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Effects of land use on soil properties and hydrological processes at the point, plot, and catchment scale in volcanic soils near Turrialba, Costa Rica

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ABSTRACT

Deforestation and conversion to crop land and pasture in tropical regions has important effects on hydrological processes including increased flooding and reduced drought flows. We investigated: 1) differences in soil characteristics between four tropical land uses (forest, coffee, sugar cane and pasture), and 2) how hydrological processes differ between these four land uses. We measured bulk density, saturated hydraulic conductivity (K_{sat}), soil moisture content, catchment discharge and conducted infiltration, mass balance, and dye tracing tests at four catchments within the Reventazón watershed near Turrialba, Costa Rica at the point scale, the plot scale (1 m^3), and the catchment scale (1–6 ha). While most of the soil characteristics between the field sites were similar, bulk density at the forest site (0.7 g cm^{-3}) was significantly lower than bulk density at the other field sites (1.0 g cm^{-3}). At the forest and coffee sites, K_{sat} (> 32 mm hr^{-1}) was at least twice the K_{sat} (< 13 mm h^{-1}) at the sugar cane and pasture sites. During mass balance experiments at the plot scale, sugar cane and pasture had greater surface runoff and lateral flow coefficients (> 30%) than the coffee and forest (< 16%). Irrigated dye experiments revealed roots and macropores were important flow paths in the forest and coffee sites, while machinery, cattle compaction, and lack of large roots impacted the sugar cane and pasture hydrological processes. At the surface, seasonal soil moisture in the sugar cane and pasture sites was consistently greater than in soils of the forest and coffee sites. At the catchment scale, discharge was minimal (< 10%). The sugar cane site had the greatest catchment scale discharge coefficient (7%), event frequency, depth and rate. Overall, the forest and coffee land use had greater water storage capacity, hydraulic conductivity, and percolation compared to the pasture and sugar cane sites. The interplay of different root distributions, compaction, and different soil moisture dynamics affected infiltration and storage dynamics. These findings have important implications for tropical groundwater recharge and runoff predictions.

1. Introduction

In humid tropical countries, hydrological processes profoundly affect economic livelihoods, energy production, human health and the quality of the environment. In Costa Rica, storm runoff has led to loss of human lives, residences, crops, and public infrastructure (Waylen and Laporte, 1999). Extreme peak flows and sediment transport reduce the capacities of the many small scale hydropower projects that produce a majority of the country's electricity demand (Jansson and Erlingsson, 2000; Sanchez-Azofeifa et al., 2002). Percolation, surface runoff, and subsurface lateral flows direct chemical loading that negatively affects water quality as the population increases (Reynolds-Vargas et al., 1994; Rawlins et al., 1998; Renderos-Duran et al., 2002.) Increased understanding of the effects of land use on hydrological processes that drive flooding, erosion, and contamination will contribute to better water resource management in the humid tropics. Specific knowledge about the hydraulic conductivity, water retention characteristics and rooting patterns of upland crops in tropical environments is needed both in Costa Rica and within the tropical hydrology community (Bonell, 1993; Giambelluca et al., 1999; Bigelow, 2001; Godsey and Elsenbeer, 2002; Bruijnzeel, 2004; Wohl et al., 2012).

Land use affects soil hydrological characteristics such as preferential flow paths, saturated hydraulic conductivity (K_{sat}), macropore connectivity, root mass and water retention (Himo et al., 1987; Hendricks and Flury, 2001; Hanson et al., 2004; Williamson et al., 2004). Preferential flow paths often determine flow directionality (e.g., lateral vs.

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vertical) in humid forested hillslopes (Mosely, 1979; McGlynn et al., 2002; Tromp-van Meerveld and McDonnell, 2006). The K_{sat} can be used to distinguish the dominant hydrological paths in tropical soils (Elsenbeer, 2001; Ziegler et al., 2004). Non-forested land consistently has lower K_{sat} than forested landscapes (Godsey and Elsenbeer, 2002; Zimmerman et al., 2006, 2010; Germer et al., 2010). Compaction from cattle, tractors, plows and foot paths lowers infiltration rates, reduces percolation, destroys macropores, and increases surface runoff (Mendoza and Steenhuis, 2002; Hanson et al., 2004; Ziegler et al., 2006; Verbist et al., 2007). Integrative field campaigns that examine soil moisture dynamics with depth and quantify field hydrological characteristics in the humid tropics are greatly needed to better understand tropical hydrology (Wohl et al., 2012). The specific objectives of this field study were to 1) quantify differences in the hydrologic soil characteristics with depth of coffee, sugar cane, pasture, and forested land uses in a humid tropical region, and 2) compare the extent to which the unique soil hydrologic characteristics of each of these land uses drives hydrological processes at the point, plot, and catchment scales.

