Land disturbance effects of roads in runoff and sediment production on dry-tropical settings

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Abstract

Accelerated soil loss due to human land use is still one the most critical environmental problems as it can degrade both soils and downstream resources. Major gaps still exist in our knowledge of erosion, particularly in the dry tropics that make up about a fourth of the world's tropical landmass. The Insular Caribbean presents a particular need because erosion here has deleterious effects on soils, nearshore coral reefs, and their associated myriad of ecosystem services. Through plot-scale monitoring of runoff and sediment production over an eleven-month period, this study quantified the impacts of land disturbance on runoff development and sediment production relative to background rates on disturbed surfaces (i.e., roads) in a dry tropical area of Puerto Rico. Results demonstrate that unpaved road surfaces have the potential to generate runoff two to three-and-a-half times more frequently than under natural conditions and that they can produce sediment at rates that are between six to two-hundred times greater than background. These results suggest that

land development in small dry-tropical coastal watersheds can potentially induce an increase in the frequency of runoff and sediment delivery into coastal waters even when a relatively small percentage of the land is disturbed. Soil formation simply cannot keep up with accelerated erosion, which implies a net exhaustion of the soil mantle and a decay of the ecological services it provides. Offsetting these soil losses will require implementing proven conservation practices to protect soils and coral reef ecosystems in this and other dry tropical settings.

Keywords: dry tropics, coral reefs, sustainable soil erosion, shrubland, deciduous forest

1. Introduction

1.1 Background

Evaluating whether human-induced alterations of Earth’s biogeochemical processes merit naming a new geologic epoch after ourselves is still a contentious topic (Lewis and Maslim, 2015; Monastersky, 2015; Syvitski and Kettner, 2011; Zalasiewicz et al., 2011). Global evidence for a new geologic epoch can only be assembled by leveraging many local case studies. Nevertheless, such local-scale assessments of human-induced changes are relevant in themselves because they show the diverse range of global patterns (Caro et al., 2011; Edgeworth et al., 2015) at scales that humans can better manage impacts (Biermann et al., 2016; Messina and Biggs, 2016). Globally, sediment yield rates to the Earth’s oceans peaked prior to the 1950s before the proliferation of dams (Walling and Fang, 2003). However, the geologic record of the Insular Caribbean suggests that sediment accumulation rates on insular shelves actually accelerated during the 20th century and have remained high until the present(Bégin et al., 2014; Brooks et al., 2015; Lane et al., 2013; Ryan-Mishkin et al., 2009).

Heightened sediment delivery rates represent a critical source of stress to coral reef systems worldwide (McLaughlin et al., 2003; Risk, 2014), and the Insular Caribbean is no exception. Even though coral reefs of the Caribbean are affected by hurricanes (Gardner et al., 2005), mortality of reef grazing species (e.g., sea urchins) (Knowlton, 2001), overfishing (Jackson et al., 2014), and thermal-induced bleaching and disease (Eakin et al., 2010) the delivery of terrestrial sediments to coastal waters is still considered a key regional stressor (Appeldoorn et al., 2009; Mora, 2008; Paris and Chérubin, 2008; Restrepo et al., 2016). Curtailing sediment yields to coral bearing waters of the Caribbean, and particularly Puerto Rico (PR), remains a key management priority (Ballantine et al., 2008; Commonwealth of PR and NOAA, 2010; Larsen and Webb, 2009; Torres, 2001).

As a response to shifts in PR's economic model, the island underwent drastic land cover changes throughout the 20th and early 21st centuries (Martinuzzi et al., 2007; Ramos-Scharrón et al., 2015). The effects of land use in runoff and sediment yields have been evaluated locally through both empirical evidence and model application (e.g., Cruise and Miller, 1993; Ramos-Scharrón and Thomaz, 2016). In addition, studies have documented the consequences of heightened erosion associated to agriculture (Abruña et al., 1959), reservoir sedimentation (Gellis et al., 2006; Soler-López, 2001; Yuan et al., 2015), and both fresh and coastal water quality degradation (Carriger et al., 2013; Ortiz-Zayas et al., 2010). However, with only few exceptions (e.g. Ramos-Scharrón, 2010; Ramos-Scharrón et al., 2012), most previous work in PR has taken place in wet tropical settings and limited documentation exists for the ~14% of the island characterized by a dry tropical climate (Ewel and Whitmore, 1973). Dry tropical areas are those with a mean annual temperature that exceeds 17° C and an overall potential evapotranspiration greater than 25 – 200 cm of annual precipitation (Holdridge, 1967). Dry tropics extend over 42% of the world's tropical landmass (Murphy and Lugo, 1986) and their soils are particularly vulnerable to land disturbance due to their low organic content and slow soil formation rates (MacDonald et al., 2001).

Land disturbance in dry tropical areas represents a major threat to nearshore coral ecosystems in PR as many reefs of utmost importance (e.g., Culebra, Jobos Bay, and La Parguera) formed under the oligotrophic conditions that undeveloped watersheds with such low annual precipitation tend to promote (Goenaga and Cintrón, 1979). In addition, coral reefs receiving discharges from many dry areas of PR are very susceptible to increased erosion because they are drained by very small coastal watersheds (< 10 km^2) typified by a high sediment delivery potential (de Vente et al., 2007) where the sediment-filtering role of coastal wetlands has been diminished by human disturbance (Martinuzzi et al., 2009). La Parguera in Southwestern PR exactly represents that type of physical setup and coral reef resources of utmost ecological and social importance are at risk of land development (Hertler et al., 2009; Valdés-Pizzini and Schärer-Umpierre, 2014). In fact, La Parguera was home to some of the first ever experimental research on the effects of terrestrial sediments on coral reefs (Rogers, 1979).

1.2 Study Objectives

Through plot-scale runoff and erosion monitoring, this study improves our quantitative understanding of land disturbance associated with unpaved roads on both organic and inorganic sediment production in a dry tropical setting. The specific objectives of this study were to: (1) measure differences in runoff response between freshly-disturbed and undisturbed surfaces; (2) quantify organic and inorganic sediment production rates by rainsplash and sheetwash erosion from both freshly-disturbed and undisturbed surfaces; and (3) compare annualized sediment production rates with other studies in similar climatic settings and to background soil generation and particulate organic matter replenishment rates.

1.3 Study area

The study area is located in southwestern Puerto Rico about 120 km from San Juan (Figure 1). The lithology is dominated by bioclastic limestones, mudstones, and cherts of the Upper Cretaceous La Parguera Formation (Volckman, 1984). Soils are mostly shallow (< 30cm), well-drained, and moderately permeable gravelly clays and clay-loams (Beinroth et al., 2003). Background erosion processes include dissolution, soil creep (Lewis, 1975), and sheetwash (Ramos-Scharrón, 2010). Annual average temperature, rainfall, and potential evapotranspiration are 27° C, 110 cm yr^{-1}, and 186 cm yr^{-1}, respectively (Goyal, 1988; NOAA, undated). Roughly, half of the rainfall occurs during the months of August through November. Vegetation is typical of dry to very dry forest conditions characterized by thorny and spiny species in shrubland and open woodland assemblages(Ewel and Whitmore, 1973).

Land uses in La Paguera remained limited to low-intensity grazing, wood cutting for charcoal production, and provision agriculture until the mid-20th century (Feliú, 1983) when land policies reorganized the original fishing-village into government-distributed lots (Brusi-Gil, 2008). However, it was not until the late 1980s-90s when the local landscape turned into the overly urbanized area it is now (Valdés-Pizzini & Schärer-Umpierre, 2014). Sub-divisions and condos became the preferred development style, which involved vegetation removal and soil compaction and this accelerated soil erosion and sediment yield rates (Ramos-Scharrón, 2010).

The 8 - 10 km wide insular shelf off La Parguera harbors sea grass beds (González-Liboy, 1979) and a variety of coral reef assemblages (Morelock et al., 1977), and acts as an effective depositional setting for terrestrial sediment (Ryan-Mishkin et al., 2009). Local coral studies have disclosed species-specific impacts of varying sedimentation levels on linear-growth rates (Torres and Morelock, 2002), survival tolerance (Rogers, 1983), and ecosystem-level zonation (Acevedo et al., 1989). In addition, the brilliance of a bioluminescent bay has proven sensitive to land-based inputs (Soler-Figueroa and Otero, 2015). Both the scientific community and local fishermen perceive that overall ecosystem degradation in La Parguera has been strongly influenced by land development (Pittman et al., 2010; Valdés-Pizzini and Garcia-Quijano, 2009).

2. Methods

2.1 Rainfall

Rainfall, runoff, and sediment production monitoring extended from 2-August-2006 to 30-June-2007. Fifteen-minute rainfall intensity was measured by a recording tipping bucket rain gauge with a resolution of ± 0.2 mm. Total rainfall and maximum 15-min intensities were determined for every individual storm event, where an event was defined as an individual pulse of rainfall isolated from others by at least one hour with no precipitation. Intensity data also was used to calculate 30-min rainfall erosivity (Renard et al., 1997).

2.2 Runoff and sediment production

Plot-scale sediment production was collected with Gerlach troughs (Gerlach, 1967) situated at the bottom of nineteen small (~3 m^2) bounded plots (Figure 2a). Gerlach troughs were constructed of plastic gutter material; a wooden lid covered the top to prevent rainfall, sediment, and litter not generated on the plot from entering the trough. A roughly 4-inch wide strip of tightly-woven, plastic filter fabric material was glued to the upslope lip of each trough and secured underneath the soil surface to protect the trough from being undercut (Figure 2b). Each plot connected to a pair of 100 L runoff collection containers by heavy-duty garden hoses (Figure 2a). Containers were pre-calibrated so that the volume of runoff captured (in L) could be determined by a depth measurement.

