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Implications of land use change on runoff generation at the plot scale in the humid tropics of Costa Rica

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ABSTRACT

Recent land use changes in Central America have involved the abandonment of marginal farmland activities, the regeneration of secondary forest and the spread of high return crops such as oil palm plantations. The potential impacts of land use change on overland flow are evaluated using data from Tinoco Experimental Catchment (South Pacific Costa Rica). Our main hypothesis is that secondary forest overland flow is lower than the one generated under the other land cover types. For this purpose, runoff responses at plot scale are analyzed for different land uses: secondary forests, forest plantations, oil palm plantations and grasslands. Runoff plots were situated over former grasslands, abandoned 8–15 years prior to plot settlement. Measurements were conducted at two complementary spatial scales i) the plot (150 m^2) under natural precipitation and ii) rainfall simulation on microplots (0.0625 m^2). The combination of natural and simulated rain runoff response measurements provides a more accurate picture of the overland flow generation in the study site. Secondary forest shows a significantly lower runoff response than grassland and oil palm plantations, although there are no significant differences among the plots in variables such as saturated hydraulic conductivity (Ks). The oil palm plantation plot presented the highest runoff coefficient (mean RC = 32.6%), twice that measured under grasslands (mean RC = 15.3%) and 20-fold greater than in secondary forest (mean RC = 1.7%). The runoff plots part of the Tinoco Experimental Catchment provide valuable data and coefficients for evaluating the influence on overland flow of secondary forest recovery and oil palm plantation expansion over hillsides, contributing to a better understanding of the effects of land cover dynamics on water resources in the humid tropics.

1. Introduction

Mountain ecosystems play an essential role in the water cycle as regulators and sources (Price, 1999). More than 50% of the global population relies on water from mountain areas for drinking, agriculture and other purposes (Viviroli et al., 2003). Central American rural areas have a strong dependence on these mountain catchments for water supply as there is a lack of aquifers and water reservoirs for drinking purposes and surface water supply systems from creeks or streams are common. At present, many of the water supply priority basins in the tropics comprise a mosaic of land uses: forests, agricultural areas and other abandoned land in various stages of recovery. Understanding the hydrological responses of mountain catchments with differing histories as regards land use and land cover allows us to assess the effects of ongoing or future changes in land use and land cover on surface runoff and water availability. More specifically, overland flow generation on hillsides is crucial to evaluating the impact of land use change on hydrological functions (Ceballos and Schnabel, 1998).

The hydrological responses of these systems are affected by factors such as soil physical characteristics, vegetation type and topography. Changes in any of these factors are likely to affect the catchment runoff responses. Although an increasing amount of research is directed towards evaluating the effect of global changes on the water cycle, quantitative assessments of the impact of recent land use/land cover change on hydrological processes require more measurements in the field in order to characterize runoff processes, particularly in tropical areas (Hassler et al., 2011).

Recent land use changes occurring in Central America are linked to the abandonment of marginal farmland activities and to the spread of high return crops such as oil palm (*Elaeis guineensis* Jacq.) plantations (FAOSTAT, 2014). Furthermore, secondary forests are expanding due to the abandonment of grassland and reforestation initiatives, mainly in the upper-catchment areas. Evidence of the effect of these processes

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on the water cycle and on soil recovery is still scarce, although a number of quantitative studies exist which highlight their importance (Hassler et al., 2011; Ziegler et al., 2004; Zimmermann et al., 2006, 2010).

Oil palm plantations are increasing their presence on the hillsides of some Latin American countries such as Costa Rica thanks to their high profitability in comparison to rangelands (Janssen and Rutz, 2011; Mingorría et al., 2014). This land cover change process has been documented in Costa Rica (Höbinger et al., 2012), where it is more intense in the Southern Pacific region. Research into the impacts of oil palm cultivation has not so far provided a comprehensive assessment of its effect on the water balance since most studies have focused on deforestation, biodiversity and ecosystem services (Höbinger et al., 2012) or nutrient cycling (Comte et al., 2012). In addition, most of these studies have been conducted in the lowlands, with relatively flat topography. The main factor affecting soil infiltrability under oil palm plantation is soil compaction (Lestariningsih et al., 2013) and its high spatial variability in the plantation (Banabas et al., 2008). Soil infiltrability and erosion processes have been highlighted by several authors as an especially problematic impact (Comte et al., 2012; Hartemink, 2003, 2006), particularly when oil palms are planted on steep slopes. At global scale, few studies provide field data measurements on this issue and to our knowledge, no case studies have been documented in Latin America.

The objective of this study is to characterize hillslope overland flow processes and compare them between main land cover types at plot scale in order to estimate the effects of ongoing grassland abandonment, reforestation and oil palm plantation expansion in overland flow in mountain catchments in South Pacific Costa Rica. Our main hypothesis is that secondary forest overland flow is lower than the one generated under the other land cover types. Results and coefficients obtained would be useful to future hydrological and catchment modeling in the region.

