Catena 135 (2015) 263–270

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

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

Nur Algeet-Abarquero [a,b,*], Miguel Marchamalo [a,*], Javier Bonatti [c], Jesús Fernández-Moya [b,d], Roger Moussa [e]

[a] Departamento de ingeniería y morfología del terreno, Universidad Politécnica de Madrid, 28040 Madrid, Spain
[b] Lab. Recursos Naturales, Centro de Investigaciones Agronómicas, Universidad de Costa Rica, San José, Costa Rica
[c] Centro de Investigaciones en Ciencias Atómicas, Nucleares y Moleculares, Universidad de Costa Rica, San José, Costa Rica
[d] Dpto. Silvopascicultura, Universidad Politécnica de Madrid, C. Universitaria s/n, 28040 Madrid, Spain
[e] INRA, UMR LISAH, 2 Place Viala, 34060 Montpellier, France

ARTICLE INFO

Article history:
Received 12 September 2014
Received in revised form 17 July 2015
Accepted 10 August 2015
Available online 2 September 2015

Keywords:
Overland flow generation
Land use change
Secondary forest
Oil palm
Grassland abandonment
Runoff plots

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

---

* Corresponding authors.
E-mail address: nuralgeet@gmail.com (N. Algeet-Abarquero).

http://dx.doi.org/10.1016/j.catena.2015.08.004
0341-8162/

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.