Each rectangular plot was aligned along the maximum gradient with a width and a downslope length of about 1 and 3 m, respectively. Plots were bounded along the top and sides with 15-cm wide plastic lawn-edging material inserted vertically into a ~8-10 cm-deep trench. Plots were located on a hill within a restricted-access, privately owned area as a prevention against vandalism. Thirteen plots representing disturbed conditions (Figure 2c) were located on the same unpaved road network where a previous erosion study had been conducted (Ramos-Scharrón, 2010). No vehicles traveled on the road surfaces during the study period. Nine of these disturbed plots were along a lower road and represent a cut-and-fill style of construction (D-Low). The remaining four were located on a steeper ridge-top road (D-Top) (Figure 1). The exact date of road construction is unknown, but the road was last graded during the early 2000s. The surfaces of the disturbed plots were intentionally tampered with by removing all of the understory vegetation by hand and by breaking up the surface with a pick. Road surfaces were compacted with a 6.3 kg hand tamper following boundary installation. Although plot boundaries were also installed surrounding the six undisturbed plots, care was taken to avoid altering their surfaces. Three undisturbed plots (U-Low) were located in close proximity to the D-Low plots, and three others were located near the top of the ridge (U-Top). All six undisturbed plots were located in surfaces covered by shrubland (Figure 2d).

Following border installation, plot dimensions were measured with a cloth tape and slope was measured in percent with a hand clinometer (Table 1). D-Top plots were on average 2.5 times steeper than D-Low plots, while average slopes for undisturbed plots were 0.12 and 0.20 m m^{-1}. The proportion of the plot surface covered by live vegetation was measured by characterizing the surface cover at a total of 100 points along multiple transects (Levy and Madden, 1933). For most plots, surface cover was assessed the day of plot installation and three to four times afterward. Surface sediment samples were collected between one to three times during the study period from 14 of the 20 plots for textural analyses based on the dry-sieving method (Bowles, 1992).

Plots were visited on average once every four weeks. Sediment trapped in the Gerlach troughs was placed in water-tight 1 Gallon bags. Troughs were cleaned with a wet cloth in preparation for the next measurement. The dry weight of each sample was determined gravimetrically in the lab (Gardner, 1986). Textural analyses were conducted by dry-sieving (Bowles, 1992). Sub-samples of the material finer and coarser than 2 mm were isolated in order to split the material into its inorganic and organic portions (i.e., particulate organic matter or POM) through loss-on-ignition (Storer, 1984).

The depth of slurry in each container was measured to determine the runoff volume. Volumes were normalized by area and reported in cm of runoff. The slurry in each container was thoroughly stirred to suspend the sediment prior to collecting two 0.5 L samples. In preparation for subsequent measurements, hoses were flushed and the containers were rinsed with clear tap water. Suspended sediment concentration in mg L^{-1} was determined for each sample by gravity-driven filtering (ASTM, 2000). Total sediment in each container was determined as the product of the volume of runoff times the average suspended sediment concentration of the two samples.

Runoff and runoff coefficients were analyzed by surface type (i.e., undisturbed and disturbed) and by location (i.e., lower hillslope or ridge top) for a total of four plot types. The approximate storm total and maximum 15-min intensity rainfall thresholds required to generate runoff from both disturbed and undisturbed plots were established graphically. All individual storm rainfall totals were plotted against maximum 15-min intensities for periods with no runoff response and these were compared to the rainfall total and intensity values for the largest storm event recorded during periods with observed runoff. In addition, cumulative runoff was plotted against cumulative rainfall to determine differences in the magnitude and frequency of runoff generation. Average runoff coefficients for each of the four groups were compared based on a Kurkal-Wallis non-parametric ANOVA test (Zar, 1984) due to the heteroscadastic nature of the data and the presence of many zero values which precluded the use of any standard transformations.

Total sediment produced by each plot was calculated as the sum of the dry weight of trough sediment plus that reaching the containers. Similar to runoff analyses, plots were segregated by type and location for analyses. Cumulative sediment production in units of kg m^{-2} were plotted against cumulative precipitation to determine differences in sediment production magnitude. Sediment production (i.e., erosion) rates were calculated as the total dry sediment normalized by area and total rainfall (in kg m^{-2} cm^{-1}). Separate analyses were performed on erosion rates normalized by erosivity units. Due to the heteroscadastic distribution of the data and the abundance of zero values, differences in average erosion rates between the four groups were determined by the Kurkal-Wallis non-parametric ANOVA test.

Identification of the most important factors controlling erosion rates were determined based on linear regression analyses on individual factor-by-factor basis. Independent factors considered were rainfall, slope, and vegetation cover. In addition, backward stepwise regression analysis was used to evaluate effects pertaining to interaction terms including three-way interactions of rainfall, slope, and vegetation.

Sediment production rates were annualized by multiplying the average per unit rainfall rate by 110 cm yr^{-1}. Annualized total erosion rates were compared to sediment production rates reported for other dry tropical areas. Annual losses of both organic and inorganic material were compared to loading rates of litterfall and soil creep rates measured in similar dry tropical settings in Puerto Rico.

3. Results

3.1 Rainfall

A total of 60.7 cm of rainfall were recorded between August 2006 and June 2007 and this was only 52% of normal (Figure 3a). Normal monthly rainfall was exceeded only once during January-2007 and was almost matched in August-2006. The rainy season, between the months of August to November, only produced 30.8 cm or 28% of normal annual rainfall, whereas typical rainy seasons bring about 55 cm or rainfall or almost half of annual. About 58% of the 15-min periods with recorded rainfall had intensities equal to or less than 0.30 cm hr^{-1}, while only 19% had intensities exceeding 1.0 cm hr^{-1} (Figure 3b). The largest event recorded dropped only 4.4 cm of rainfall. The average erosivity per unit rainfall for the entire period was 48.9 Mg ha^{-1} mm hr^{-1} per cm. Based on this average value and an annual rainfall of 110 cm yr^{-1}, this suggest an annual erosivity of 5380 Mg ha^{-1} mm hr^{-1}.

3.2 Vegetation cover and surface texture

As expected, vegetation cover for disturbed plots was lower than that for undisturbed plots (Table 1). For most plots, vegetation cover did not vary more than 10% during the study period. Even though some of the disturbed plots (i.e., D–Low–2, D–Low–3, D–Low–9, D–Top–2, and D–Top–3) displayed increases in vegetation cover, this pattern was not consistent throughout all plots. Only minor variations in vegetation cover occurred for undisturbed plots.

The surface textures of D–Top plots were generally coarser than those from D–Low plots. The proportion of the plot surface composed of gravel–sized (> 2 mm) material for D–Top plots ranged from 26% to 67%, while the range for D–Low plots was from 4% to 49% (Table 1). Coarsening of the plot surface through time was noted for only three of the disturbed plots (D–Low–1, D–Low–2, and D–Top–4).

3.3 Runoff

There were noticeable differences between the runoff response frequency and magnitude of disturbed plots in comparison to undisturbed plots. About 64% and 74% of the observations taken from D–Top and D–Low plots represented runoff responses (respectively), but only 31% of all undisturbed plot observations had any runoff. Average runoff from D–Top and D–Low plots were 0.93 and 1.7 cm, respectively.

In contrast, average response for undisturbed plots was only 2.8% and 1.5% of the average values for D-Top and D-Low plots, respectively.

The storm rainfall total and maximum 15-min intensity values required for triggering runoff from disturbed plots were very different from those of undisturbed plots (Figure 4a-c). At least 0.7 - 0.8 cm of total rainfall and roughly 0.7 to 1 cm hr^{-1} of 15-min intensities were required to generate runoff from D-Low and D-Top plots. In contrast, an excess of 1.75 cm of total rainfall and 3.0 cm hr^{-1} of 15-min rainfall intensities were required to initiate runoff from undisturbed plots. The combined effects of reduced frequency of runoff generation and magnitude led to a clear difference in cumulative runoff among D-Top, D-Low, and undisturbed plots (Figure 5a). On average, D-Top and D-Low plots generated 0.17 and 0.38 cm of runoff per every cm of rainfall, respectively. In comparison, undisturbed plots generated 0.006 cm of runoff per cm of rainfall, and this is only 1-3% of that generated from disturbed plots.

Mean runoff coefficients for U-Top and U-Low plots were 0.53% and 0.49%, respectively (Figure 5b; Table 2). In comparison, runoff coefficients for D-Top and D-Low plots were 23 and 60 times greater (12.2% and 29.6%, respectively). Kurkal-Wallis analyses indicated that runoff coefficients for D-Low and U-Low plots were significantly different from those of any other plot types and locations, but analyses signaled no significant differences between D-Top and U-Top plots. This lack of difference is due to a number of no runoff response values for D-Top plots [plot D-Top-2 in particular]. No obvious trends stand out between vegetation cover and runoff coefficients other than the differences between disturbed and undisturbed plots (Figure 5c). This is likely due to the dominant role of precipitation characteristics and soil compaction in generating runoff, and to the limited range of vegetation cover values for disturbed plots that typified the abnormally dry study period.

