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Research article

Plot-, farm-, and watershed-scale effects of coffee cultivation in runoff and sediment production in western Puerto Rico

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ABSTRACT

The combination of a topographically abrupt wet-tropical setting with the high level of soil exposure that typifies many sun-grown coffee farms represents optimal conditions for high erosion rates. Although traditionally considered as a main cause for water resource degradation, limited empirical evidence has existed to document its true contribution. This study relies on plot-scale experimental results conducted in western Puerto Rico to assess the impact of cultivated surfaces and farm access roads on runoff and sediment production from the plot to the farm and watershed scales. Results show that unsurfaced and graveled road surfaces produce one- to two-orders of magnitude more per unit area runoff than cultivated lands. Similarly, erosion rates from unsurfaced roads are about 102 g m^{-2} per cm of rainfall and these are two-orders of magnitude greater than from actively cultivated surfaces. Mitigation practices such as uncompacting road surfaces by ripping and gravel application reduce onsite erosion rates to 0.6% and 8% of unsurfaced conditions, respectively. At the farm scale, coffee farms are estimated to produce sediment at a rate of 12–18 Mg ha^{-1} yr^{-1}, and roads are undoubtedly the dominant sediment source responsible for 59–95% of the total sediment produced. The costs associated to ameliorating erosion problems through road graveling are high. Therefore, a combined approach that treats road erosion onsite with one that traps sediment before it reaches river networks is the viable solution to this problem.

1. Introduction

Soil erosion from agricultural lands is one of the world's most pressing environmental problems as it may degrade both soils and water resources (Clay, 2004). Erosion due to coffee cultivation is an environmental threat in continental settings in Africa, Central and South America, (e.g., Temple, 1972; Angima et al., 2003; Lufafa et al., 2003; Hoyos, 2005; Vrieling et al., 2006; Meylan et al., 2013) as well as in island settings throughout Southeast Asia, the Pacific, and the Caribbean (Craswell et al., 1998; McDonald et al., 2002). Although soil erosion from coffee farms has been assumed as a cause of water resource degradation in Puerto Rico (PR), its reputation owes mostly to either anecdotal evidence (Campbell, 1947) or to watershed modeling (e.g., Cruise and Miller, 1993; López et al., 1998). The 13,000 ha of coffee farms in PR (USDA, 2014) occupy the headwaters of watersheds representing about a third of the island's landmass. Therefore, coffee cultivation is likely responsible for a significant portion of PR's poor stream water turbidity rating (U.S. EPA, 2014), water reservoir capacity losses due to sedimentation (Soler-López, 2001a), and coral reef degradation (Miller and Cruise, 1995; Larsen and Webb, 2009).

The reputation of coffee farms as sources of sediment in PR led to the development and implementation of erosion mitigation plans for selected watersheds (CWP, 2008). Understandably, most of the literature on coffee farm erosion in PR (e.g., Smith and Abruña, 1955), like elsewhere, has been mostly concerned with soil productivity issues (Lal, 1998; Pimentel, 2006). Hence, prescribed erosion control practices have focused on cultivated hillslopes presumably due to lack of scientific evidence suggesting other alternatives and farmers' perceptions of soil erosion effects on coffee yields (Abruña et al., 1959; Borkhataria et al., 2012).

Downstream water quality concerns merit a farm- and watershed-scale approach that recognizes coffee farms as a mosaicked terrain with various landscape units, each with unique runoff and sediment production responses (Reid and Dunne, 1996).

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Cultivated lands tend to erode at rates that are 10- to 100-times higher than background rates (Montgomery, 2007) and coffee-growing surfaces in PR appear to be no exception (Smith and Abruña, 1955). Nevertheless, farm management styles vary and each implies relevant differences in weed removal patterns (Vicente-Chandler et al., 1968; Estación Experimental Agrícola, 1999). Hence, cultivated surfaces have a variety of understory cover densities, a key factor controlling soil erosion (Smith and Abruña, 1955; Durán-Zuazo and Rodríguez-Pleguezuelo, 2008). A landscape unit within coffee farms that deserves attention is the unpaved road network because previous research indicates that unpaved roads can be responsible for the majority of the sediment produced at the farm and watershed scales (Harden, 2001; Motha et al., 2004; Ziegler et al., 2004; Rijsdijk et al., 2007; Thomaz et al., 2014; Thomaz and Ramos-Scharrón, 2015). However, limited work has proven their importance in coffee farm settings.

Modeling approaches to assess the impacts of agricultural activities on runoff and sediment generation are no substitute to empirical data (Trimble and Crosson, 2000). Through the identification of unique landscape units (Wallbrink and Croke, 2002), this study assessed the impacts of land management in a coffee farm setting through experimental runoff and sediment budget approaches (Renschler and Harbor, 2002). Therefore, this study has the following two main objectives: (1) to quantify plot-scale runoff and sediment production rates from different landscape units through rainfall simulation experiments; and (2) to evaluate the relevance of these landscape units in the amount of runoff and sediment generated at the farm and watershed scales. This study adds to the limited literature on the hydro-geomorphic effects of roads in coffee farms by using the experimental results to conduct a storm-by-storm analyses of runoff and sediment production and develop a farm-scale annual accounting of precipitation excess and sediment production. In addition, this study compares the potential benefits of various erosion mitigation strategies at scales ranging from the plot-, farm-, and watershed scales.