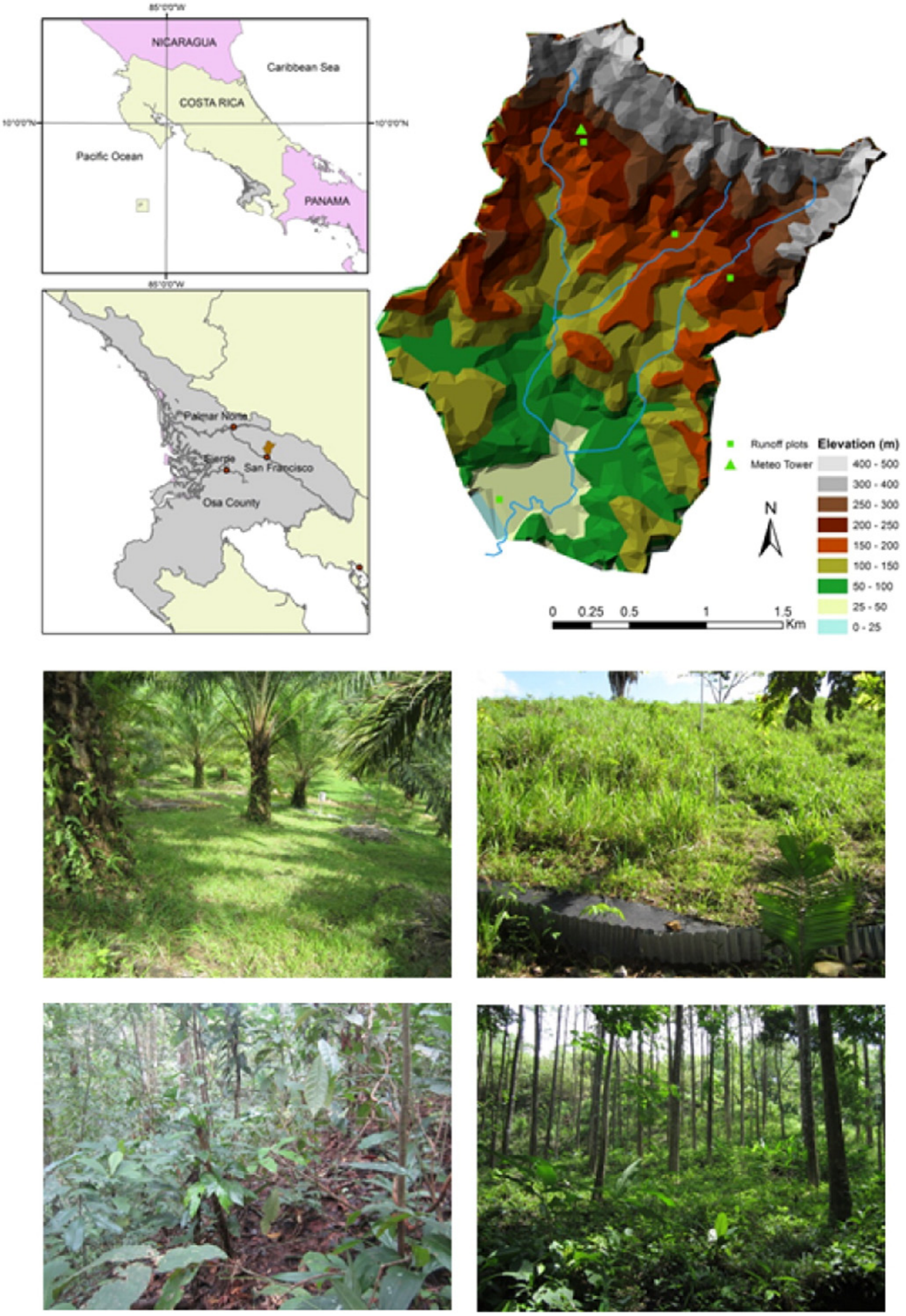

Fig. 1. Location of the study site in Tinoco Catchment, in the Southern Pacific region of Costa Rica. The pictures show the land uses studied: oil palm plantation; grassland; oil secondary forest; and forest plantation.

2.3. In situ rainfall simulation runoff measurements

A rainfall simulator manufactured and sold by Eijkelkamp Agrisearch Equipment was used to evaluate the runoff response and the sediment yield generation of the different land uses under high intensity rainfall. The device consists of a capillary sprinkler with a built-in pressure regulator for the production and control of a standard rain shower, an adjustable support for the sprinkler and a ground frame, which is placed on the soil and prevents the lateral movement of water from the test plot to the surrounding soil (Iserloh et al., 2013). The device has a surface area of test microplot of 0.0625 m^2. The duration of the rain simulation was 5 min and the rain intensity defined for the study was 384 mm h^{-1}. The simulation measurements were performed at microplots in the same sites where the runoff plots were established, but not inside the plots themselves. Besides secondary forest, grassland and oil palm plantation, the forest plantation (white teak, *G. arborea* Roxb) site was also evaluated under this experiment. Field measurements, with 5 repetitions per land use, were performed during the 2013 rainy season (September), when the soil water content was at field capacity. Microplots where located at different positions in the

Table 1
Median and range values of soil parameters for oil palm plantation, grassland, forest plantation and secondary forest in the Tinoco Catchment (Costa Rica).

		Oil palm		Grassland		Forest		Forest plantation	
		Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil	Topsoil	Subsoil
Ks	Median	0.60	0.03	0.41	0.68	0.12	0.37	0.33	0
(cm h^{-1})	Range	0–75.85	0–5.99	0–6.55	0–7.54	0–28.05	0–1.89	0–7.14	0–0.89
WHC (%)	Median	8.50	23.00	10.85	31.00	8.50	39.50	7	14
	Range	1–23	6–36	6–19	10–55	2–18	8–63	2–16	5–20
Porosity	Median	59.35	56.63	70.33	65.80	67.44	55.66	60	53
(%)	Range	42–72	56–59	62–71	63–75	57–70	51–60	59–62	37–61
Macroporosity	Median	10.13	0.00	23.34	2.18	26.27	0.00	12	0
(%)	Range	0–15	0–12	0–58	1–3	6–43	0	7–16	0–1
Clay	Median	50.00	50.00	50.00	52.50	50.00	32.50	55	58
(%)	Range	35–58	25–63	50–60	50–58	30–55	30–43	50–56	50–58
Sand	Median	34.00	47.50	45.00	37.50	40.00	50.00	36	30
(%)	Range	25–40	32–55	25–48	25–40	25–60	33–64	35–43	24–45
Silt	Median	10.00	5.00	5.00	12.00	10.00	20.00	8	12
(%)	Range	8–40	2–20	2–15	2–22	5–25	3–24	7–10	5–18