3.4 Sediment Production

On average, 99.9% of the sediment produced by all plots was captured by the troughs and did not reach the runoff containers. Average area- and rainfall-normalized erosion rates were highest for D-Low plots and lowest for undisturbed surfaces (Figure 6b; Table 2). The average production rate for D-Low plots was 0.31 kg m^{-2} cm^{-1}, and this was about 200 times higher than that for all undisturbed plots (0.015 kg m^{-2} cm^{-1}). D-Top plots had a surprisingly low erosion rate of 0.0091 kg m^{-2} cm^{-1}, which was only about 3% that of D-Low plots and six times higher than undisturbed. Kurkal-Wallis analyses indicated that mean D-Low and U-Low sediment production rates were each significantly different than those from any other plot type, but that production rates from D-Top and U-Top plots were undistinguishable. Equivalent results ensued when the analysis was conducted using sediment production rates normalized by erosivity.

Individual plots displayed a wide variability in sediment production rates, even for those within the same type and location. The relatively narrow range in cumulative runoff responses described above was generally not observed for cumulative sediment production

(Figures 6a). D–Low plots displayed the widest range in cumulative sediment production due to an order of magnitude range of average production rates among plots [0.0042 – 0.05 kg m^{-2} cm^{-1} (D–Low–9 and D–Low–5, respectively)]. Average production rates for D–Top plots displayed a slightly more restricted range of values (0.0046 – 0.015 kg m^{-2} cm^{-1}), while values for all undisturbed plots ranged from no sediment to 0.004 kg m^{-2} cm^{-1}.

The lack of a tighter range in sediment production rates for individual plot types could be potentially explained by the influence of factors other than rainfall. Linear regression analyses displayed no relationship between slope and sediment production rates (normalized by area and rainfall) for any of the plot types (i.e., D–Top, D–Low, and undisturbed) ($R^2 < 0.05$; p–values > 0.2).

Normalized sediment production rates appear to be somewhat influenced by vegetation cover. However, the range of vegetation cover for disturbed plots (0% – 36%) was too limited for an overall appreciation of its effects on sediment production. The range of vegetation cover values for undisturbed plots was wider (10% – 83%) and linear regression analyses displayed a significant yet weak correlation ($R^2 = 0.19$, p–value = 0.001). Linear regression analyses between vegetation cover and sediment production for all plots indicated a weak but still statistically significant correlation ($R^2 = 0.09$, p–value = 0.0003; Figure 6c).

Regression analyses through backward elimination for all possible interaction terms was conducted for each of D–Low, D–Top and undisturbed plot types to discern the role of rainfall, slope, and vegetation cover on sediment production. Rainfall was the only significant factor related to sediment production for D-Top and undisturbed plots (p-values of 0.004 and 0.01, respectively) but it was able to explain only 20% and 10% of the variability in sediment production, respectively (Table 3). In contrast, the interaction term between precipitation and vegetation proved to be a significant factor controlling sediment production for D-Low plots ($p = 0.005$) and it explained up to 33% of the variation in sediment production.

Sediment produced from D-Low plots consisted on average of 5% gravel, 79% sand, and 16% silt & clay, and this was noticeably finer than that produced from D-Top plots (Table 4). About a third of the sediment produced from undisturbed plots consisted of gravel-sized material; sand ranged from 57% to 63% and silt and clay was slightly less than 10%.

3.5 Particulate Organic Matter content and yield rates

There were no sharp differences in the POM content of eroded material among the different plot types. Overall, the average POM content for material coarser than 2 mm ranged from 3% to 6%, and between 8% and 18% for material finer than 2 mm (Table 4). However, between 10% and 13% of the sediment produced from undisturbed plots consisted of POM and this was between 1.2 and 1.8 times higher than from either D-Low and D-Top plots. POM yield rates from undisturbed plots were between 0.0003 and 0.0006 kg m^{-2} cm^{-1} and these are only between 14% and 33% of the POM yield rates for disturbed plots.

Similarly, rates of inorganic sediment production rates for disturbed plots ranged from 0.0081 to 0.022 kg m^{-2} cm^{-1} and these were between 6 and 17 times higher than those from undisturbed plots.

4. Discussion

4.1 Rainfall

Even though total rainfall during the study period was only 52% of normal for La Parguera, the frequency distribution of 15-min intensities were very similar to those recorded by a previous study (Aug-03 to Mar-05; Ramos-Scharrón, 2010). Similar to the 2006-07 study period, 55% of the 15-min rain periods from Aug-03 to Mar-05 had intensities less than or equal to 0.30 cm hr^{-1}, and 18.5% equaled or exceeded 1.0 cm hr^{-1} (Figure 3b). Therefore, the per unit rainfall sediment production rates reported here can be considered as representative for La Parguera.

A noticeable limitation related to the rainfall pattern of the study period was the lack of any progression in vegetation cover through time, particularly for the D-Low and D-Top plots that were exclusively disrupted at the beginning of the study period. Road-segment scale observations previously conducted on the same study area showed a marked increase in vegetation cover only when monthly rainfall exceeded 41.7 cm (Nov-03) which presumably allowed soil moisture content to satisfy that required to promote vegetation growth (Ramos-Scharrón, 2010). The maximum monthly rainfall recorded during the study period was only 9.7 cm (Oct-06), and this proved insufficient to initiate vegetative succession on most disturbed plots.

4.2 Runoff

Average runoff coefficients from disturbed road surfaces in La Parguera were 12% and 30% for D-Top and D-Low plots (respectively), while individual measurements ranged from 0% up to 86%. Runoff coefficients for unpaved road surfaces reported in the literature are very variable even during controlled rainfall simulation experiments (e.g., Ramos-Scharrón and Thomaz, 2016) as they may span from 0% to 100% and are influenced by total rainfall (Ramos-Scharrón and MacDonald, 2007). However, disturbed road plots in La Parguera had runoff coefficients that were on average between 23 and 60 times higher than those from undisturbed hillslopes and this is in agreement with those previously reported in the literature (Harden, 1992; Ziegler and Giambelluca, 1997; Ramos-Scharrón and LaFevor, 2016).

The likelihood of runoff being generated from D-Top and D-Low plots increased when 15-min rainfall intensities exceeded about 0.7 to 1.0 cm hr^{-1} or when storm rainfall surpassed 0.7 – 0.8 cm. Since the process responsible for generating overland flow from unpaved roads is through precipitation excess (Luce, 2002), the rainfall intensity thresholds reported here may be used as a crude approximation of infiltration rates and presumably saturated hydraulic conductivity. Steady state infiltration rates for unpaved roads reported in the literature span several orders of magnitude but are typically between 0.3 and 3.0 cm hr^{-1}, while either empirically- or model calibration-derived saturated hydraulic conductivity values have spanned from 0.02 to about 2 cm hr^{-1} (Ramos-Scharrón and MacDonald, 2007; Ramos-Scharrón and LaFevor, 2016). Therefore, the 15-min rainfall intensity thresholds reported here for disturbed plots are within the range of those expected on roads elsewhere. In a similar dry tropical setting on St. John in the US Virgin Islands, a 0.6 – 1.0 cm rainfall total has been suggested as a threshold for road runoff generation (MacDonald et al., 2001; Ramos-Scharrón and LaFevor, 2016).

In contrast to disturbed plots, undisturbed surfaces required minimum rainfall intensities of ~3 cm hr^{-1} and storm totals of more than 1.75 cm to initiate runoff. This rainfall intensity threshold for natural hillslopes in La Parguera is within the 0.8 to 3.9 cm hr^{-1} measured hydraulic conductivity range for undisturbed loamy soils in a similar dry tropical setting in the US Virgin Islands (Ramos-Scharrón and LaFevor, 2016). Similarly, a 2 cm rainfall threshold has been suggested for precipitation excess runoff generation on natural hillslopes also on the US Virgin Islands (Ramos-Scharrón and MacDonald, 2007).

Rainfall data spanning 26 months (Aug-03 to Mar-05 and Aug-06 to Mar-07) suggests a total of 169 individual storm events occur on average every year in La Parguera. Out of those rainstorms, only 9% or 15 storms per year exceed 3.0 cm hr^{-1} in 15-min intensities or 1.75 cm in total rainfall. This suggests that runoff on undisturbed hillslopes can be expected to occur on average only fifteen times per year. In contrast, storms with sufficient rainfall intensities and totals to exceed the thresholds for runoff generation on disturbed surfaces (i.e, 0.75 cm hr^{-1} & 0.75 cm) represent between 32% and 20% of the total number of storms occurring every year, respectively. This suggests that storms exceeding these thresholds tend to occur between 34 to 54 times every year. Therefore, disturbed surfaces can be expected to generate runoff 2.2 to 3.5 times more frequently than undisturbed hillslopes. This is of particular importance in a dry tropical setting such as La Parguera, characterized by ephemeral channels from which runoff delivery to coastal waters is infrequent, short-lived, and exclusively triggered during large storms (Cosner, 1972; MacDonald et al., 1997).

4.3 Sediment production

Sediment production rates from D-Low plots were on average 34 times higher than those from D-Top surfaces. This was unexpected because D-Top plot locations were chosen to represent steeper disturbed surfaces and therefore had slopes that were on average 2.7 times greater (Table 1). The contrasting sediment production rates cannot be explained by differences in vegetation cover as these were very similar for both locations. Some of the differences in sediment production rates could be attributed to disparities in runoff response as D-Low plots produced on average 2.4 times more runoff than D-Top. In fact, inferred average infiltration rates for the ridgetop D-Top plots were 1.4 times greater than those for the cut-and-fill D-Low road surfaces. These infiltration rate differences between these two road types (i.e., ridgetop vs. cut and fill) have been noted elsewhere. Ridgetop roads in New South Wales (Australia) displayed infiltration rates that were about 2.6 times greater than those from cut and fill roads (Croke et al., 2006). Distinct runoff and sediment production rates for the two road types might be in part due to differences in particle size distribution of substrate materials since coarser substrates are generally associated with higher infiltration rates (Arya et al., 1999) and a higher resistance to the forces of erosion (Black and Luce, 1999; Megahan, 1974). D-Top surfaces were generally coarser as they consisted of 26% - 67% of gravel-sized material while D-Low road surfaces contained from 4% to 49% of gravel.