2. Materials and methods

2.1. Study region

This study was conducted in the Osa region on the South Pacific coast of Costa Rica, where the foothills of the Fila Costeña (with a maximum altitude of approximately 500 m) meet the coastal plain (Fig. 1). The region is characterized by mean annual precipitation ranging from 3000 to 6000 mm, which is distributed between a dry season (December–April) and a wet season (May–November). The region encompasses large areas of Humid Tropical Forest (including various National Parks), the largest mangrove reserve in Costa Rica (RAMSAR Wetland Térraba-Sierpe) and a lowland agricultural area with extensive oil palm, plantain (*Musa* sp. L.) and banana plantations. The Fila Costeña Coastal Range is covered by a mosaic of land uses including small patches of old forests, secondary forests, small scale agriculture (basic grains, plantain and banana), grasslands, forest plantations and more recently, oil palm plantation and dispersed urbanization projects. In addition, the Fila Costeña provides a key environmental service, being the main source of water collection and recharge for rural communities in the region. These characteristics of the Osa region are also representative of many other coastal regions in Northern Latin America. Hence, the Osa region was identified as an ideal scenario to analyze the impacts of land use changes on the hydrological processes in these systems.

The Tinoco river basin, a representative watershed in the Fila Costeña (Fig. 1), was chosen as an experimental catchment. The land cover types present in the Tinoco Experimental Catchment are representative of the main land covers of the region, such as permanent tree crops (African oil palm), grassland in different stages of degradation due to overgrazing, forest plantations and secondary forest patches, which are mainly situated in remote areas on hillsides, particularly in the upper-catchment areas. Runoff response of these land covers was analyzed at plot scale at two complementary spatial scales i) the plot (150 m^2) under natural precipitation and ii) rainfall simulation on microplots (0.0625 m^2). The basin is located within a sedimentary rock formation originating from deep waters. Soils in the basin are relatively young Inceptisols and Entisols derived from lutites (Soil Survey, 2010). Differences in the physical properties of the soil under different land cover types are small for most of the parameters (Table 1). Water Holding Capacity presents values considered normal for the soils in the region, with significantly higher values in the subsoil compared with the topsoil, and high variability within each site. Saturated hydraulic conductivity (Ks) values indicate a slow water movement in saturated conditions (which is considered normal in the clayey soils in the study region) and a generalized high variability within each site. In all the plots soils display fast recovery of water content during the first storms of the season, with values remaining near field capacity over the whole rainy season (Table 2).

2.2. Storm-runoff measurements

Runoff plots of 150 m^2 were established in an oil palm plantation, a grassland field, a secondary forest land, and a forest plantation field (Fig. 1). The oil palm plantation is 10 years old and the average height of the palms is 3 m. The 12–15 years old secondary forest plot is situated in the upper catchment area. Forest plantation (white teak, *Gmelina arborea* Roxb) is 10 years old. Forest plantation plot measurements were not included in this study due to problems with the devices installed for automatic measurement of the storm-runoff response. All plots were located over clay soils and former grasslands to avoid the effects of prior land use differences on current soil properties. This information along with the age of both the plantations and the secondary forest were gathered from interviews with farmers and land owners. The plots were selected according to a slope range between 25–35%. Site parameters (climate, geology and soil) in the basin are uniform and the plots established are considered comparable. Surface runoff was automatically monitored using a specifically designed sensor, based on the conventional tipping bucket rain gauge. The volume of the bucket on our device was 1 L. Sensors were calibrated in the laboratory for different rainfall intensities and were installed in the field inside a safety structure.

The measurement of the storm events selected for this study was carried out during the rainy season 2011 (July–December) using a Campbell Sci. rainfall tipping bucket device installed in the upper part of the catchment. The highest recorded rainfall occurred on 21st October (227 mm), coinciding with the influence of the Rina tropical storm on the Pacific coast of Costa Rica. The 26 storms had a differing range of intensities and durations and were selected according to the criteria of Wischmeier and Smith (1978). In general, a storm is defined as an event in which rainfall exceeds 12.7 mm and which does not include a rain-free period exceeding 4 h or an event in which at least 6.4 mm of rainfall accumulates within a 15 min period. The selected storm events vary from 17.53 mm to 227.60 mm of precipitation, with durations between 1 h and 36 h (Table 2). Event characterization was performed according to rainfall volume, duration and event intensity. Additionally, the 30-minute maximum rainfall intensity was calculated for each event (I_{30_max}). Events that occurred after two rain-free days (T9, T14, T23, and T26) where considered “dry” events; although there were no differences in soil water content prior the events as this parameter was almost constant during the rainy season (Table 2). The runoff coefficient for each recorded storm was calculated as Eq. (1):

$$RC = (RD/PD) \times 100\%$$

where, RC (%), RD (mm) and PD (mm) denote runoff coefficient, runoff and precipitation of the event respectively.