field, trying to cover the spatial variability of the soil surface and land cover of the plots. Sediment samples from these rainfall simulation tests were dried out and weighed at the Natural Resources Laboratory facilities of the University of Costa Rica.

2.4. Statistical analysis

Paired t-tests were used to evaluate the statistical significance of the differences between the means of the variables analyzed (runoff coefficients based on storm data from the runoff plots; and runoff and sediment based on rainfall simulation data from the microplots) under the land uses evaluated (secondary forests, grasslands, palm plantation and forest plantation). A 90% confidence level was considered for all the statistical tests, if the contrary is not assessed. R software was used for the statistical analyses (R Development Core Team, 2006).

3. Results

3.1. Storm/runoff response

The runoff responses to the storm events are characterized by total runoff volume, peak runoff flow and runoff coefficients. Responses are not affected by prior wetness condition of the soil (Fig. 2). Soil water content of the plots measured at 15 and 45 cm shows a permanently saturated condition of the soil from the beginning of the rainy season. Water content at 15 cm prior rain events (Table 2) ranges between 88–91% for the oil palm plantation plot, between 80–82% for the grassland plot and between 78–96% for the secondary forest plot. Runoff response to storms that occurred after two rain-free days (T9, T14, T23, and T26) is similar to the responses of the rest of the storms (Fig. 2).

Our study illustrates fundamental differences in storm flow responses between land uses (Fig. 2 and Fig. 3). The secondary forest plot generates a reduced amount of runoff, regardless of storm intensity

Table 2
Storm characterization and initial soil water content of the study plots in Tinoco Catchment (Costa Rica). P is the precipitation, T is the duration of the rain event, I30_max is the maximum intensity over a 30 minute period of the event, I_{event} is the mean intensity of the event and Θ_{i}_15 cm is the initial water content at 15 cm depth for each study plot (PAL, oil palm plantation; GRA, grassland; FOR, secondary forest).

	P (mm)	DOY	T (h)	I_{30_max} (mm/h)	I_{event} (mm/h)	Θi_15cm (%)		
						PAL	GRA	FOR
T 1	17.78	2011-08-20 13:30	4.25	12.70	4.18	88.79	80.37	79.44
T 2	18.54	2011-08-21 14:35	4	21.34	4.64	90.65	80.37	79.44
T 3	64.51	2011-08-22 13:20	6	87.37	10.75	88.79	80.37	79.44
T 4	47.49	2011-08-28 12:35	5	37.08	9.50	88.79	80.37	78.50
T 5	41.91	2011-09-01 1:45	2	58.42	20.96	90.65	81.31	79.44
T 6	67.06	2011-09-04 15:00	3.5	102.12	19.16	87.85	80.37	79.44
T 7	75.44	2011-09-24 15:00	6	35.06	12.57	87.85	80.37	79.44
T 8	64.76	2011-09-25 12:30	7	60.96	9.25	87.85	81.31	79.44
T 9[a]	65.27	2011-09-28 14:00	5.5	61.46	11.87	87.85	80.37	79.44
T 10	38.35	2011-09-29 20:30	1	47.24	38.35	87.85	81.31	79.44
T 11	14.98	2011-09-30 12:30	4	12.19	3.75	88.79	81.31	79.44
T 12	28.70	2011-10-01 14:30	7.5	14.73	3.83	87.85	80.37	79.44
T 13	17.52	2011-10-02 17:00	3.5	15.75	5.01	87.85	80.37	79.44
T 14[a]	45.46	2011-10-07 13:00	9	44.20	5.05	87.85	80.37	79.44
T 15	104.9	2011-10-08 12:00	7.5	70.10	13.99	87.85	81.31	79.44
T 16	32.25	2011-10-09 5:00	16	18.28	2.02	88.79	81.31	96.26
T 17	49.78	2011-10-10 9:00	13	10.67	3.83	87.85	81.31	79.44
T 18	10.41	2011-10-11 12:30	6	3.05	1.74	87.85	80.37	80.37
T 19	44.19	2011-10-13 14:00	13	11.68	3.40	87.85	81.31	81.31
T 20	38.35	2011-10-14 12:30	8.5	12.70	4.51	88.79	81.31	81.31
T 21	30.98	2011-10-16 4:00	11.5	13.21	2.69	89.72	82.24	81.31
T 22	86.36	2011-10-17 8:00	35	11.18	2.47	87.85	81.31	80.37
T 23[a]	227.6	2011-10-21 13:00	29	34.04	7.85	87.85	80.37	79.44
T 24	17.53	2011-10-23 13:30	6.5	17.28	2.70	88.79	81.31	79.44
T 25	16.51	2011-10-24 14:30	9	8.64	1.83	87.85	80.37	79.44
T 26[a]	11.93	2011-10-27 19:00	2	15.75	5.97	87.85	81.31	79.44