The lack of a better-defined relation between sediment production with slope and vegetation might be due to unresolvable factors associated with the limitations of this study. Slope-dependent effects of surface erosion are typically linked to slope length (e.g., Luce and Black, 1999) and are therefore better represented when length is considerable and plot size is greater than 10 m^2 (García-Ruiz et al., 2015). Therefore, the 3 m long plots used for this study might have been inadequate to produce sufficient shear stresses given the slope gradients.

The confounding effects of varying surface texture in potentially controlling infiltration rates and resistance to erosion described above also may have precluded adequately isolating the effects of slope and vegetation. In addition, the study design had originally relied on progressive increases in vegetation cover as time elapsed to evaluate its effects on runoff and sediment production on individual plots. However, the lack of sufficient rainfall during the study period prevented the development of an abundant vegetation cover on disturbed plots. Finally, the effects of vegetation cover are complex as vegetation can intrude in the development of precipitation excess but also in the erosive forces of overland flow and incipient sediment motion (Siepel et al., 2002). Hence, these sorts of effects might be better evaluated by studies monitoring erosion on a storm-by-storm basis and not by methods that average runoff and erosion rates over a course of several weeks.

Average annual erosion rates for D-Low and D-Top plots were 204 and 10.0 Mg ha^{-1} yr^{-1} and these were 200 and 6 times greater than those from undisturbed plots (1.6 Mg ha^{-1} yr^{-1}), respectively (Figure 7). D-Top and D-Low rates were at least a full order of magnitude higher than rates previously measured on the same study sites in La Parguera (0.8 Mg ha^{-1} yr^{-1}) but at the road-segment scale (75 – 345 m^2). Previously measured rates corresponded to a wetter rain period during which vegetation cover on unpaved road surfaces ranged from 24% – 51% and it significantly impaired erosion rates (Ramos-Scharrón, 2010). Sediment production rates from undisturbed plots observed during this study were about 8 times higher than those previously measured in La Parguera at the hillslope scale (12 m^2 – 2.5 ha; Ramos-Scharrón, 2007). The differences are likely associated with a higher vegetation cover on the hillslope scale measurements (34 – 100% for hillslopes vs 10 – 83% for plots) and the higher degree of connectivity between the eroding source area and the measuring devices for the small plots relative to the longer hillslopes.

Annualized sediment production rates reported here are within the range of values reported for similarly disturbed unpaved road surfaces and footpaths in dry tropical settings in the nearby islands of St. John and St. Croix (Figure 7). Actively used unpaved roads on St. John displayed erosion rates ranging from 46 to 110 Mg ha^{-1} yr^{-1} for unmaintained and frequently graded roads, respectively. Abandoned and unmaintained roads only rarely used by vehicular traffic and having some of the travelway surface covered by vegetation eroded at about 4.6 Mg ha^{-1} yr^{-1}. Footpaths in St. Croix eroded at rates that ranged from 0.6 to 81 Mg ha^{-1} yr^{-1} for paths with a dense (up to 96%) and sparse (up to 46%) vegetation cover, respectively.

The relative impact of soil disturbance associated with unpaved roads and footpaths on erosion rates are strongly dependent on background sediment production. Background erosion rates in La Parguera range from 0.2 to 1.7 Mg ha^{-1} yr^{-1}, and these are very similar to the 0.1 Mg ha^{-1} yr^{-1} rate reported for the East End of St. Croix, which shares a similar tropical-dry shrubland cover associated to an annual rainfall rate of 85 cm yr^{-1} (Ramos-Scharrón et al., 2014). Under these conditions, disturbance appears to accelerate erosion rates by 4 to 1300 times above background. In contrast, even though disturbed surfaces on St. John erode at annual rates that are comparable to those in La Parguera and St. Croix, the level of impact can be up to four orders of magnitude above baseline due to lower background rates. Observed rates on St. John span from 0.01 to 0.2 Mg ha^{-1} yr^{-1}, with the higher rates representing areas covered by shrubland and deciduous forest and the low rates representative of tropical dry evergreen forests with an annual rainfall of about 130 cm yr^{-1} (Ramos-Scharrón and MacDonald, 2007). Therefore, annual rainfall seems to play a complex role in determining the relative impact of disturbance. On the one hand, relatively lower precipitation rates (840 – 100 cm yr^{-1}) lead to relatively higher background erosion rates due presumably to higher levels of soil exposure under shrubland and deciduous forest cover and this can somewhat dampen the relative effects of disturbance. In contrast, higher annual rainfall rates (~130 cm yr^{-1}) that promote the generation of evergreen forest cover appear to lead to improved soil cover and to lower background erosion rates.

4.4 Organic and inorganic sediment production rates

Average POM production rates from D-Low and D-Top surfaces were 0.0018 and 0.0021 kg m^{-2} cm^{-1}, respectively, and these were three to seven times higher than average POM yield rates from undisturbed plots (Table 4). Average annualized rates are 2.0 – 2.3 Mg ha^{-1} yr^{-1} for disturbed surfaces and 0.33 – 0.66 Mg ha^{-1} yr^{-1} for undisturbed plots. Rates of POM replenishment by leaves and miscellaneous litterfall in a similar tropical climate setting with a shrubland cover have been measured in the Guánica Forest just 15 km to the east of La Parguera and they averaged 0.84 Mg ha^{-1} yr^{-1} (Lugo et al., 1978). The similarity in POM loading rates by litterfall to POM erosion rates for undisturbed sites is interpreted here as evidence that undisturbed soils in La Parguera are in a sort of equilibrium state in which background POM loss rates by surface erosion are replenished by soil forming processes (Bennett and Lowdermilk, 1938), which in the case of organic material corresponds to litterfall. Therefore, the fact that POM loss rates from disturbed surfaces are greater than those from undisturbed plots implies that erosion resulting from soil disturbance leads to a non-replenishable loss of POM in La Parguera.

Processes responsible for physical removal of the inorganic portion of the soil mantle in La Parguera are limited to surface erosion and creep. The average erosion rate of inorganic material from undisturbed surfaces was about 1.4 Mg ha^{-1} yr^{-1}. Previous soil creep observations conducted in La Parguera determined an average downslope rate of about 1.0 mm yr^{-1} over a depth of 15 cm (Lewis, 1975). Assuming a bulk density of 0.92 Mg m^3 for soils within shrubland forest cover in a dry tropical setting (Lugo et al., 1978) and that 90% of the 15 cm soil profile is inorganic we can estimate that soil loss rates associated to creep are in the order of 1.2 Mg ha^{-1} yr^{-1}. Therefore, the combined soil mantle removal rate of undisturbed hillslopes by surface erosion and creep is in the order of 2.6 Mg ha^{-1} yr^{-1}. This rate is equivalent to a denudation rate of ~0.3 mm yr^{-1} and this is close to 0.1 and 0.2 mm yr^{-1}, which are the maximum soil production rates associated to bedrock weathering cited in the literature (Li et al., 2009; Montgomery, 2007). This finding is interpreted to imply that from the standpoint of the inorganic portion of soil material, undisturbed hillslopes in La Parguera appear to be in a highly vulnerable equilibrium state and are therefore very susceptible to any increases in erosion rates.

4.5 Management implications

Accelerated soil erosion is one of the most widespread and documentable effects of the Anthropocene (Syvitski and Kettner, 2011) as it may not only affect soil properties and productivity but may also have severe downstream consequences on water resources and aquatic habitats (Blum and Eswaran, 2004). Results of this study suggest that soils in this dry tropical setting naturally exist in a delicate balance between processes leading to soil formation (i.e., litterfall and bedrock weathering) and those associated to soil mantle removal (i.e., creep and surface erosion). Therefore, the reported increases of 6 – 200 times above background erosion levels induced by disturbance signify an unsustainable condition which likely leads to standard signs of degradation like deficient soil productivity due to net loss of organic material, impoverished infiltration and water holding capacity, and reductions in soil mantle thickness (Lal, 2001). The three- to seven-time increase in per unit area POM loss rates documented here implies that erosion can export POM at a rate that is twice what can be replenished by litterfall once only 14% – 33% of an area is disturbed.

Land disturbance may also enhance both hydrologic and sediment connectivity between terrestrial environments and aquatic habitats (Tetzlaff et al., 2007). In La Parguera, disturbed surfaces may generate runoff by precipitation excess about 34 – 54 times per year, and this is two to three-and-a-half times more frequent than that expected from undisturbed hillslopes. Therefore, when disturbed surfaces are hydrologically connected with the coastal environment they are capable of altering the dynamics of runoff, sediment, and organic material delivery from one that is infrequent and acute to one that is recurring or chronic (Ramos-Scharrón and LaFevor, 2016). The degree of connectivity not only depends on the frequency and quantity of runoff but also on the relative location of the runoff source areas from the water resources of concern (Ambroise, 2004). The impacts of enhanced frequency of runoff delivery to coral reef ecosystems are still mostly unexplored (Risk, 2014).