2. Methods and materials

2.1. Study site

The study was conducted on the Tropical Agricultural Research and Higher Education Center (CATIE) farm near Turrialba, Costa Rica at approximately 650 masl (Fig. 1). This farm lies approximately in the middle of the Rio Reventazón basin, which is one of the major drainages running from the central mountain range to the Caribbean Sea (Jansson, 1996). The study area receives 2500–3000 mm of rainfall annually (Chacón and Fernandez, 1985). Two volcanoes, Irazu and Turrialba, influence rainfall and soils in the study area through orographic lifting and volcanic ash deposition. During the dry season (January through April), monthly average rainfall ranges from 86.7–177.5 mm. During the wet season (May through December), average monthly rainfall ranges from 245 to 310 mm rainfall. Temperatures average between 20.6 and 22.7 °C throughout the year, with an average annual absolute maximum temperature of 33 °C (December) and an average annual absolute minimum temperature of 10 °C (January). Potential evapotranspiration (PET) ranges from 85 mm month^{-1} (July) to 115 (April) mm month^{-1} with a mean of 95 mm month^{-1}.

2.2. Land use characteristics and management

Experiments and monitoring were performed at four different catchments, with each catchment having only one continuous homogenous land use cover: forest (6.1 ha), sugar cane (4.5 ha), pasture (1.9 ha), and coffee (1.2 ha) (Fig. 1). Each catchment had a predominant eastern aspect and flow direction with similar mean slopes and flow lengths (Table 3). These land use types are representative of the predominant land uses for the upper Reventazón watershed (forest 40%, pasture 21%, coffee 14%, and sugar 12%) (Toohey, 2012). Each catchment had homogenous land use with distinct vegetation characteristics and management practices that was drained by a single intermittent stream channel (Fig. 1). At this site, mature sugar cane was burned then harvested in April every year. Following harvest, it is plowed using a large tractor and tillage discs. The sugar cane catchment was nested within the forested catchment (Fig. 1). The forest site contained a mixture of primary and secondary vegetation consisting of few large trees (> 1 m in diameter at 1.5 m in height) and a sparse understory with almost a completely closed canopy. No management had occurred at the forest site since at least the 1950s. The coffee and pasture catchments were hydrologically isolated catchments. In 2004, the pasture was active with approximately 10 cows ha^{-1} resulting in signs of compaction at the surface by hoof prints and cattle paths that were still noticeable in 2007. After January 2005, when the pasture was abandoned, razor grass with average height of 1 m quickly overtook the pasture field site. The coffee site was managed as a standard *Erythrina* spp. shade system (≈ 50% shaded) with conventional chemical management. Coffee was harvested by groups of workers three times a year. About one month prior to harvest, shade trees were pruned to a tall stump (1–1.5 m) to allow ripening of the coffee beans. Therefore, this site received full sun for about three months of the year.

2.3. Soil properties

Soil sampling was conducted at each field site in January of 2006. Soil sampling was stratified by slope location: toe slope, mid slope and ridge positions. Sampling locations were randomly selected within these stratifications. Nine soil pits (three per slope position) were hand dug in each field site to a 1 m depth. Soils were classified using the National Resource Conservation Service soil taxonomic Handbook (Soil Survey Division Staff, 1993) based on observed soil horizons, color, structure, pore size and density, and rock content of the profile. Root size and depth was measured using calipers and a ruler. Root density

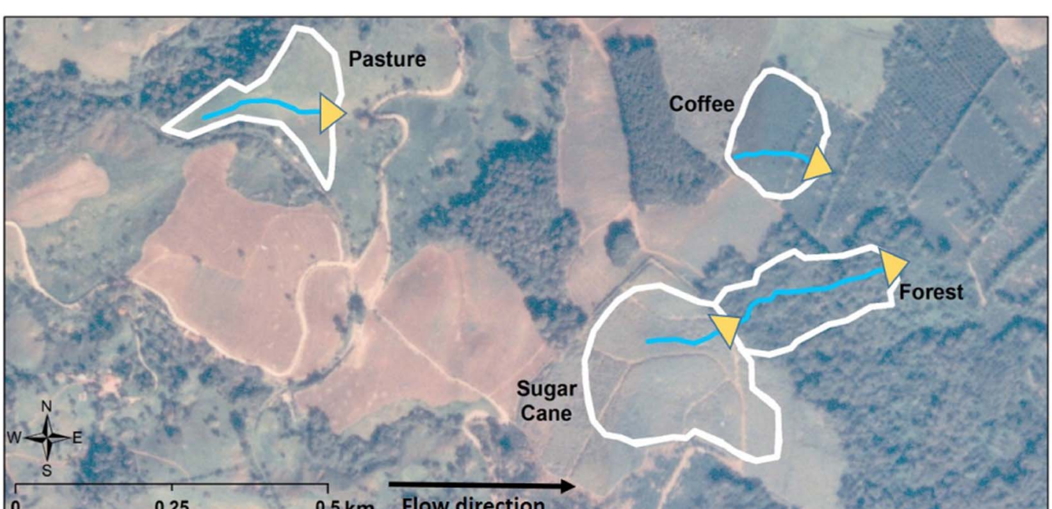

Fig. 1. Location of forest, coffee, sugar cane and pasture catchments (outlined in white). Stream channels are delineated in blue, and flume locations are indicated by yellow triangles. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)