vegetation.

## 6. Conclusion

Sediment production from nine abandoned road segments with varying slopes and contributing areas were measured with sediment traps in La Parguera, southwestern Puerto Rico, from Aug-03 to Sep-05. The observed average sediment production rate was 0.00011 kg m$^{-2}$ mm$^{-1}$, or 0.84 Mg ha$^{-1}$ yr$^{-1}$. These rates are 15–50 times higher than locally-measured natural erosion rates. The highest erosion rates were observed during the earlier portions of the study period and were generally associated with the steepest and longest road segments. Sediment production was found to be dependent on two- and three-way interaction terms containing slope raised to the 1.6th power, plot length, and rainfall (or erosivity).

Sediment production rates for individual road segments showed a steep decline as time progressed during the study period that amounted to a statistically significant one-order of magnitude difference between observations made during the early stages of monitoring (Period 1) to those taken during the latter parts of the study (Period 2). Differences in sediment production rates between the two periods are attributed to more intense rainfall patterns during Period 1 and to a notably higher vegetation cover during Period 2.

In a sub-tropical semi-arid to dry climatic region like La Parguera, rainfall appears to play a paradoxical role in controlling surface erosion rates on abandoned road surfaces. While ample rainfall is needed to generate erosion by rainsplash and overland flow, it appears that once rainfall satisfies the soil moisture required for vegetation recovery it also may contribute to declining sediment production rates. Therefore, any model that attempts to properly address the temporal variation in erosion rates occurring on abandoned roads in a climatic setting where moisture availability is a limiting factor must not only follow the more traditional surface armoring-based approach but must also integrate the effects of re-vegetation. Such types of models will eventually become useful tools to properly assess the effects of past, current, and future land use patterns on erosion rates, and to improve mitigation and land development strategies that lessen the impact on important marine habitats of Puerto Rico and the rest of the Caribbean.

## Acknowledgements

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