Increased sediment yield to coastal waters is considered a major threat to coral reef ecosystems in La Pargura (Rogers, 1983) and elsewhere (Fabricius, 2005). Average sediment production rates from disturbed plots in La Parguera ranged from 10 to 337 Mg ha^{-1} yr^{-1} and these represent a 6- to 200-fold increase in sediment production rates over background. The observed impact of land disturbance on erosion rates presented here implies that disturbing only 0.5% to 16% of an area results in a doubling of net sediment production. However, plot-scale erosion measurements described here do not translate directly to sediment yields as watersheds have diverse compartments were sediment may become trapped before reaching their outlets (Walling, 1999). Nevertheless, the relatively small proportion of disturbed land required to double sediment loads to coastal waters in La Parguera, highlights the sensitivity of this and other similar landscapes to increases in sediment yield resulting from land development. This is most certainly occurring in La Parguera where the combined effect of small watersheds, recent acceleration of land disturbance associated to urbanization, and removal of the natural buffering role of wetlands have likely resulted in a significant increase in the delivery of runoff, sediment, and organic matter to its marine ecosystems.

The environmental consequences of increased erosion merit the attention of land managers in La Parguera and in other dry tropical settings. The onsite degradation of soils by erosion has numerous consequences on its ecological services such as sustaining a protective and ecologically-diverse vegetative cover and promoting infiltration of rainwater to support vegetation, prevent flooding, and enhance aquifer recharge (Daily et al., 1997). Maintaining a strict control on the amount of disturbed land and setting the conditions for a quick vegetation recovery following disturbance are two ways to curb soil degradation. Similarly, offsite delivery of the products of erosion can have drastic consequences on nearshore marine habitats in a place like La Parguera. Reducing the delivery of these products of erosion by promoting onsite soil stabilization and enhancing the sediment retention capacities of the landscape through manmade detention basins (Mekonnen et al., 2015) and the re-establishment of natural wetland barriers are some of the options that can serve to protect these resources before their natural appeal dwindles.

5. Conclusions

Accelerated sediment yields, degraded coral reef ecosystems, and impoverished soils are trademarks of human-induced environmental impacts associated to heightened soil erosion. Although soil erosion is a thoroughly studied phenomenon, the dry tropics have received relatively little attention in the literature. Dry tropical areas should be of much interest to erosion research because soils in these regions are particularly vulnerable due to relatively slow soil production levels. In addition, background erosion rates in dry tropical areas are comparatively slow and this has fostered oligotrophic coastal waters that have promoted the development of some important nearshore coral reef ecosystems. The soils of many dry tropical areas of the Insular Caribbean have been subjected to modern-day style of disturbance particularly over the past several decades as development pressures associated to the promotion of construction- and tourism-based economic development models have been executed. This is the case in La Parguera in southwestern Puerto Rico, where the most studied marine ecosystem in the Caribbean is considered threatened by land development.

Plot-scale observations of runoff development, sediment production, and loss of organic matter were made in La Parguera between August 2006 and June 2007. Results show that rainfall thresholds for the development of precipitation excess runoff from disturbed unpaved road surfaces were between one-fifth to one-half of those for undisturbed hillslopes. These differences are projected to allow runoff to occur two to three-and-a-half times more frequently on disturbed surfaces than on undisturbed hillslopes. Therefore, disturbance can potentially alter the temporal distribution of land to coastal water connectivity from one that is infrequent to one that often recurs. Net sediment production rates from disturbed plots were between 6 to 200 times greater than from undisturbed surfaces. Hence, a net doubling of net sediment production is likely when only 0.5% to 16% of an area is disturbed. These findings highlight the potential sensitivity of sediment yields to even minor land cover changes.

Rates of particulate organic matter losses associated with surface erosion on undisturbed hillslopes were within the same order of magnitude as a previously measured rate of organic material addition by litterfall. Similarly, background erosion of inorganic material was within the same order of magnitude of a locally measured soil creep rate. The combination of background inorganic material losses by surface erosion and creep are close to the maximum rates of published soil production rates by bedrock weathering. These findings suggest that soils in this dry tropical environment exist in a very vulnerable state of equilibrium that easily leads to unsustainable conditions when disturbed. Ameliorating the effects of land disturbance on soil degradation and downstream marine habitats should be the priority of local managers and may be achieved by a combination of practices that enhance soil protection with those interrupting the delivery of runoff to coastal waters.

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Figure 1. Map of La Parguera displaying the location of the monitoring sites, land cover types in early 2000 based on the PR-GAP project (Gould, 2009), and the location of coral reef areas (Kendall et al., 2001).

Figure 2. Pictures showing (a) a bounded plot with Gerlach trough layout, (b) the runoff collection containers, (c) a disturbed plot surface, and (d) an undisturbed plot surface.

Figure 3. (a) Monthly rainfall total compared to normal monthly totals from Isla Magueyes Station (COOP ID #665693) and (b) frequency distribution of 15-min rainfall intensities for Aug-03 to Mar-05 and for Aug-06 to Jun-07.

Figure 4. Rainfall thresholds for the development of runoff from: (a) D-Low plots, (b) D-Top plots, and (c) Undisturbed plots. Circles indicate measurements when no runoff was detected and X's indicate those for which runoff was measured. Tanned area refers to runoff threshold zone.

Figure 5. Summary of runoff results: (a) Cumulative precipitation versus Cumulative runoff graph (b) Runoff coefficient box-plots [diamond indicates mean values]; and (c) Vegetation cover versus runoff coefficient. [filled circles represent D-Top plots, circles D-Low plots, and X's U-Top and U-Low plots]

Figure 6. Summary of sediment production results: (a) Cumulative precipitation versus Cumulative runoff graph; (b) Runoff coefficient box-plots [diamond indicates mean values]; and (c) Vegetation cover versus vegetation cover. [filled circles represent D-Top plots, circles D-Low plots, and X's U-Top and U-Low plots]

Figure 7. Annual erosion rates measured in this study in comparison with other studies also conducted in dry tropical areas in the Eastern Caribbean. [[†] refers to Ramos-Scharrón, 2010; [*] to Ramos-Scharrón and MacDonald, 2005; [**] to Ramos-Scharrón and MacDonald, 2007b; & [‡] to Ramos-Scharrón, 2010]

Table 1. Summary of plot monitoring period and characteristics.

Table 2. Summary of runoff coefficient and sediment production rate results.

Table 3. Summary of backward regression analyses on sediment production rates.

Table 4. Summary of erosion rates for individual plots, particle size distribution of eroded sediment, and POM and inorganic sediment production rates.

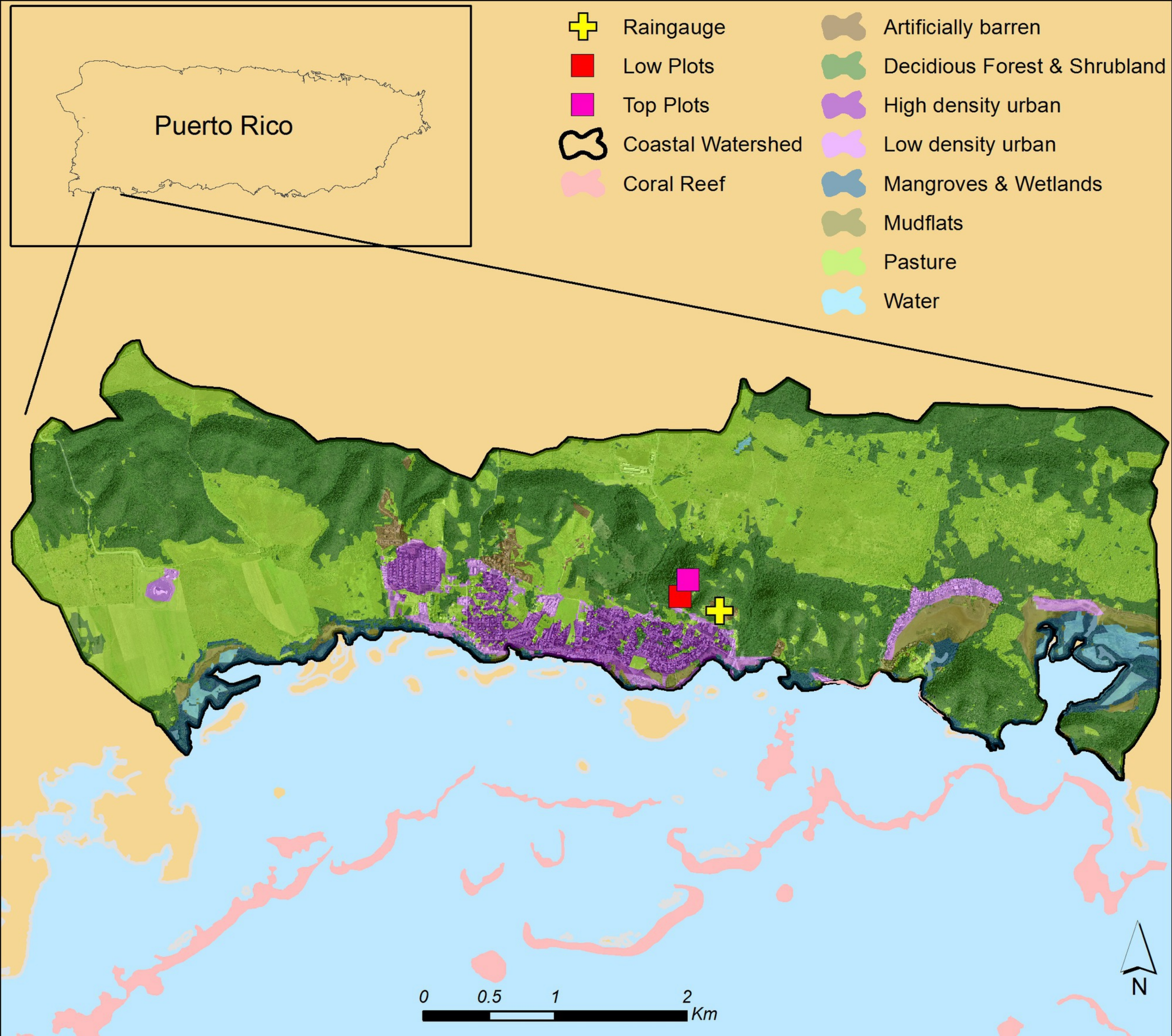

Puerto Rico
Raingauge
Low Plots
Top Plots
Coastal Watershed
Coral Reef
Artificially barren
Decidious Forest & Shrubland
High density urban
Low density urban
Mangroves & Wetlands
Mudflats
Pasture
Water
0
0.5
1
2
Km
N

Figure 2. Pictures showing (a) bounded plot with Gerlach trough layout and collection containers, (b) detail of a Gerlach trough with fabric, (c) a disturbed plot surface, and (d) an undisturbed plot surface.