The study took place in the San Carlos coffee farm in the western highlands of PR (hereafter referred to as SC). SC has a slope-corrected, real surface area of 18.0 ha and represents 1.1% of the total 1554 ha of coffee growing surface area draining towards Lago Lucchetti (Fig. 1). The 50.7 km^2 Lago Lucchetti surface area (44.2 km^2 planimetric area) has the highest sediment accumulation estimate of all water reservoirs in PR (39–46 Mg ha^{-1} yr^{-1} versus an island-wide average of 14 Mg ha^{-1} yr^{-1}; planimetric area normalized; Soler-López, 2001b). In fact, the sediment yields reported for Lucchetti are comparable to some of the highest values reported in the literature for mountainous rivers (Kao and Milliman, 2008; Milliman and Farnsworth, 2011), and surpass those for any river in PR (Río Portugués: 43 Mg ha^{-1} yr^{-1}; Larsen and Webb, 2009).

2. Materials and methods

2.1. Study site description

SC is located in the headwaters of Río Yauco (Lat 18.131N; Lon 66.889W). Slopes within SC average 28° and reach up to 53°. Cultivated land occupies a surface area of about 13.9 ha (77% of SC; Fig. 2) and it mostly consists of sun-grown coffee and mixed cropland including oranges, bananas, and plantains which is typical for coffee farms in PR (Borkhataria et al., 2012). Forests occupy only 2.7 ha or 15% of SC. The 4.78 km of unpaved access roads (0.34 km ha^{-1}) cover 1.4 ha or 8% of SC and have an average slope of 14%.

The underlying bedrock is volcaniclastic sandstone and siltstone of the Yauco formation (McIntyre, 1975). Soils are Ultisols of the Maricao and Agüeybaná clay series (~60% clays) with a shallow topsoil layer (~13 cm) and a high runoff potential (Hydrological group D) (Gierbolini, 1975). Soils are similar to the Ferrasols and Acrisols described for coffee growing areas in Southeast Asia (Iijima et al., 2003), Central America (Schmitt-Harsh, 2013), and Brazil (*terra roxa*; James, 1932). Climate is typical for subtropical wet and moist forest (Ewel and Whitmore, 1973) with normal rainfall ranging from 184 to 242 cm yr^{-1} (NOAA, 2002). About 49% of the rainfall recorded at Lago Lucchetti falls at intensities from 1.0 to 6.3 cm h^{-1} (Ramos-Scharrón and Thomaz, 2017).

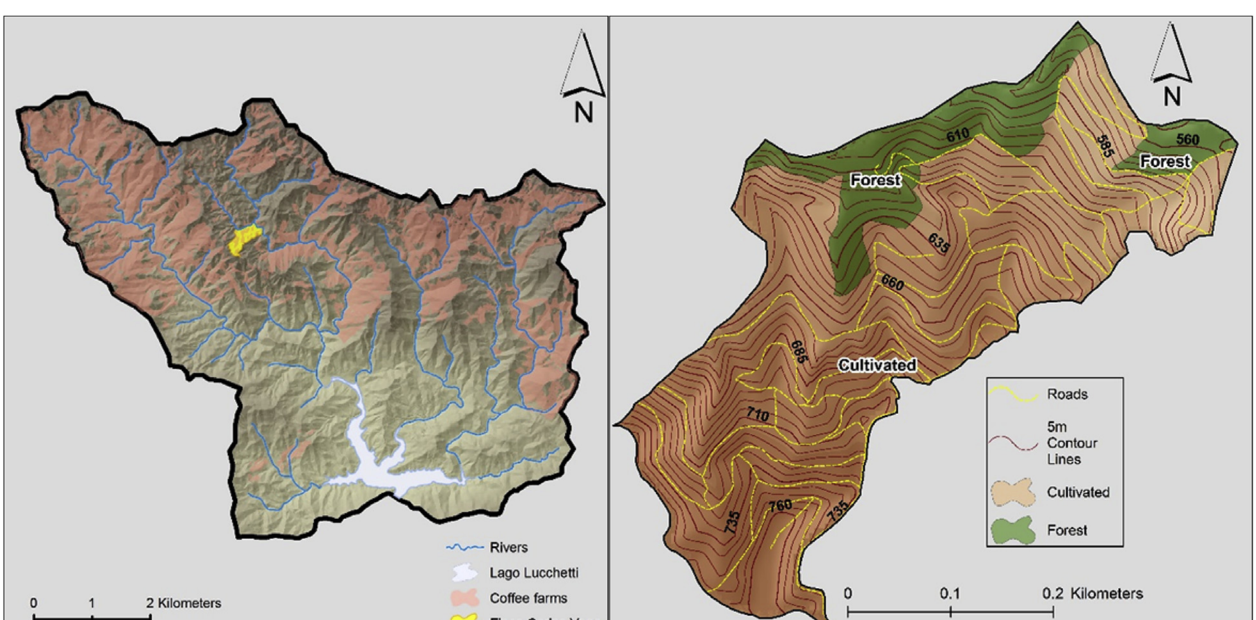

Fig. 1. Maps of the Lago Lucchetti watershed including the location of coffee-growing areas (left) and Finca San Carlos (right).