[a] Storms occurred after a minimum of 2 rain-free days.

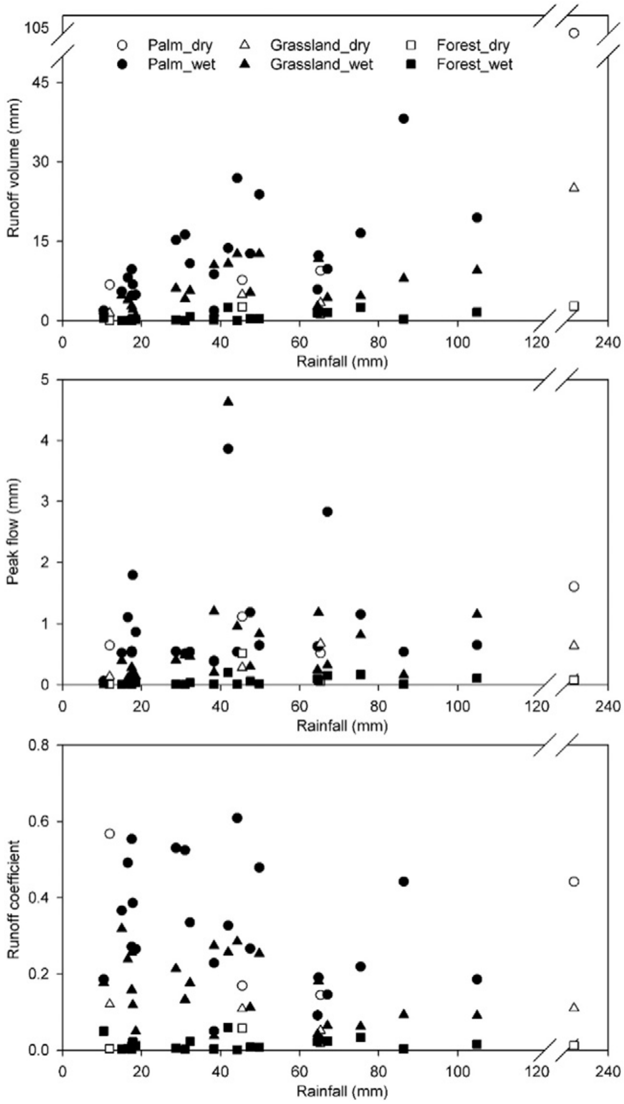

Fig. 2. Runoff response for the storm events of the rainy season of 2011 in the study plots over oil palm plantation, grassland and secondary forest. Runoff is characterized by the total volume generated (mm), the peak flow (mm per 5 min) and the runoff coefficient (calculated as the relation between runoff and precipitation of the event). Runoff response to storms that occurred after two rain-free days (white symbols of the figure) is similar to the responses of the rest of the storms.