Figure 3. (a) Monthly rainfall total compared to normal monthly totals from Isla Magueyes Station (COOP ID #665693) and (b) frequency distribution of 15-min rainfall intensities for Aug-03 to Mar-05 and for Aug-06 to Jun-07.

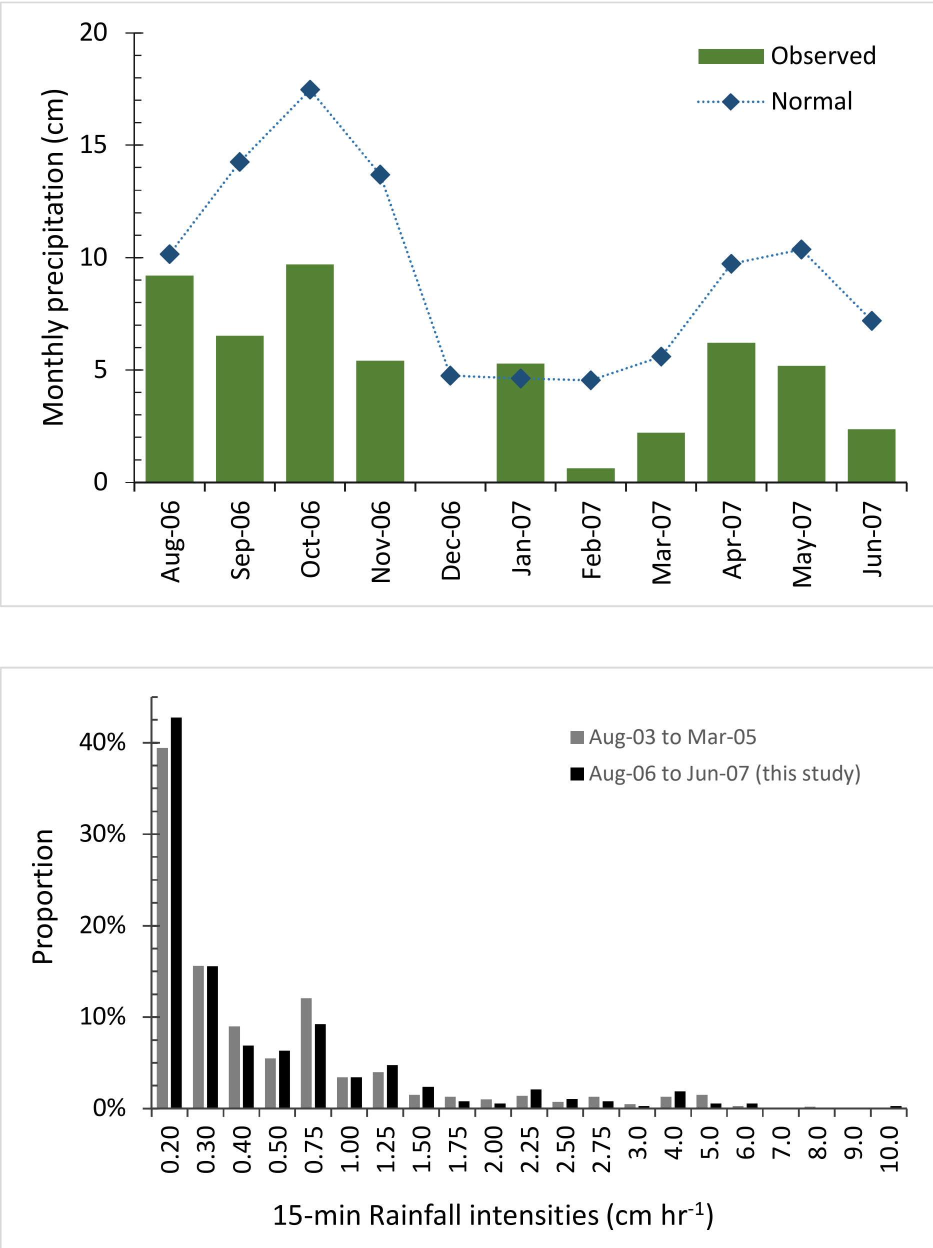


Figure 4. Rainfall thresholds for the development of runoff from: (a) D-Low plots, (b) D-Top plots, and (c) Undisturbed plots. Circles indicate measurements when no runoff was detected, X's indicate those for which runoff was measured, and those with both circles and X's are those for which runoff was observed only for some plots. Tanned area refers to an inferred runoff threshold zone.

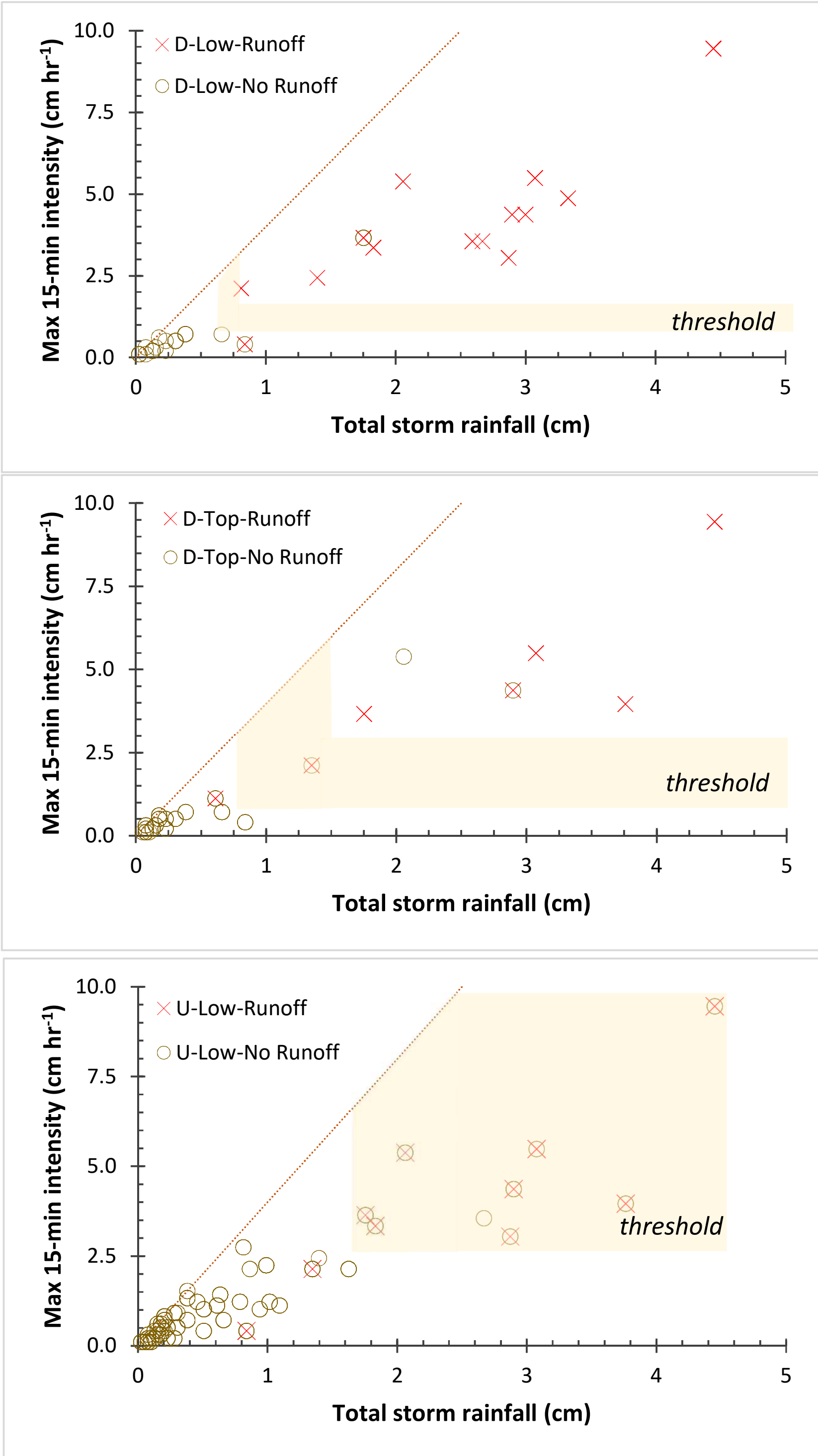


Figure 5. Summary of runoff results: (a) Cumulative precipitation versus Cumulative runoff graph (b) Runoff coefficient box-plots [diamond indicates mean values]; and (c) Vegetation cover versus runoff coefficient. [filled circles represent D-Top plots, circles D-Low plots, and X's U-Top and U-Low plots]

