



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 of 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.

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 Maslin, 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., 2012; 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; Weil, 2004) 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

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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 > 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 km²) 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 (Fig. 1). The lithology is dominated by bioclastic limestones, mudstones, and cherts of the Upper Cretaceous La Parguera Formation (Volckman, 1984). Soils are mostly shallow (< 30 cm), 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 Parguera 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 and 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 García-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 1 h 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 m²) bounded plots (Fig. 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 (Fig. 2b). Each plot connected to a pair of 100 L runoff collection containers by heavy-duty garden hoses (Fig. 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 (Fig. 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) (Fig. 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

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