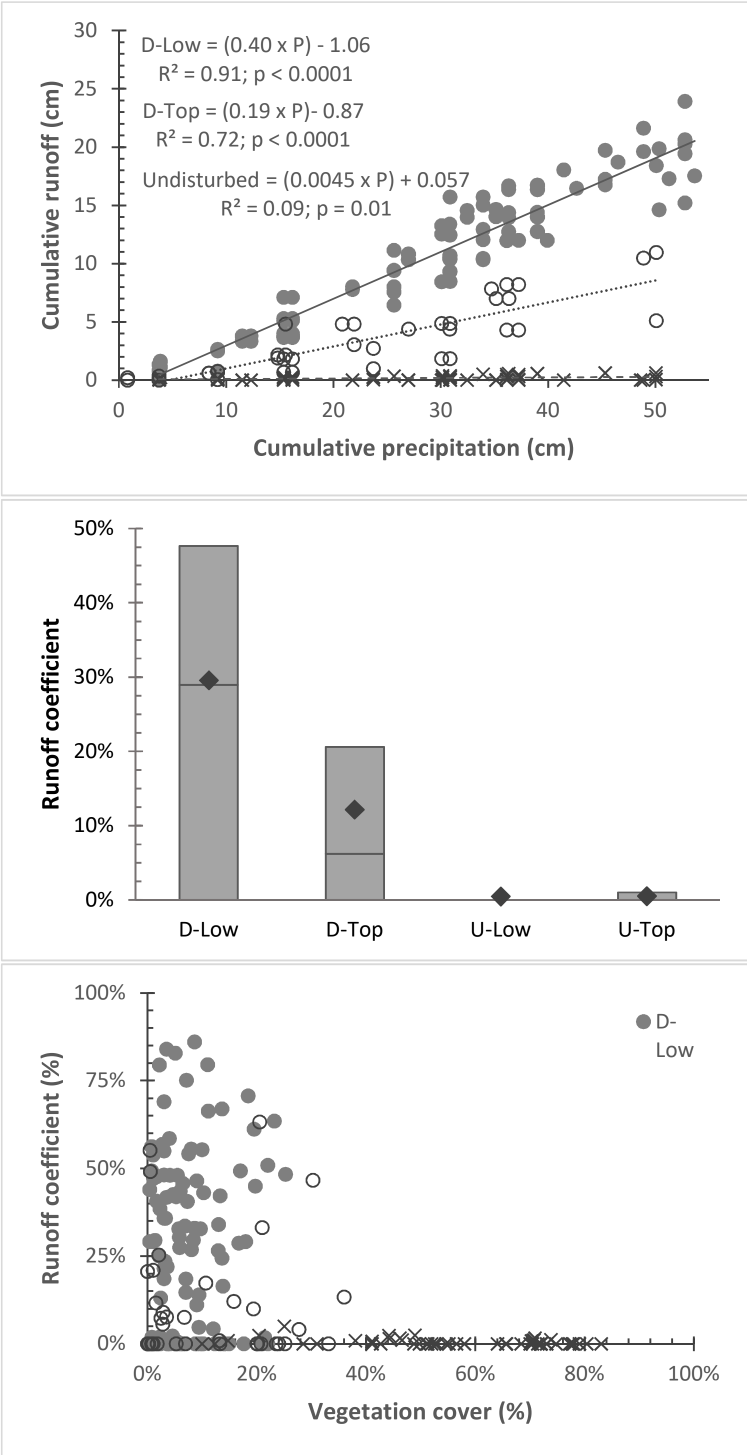
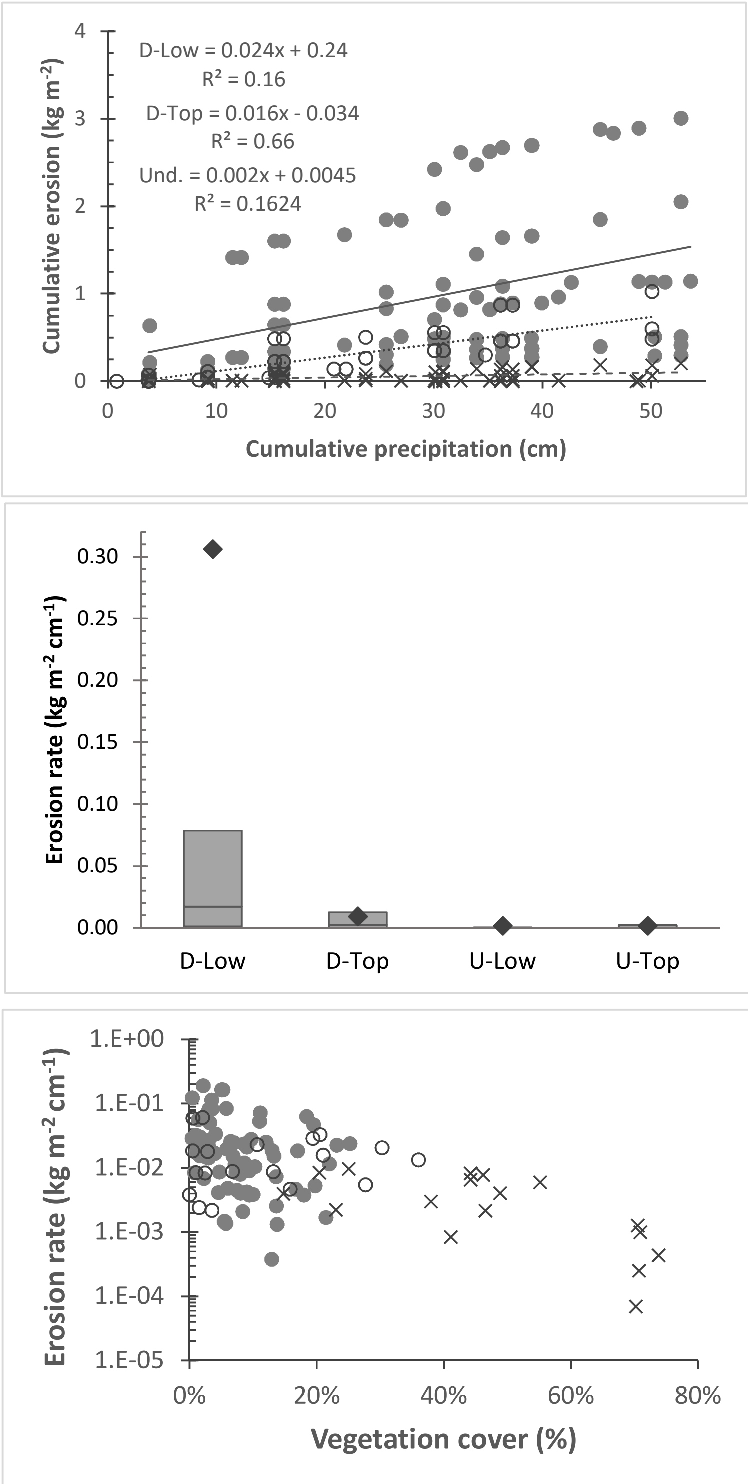
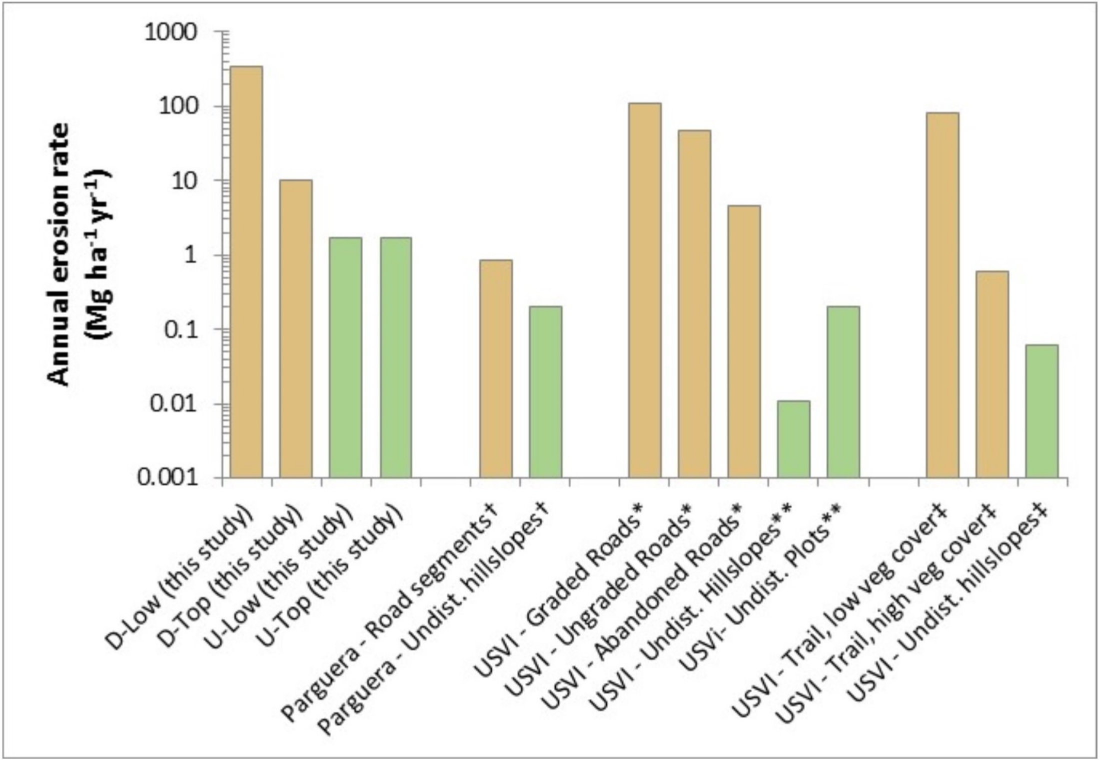


Figure 6. Summary of sediment production results: (a) Cumulative precipitation versus Cumulative runoff graph; (b) Runoff coefficient box-plots [diamond indicates mean values]; and (c) Vegetation cover versus vegetation cover. [filled circles represent D-Top plots, circles D-Low plots, and X's U-Top and U-Low plots]





Annual erosion rate (Mg ha-1 yr-1)
1000
100
10
1
0.1
0.01
0.001
D-Low (this study)
D-Top (this study)
U-Low (this study)
U-Top (this study)
Parguera - Road segments†
Parguera - Undist. hillslopes†
USVI - Graded Roads*
USVI - Ungraded Roads*
USVI - Abandoned Roads*
USVI - Undist. Hillslopes**
USVi- Undist. Plots**
USVI - Trail, low veg cover‡
USVI - Trail, high veg cover‡
USVI - Undist. hillslopes‡

	Measurement Period		Area	Slope	Vegetation Cover		Surface texture		Number of erosion measurements
Plot Id	**Start**	**End**	**(m^2)**	**($m\ m^{-1}$)**	**Min**	**Max**	**> 2mm**	**≤ 2mm**	
D-Low-1	02-Aug-06	30-Jun-07	3.3	0.05	1%	4%	9 - 26%	74 - 91%	12
D-Low-2	02-Aug-06	30-Jun-07	3.6	0.13	3%	28%	24 - 34%	66 - 76%	11
D-Low-3	02-Aug-06	30-Jun-07	3.4	0.02	0%	14%	4 - 6%	94 - 96%	11
D-Low-4	02-Aug-06	30-Jun-07	3.1	0.03	1%	10%	23 - 28%	72 - 77%	12
D-Low-5	02-Aug-06	30-Jun-07	3.4	0.05	0%	7%	39 - 49%	51 - 60%	12
D-Low-6	02-Aug-06	30-Jun-07	2.9	0.08	0%	5%	28 - 37%	63 - 72%	11
D-Low-7	02-Aug-06	30-Jun-07	3.4	0.03	3%	13%	20 - 48%	52 - 80%	11
D-Low-8	02-Aug-06	30-Jun-07	3.6	0.05	0%	10%	23 - 45%	55 - 77%	12
D-Low-9	02-Aug-06	30-Jun-07	3.5	0.07	2%	22%	21 - 30%	70 -79%	13
		Mean	***3.4***	***0.06***	***1%***	***13%***			***105***
D-Top-1	02-Aug-06	07-Jun-07	3.3	0.18	0%	3%	67%	33%	11
D-Top-2	02-Aug-06	07-Jun-07	3.5	0.17	4%	36%	30 - 42%	58 - 70%	11
D-Top-3	02-Aug-06	07-Jun-07	2.9	0.15	1%	21%	51%	49%	11
D-Top-4	23-Sep-06	07-Jun-07	3.3	0.11	0%	7%	26 - 58%	42 - 74%	8
		Mean	***3.2***	***0.15***	***1%***	***17%***			***41***
U-Low-1	18-Aug-06	30-Jun-07	3.1	0.20	64%	79%	--	--	12
U-Low-2	18-Aug-06	30-Jun-07	3.1	0.19	10%	31%	--	--	12
U-Low-3	02-Aug-06	02-Jun-07	3.9	0.20	72%	83%	--	--	10
		Mean	***3.4***	***0.20***	***49%***	***64%***			***34***
U-Top-1	02-Aug-06	07-Jun-07	3.0	0.05	45%	58%	--	--	11
U-Top-2	02-Aug-06	07-Jun-07	3.0	0.17	38%	51%	--	--	11
U-Top-3	02-Aug-06	07-Jun-07	2.9	0.15	70%	78%	61%	39%	11
		Mean	***2.9***	***0.12***	***51%***	***62%***			***33***

	Runoff Coefficient (%)				Sediment production rate (kg m^{-2} cm^{-1})				Sediment production rate (kg m^{-2} $eros^{-1}$)*			
Plot Group	**Mean**	**Std. Dev.**	**Median**	**Kurkal-Wallis Groupings****	**Mean**	**Std. Dev.**	**Median**	**Kurkal-Wallis Groupings****	**Mean**	**Std. Dev.**	**Median**	**Kurkal-Wallis Groupings****
D-Low	29.6%	12.2%	29.4%	A	0.31	0.721	0.017	A	7.00E-03	2.50E-02	4.00E-04	A
D-Top	12.2%	16.5%	6.2%	B	0.0091	0.014	0.0024	B	1.50E-04	1.90E-02	8.20E-05	B
U-Low	0.49%	1.4%	0.00%	C	0.0015	0.0039	0.0000	C	2.70E-05	8.10E-05	0.00E+00	C
U-Top	0.53%	0.73%	0.00%	B	0.0015	0.0024	0.0000	B	2.70E-05	4.30E-05	0.00E+00	B

** $eros^{-1}$ refers to rainfall erosivity units of MJ ha^{-1} mm hr^{-1}*

*** Kurkal-Wallis Non-parametric ANOVA test*

Plot type	Equation	R^2	p-value
D-Low	Er = -0.0344 + [P*0.0459] + [V * 0.3916] - [P * V * 0.2434]	0.33	0.005
D-Top	Er = 0.01245 + [P * 0.00998]	0.20	0.004
Undisturbed	Er = 0.00211 + [P * 0.00129]	0.10	0.01

Where *Er* is sediment production in kg m^{-2}, *P* is rainfall in cm, and *V* is vegetation cover in decimal

	Erosion rate	Particle sizes of sediment				POM Content and Yields					
Plot	(kg m^{-2} cm^{-1})	Gravel	Sand	Silt & Clay	No. samples	% > 2mm POM	% < 2mm POM	POM yields* (kg m^{-2} cm^{-1})	% Sediment Production as POM	No. POM Samples	Inorganic yields (kg m^{-2} cm^{-1})
D-Low-1	0.033	4%	77%	19%	8	1.0%	6.3%	0.0037	6.2%	9	0.031
D-Low-2	0.020	12%	67%	21%	7	4.5%	5.6%	0.0014	5.0%	6	0.019
D-Low-3	0.018	9%	80%	11%	7	10%	11%	0.0040	11%	8	0.016
D-Low-4	0.0053	1%	72%	27%	7	11%	11%	0.0014	11%	7	0.0047
D-Low-5	0.050	5%	85%	12%	7	1.2%	5.4%	0.0002	0.87%	8	0.050
D-Low-6	0.045	10%	82%	11%	8	2.0%	4.7%	0.0006	1.6%	7	0.045
D-Low-7	0.018	2%	83%	15%	7	3.5%	3.9%	0.0014	3.9%	7	0.017
D-Low-8	0.0083	1%	84%	15%	9	11%	7.0%	0.0016	7.0%	7	0.0077
D-Low-9	0.0042	4%	83%	13%	7	11%	16%	0.0017	16%	7	0.0035
Average	*0.023*	*5%*	*79%*	*16%*	*7*	*6.1%*	*7.9%*	*0.0018* [A]	*6.9%*	*7*	*0.022*
D-Top-1	0.015	14%	78%	8%	8	7.0%	8.0%	0.0036	7.8%	6	0.014
D-Top-2	0.0072	19%	71%	10%	6	2.9%	11%	0.0020	9.6%	5	0.0065
D-Top-3	0.0081	22%	68%	11%	6	1.8%	9.4%	0.0016	7.6%	6	0.0075
D-Top-4	0.0046	28%	55%	17%	6	1.4%	9.3%	0.0010	7.8%	3	0.0043
Average	*0.009*	*21%*	*68%*	*11%*	*7*	*3.3%*	*9.4%*	*0.0021* [A]	*8.2%*	*5*	*0.0081*
U-Low-1	0.0001	19%	78%	3%	1	10%	10%	0.0001	10%	1	0.0001
U-Low-2	0.0040	45%	46%	9%	7	1.6%	9.4%	0.0007	5.3%	7	0.0038
U-Low-3	0.0000	27%	64%	9%	2	5.7%	16%	0.0001	13%	2	0.0000
Average	*0.0014*	*30%*	*63%*	*7%*	*3*	*5.8%*	*12%*	*0.0003* [B]	*10%*	*3*	*0.0013*
U-Top-1	0.0014	38%	55%	7%	2	2.1%	16%	0.0007	11%	2	0.0012
U-Top-2	0.0026	27%	65%	8%	7	3.4%	17%	0.0007	13%	7	0.0022
U-Top-3	0.0006	37%	52%	11%	6	4.8%	21%	0.0004	14%	6	0.0005
Average	*0.0015*	*34%*	*57%*	*9%*	*5*	*3%*	*18%*	*0.0006* [B]	*13%*	*5*	*0.0013*

** ANOVA One-Way Test on ln transformed values: p-value < 0.0001; A & B denotes Tukey multiple comparison test results on transformed yields*