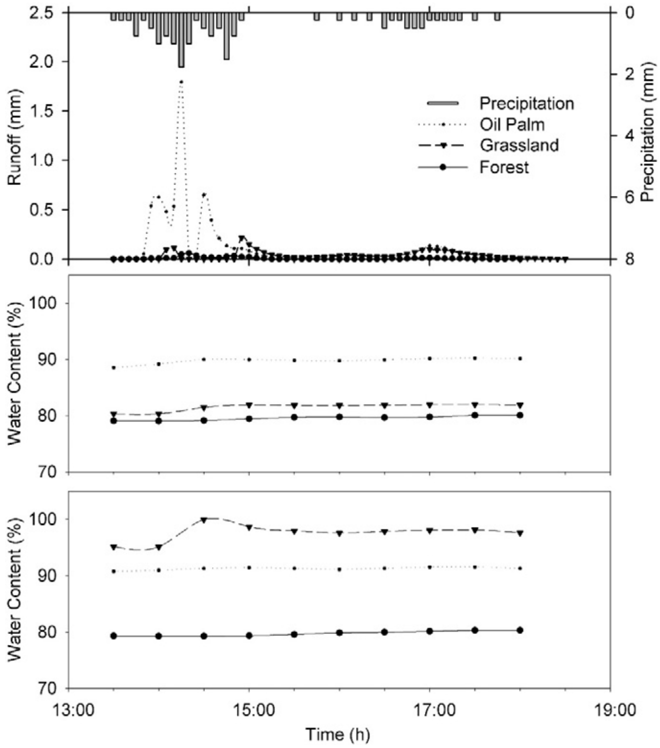

Fig. 3. Storm runoff and soil water content response for the event of the date 20 / 08 / 2011 measured in the study plots. Storm runoff is measured in 5 min time intervals. Bars in the top of the figure indicate 5-min rainfall accumulations. Water content of the soil profile for each plot was recorded at 15 and 45 cm depth in 30 min time intervals.

and duration, with a mean runoff coefficient of 1.7%. The oil palm plantation generates the highest runoff response, with a mean runoff coefficient of 32.6%, twice the mean runoff coefficient measured under grassland (15.3%). The secondary forest runoff coefficient is significantly lower than that of the grassland and oil palm plantation (p-value < 0.0001). The runoff coefficient of the oil palm plantation, however, is significantly higher than the grassland (p-value < 0.0001).

3.2. In situ rainfall simulation runoff response

Runoff measurements from the rainfall simulation tests in the microplots at the secondary forest are significantly lower than those in the grassland (mean RC_s forest = 5.7%, mean RC_s grassland = 45.9%, p-value = 0.0737), the forest plantation (mean RC_s plantation = 40.5%, p-value = 0.0117) and the oil palm plantation (mean RC_s oil palm = 76.55%, p-value < 0.0001). The forest plantation measurements are significantly lower than those from the oil palm plantation (p-value = 0.0084) but they are not significantly different from the grassland measurements (p-value = 0.7014) (Fig. 4). Similarly, the oil palm plantation and grassland measurements do not show statistically significant differences (p-value = 0.1073), mainly because of the high variability of the grassland measurements (Fig. 4).

The sediment yield generated by the simulated rainfall in the secondary forest plot is significantly lower than that generated in either the grassland test (mean SY forest = 0.02 g, mean SY grassland = 0.67 g, p-value = 0.0623), the oil palm plantation test (mean SY oil palm = 0.91 g, p-value = 0.0205) or the forest plantation test (mean SY plantation = 0.49 g, p-value = 0.0350). Unlike the runoff results described above, there are no statistically significant differences between the sediment yields generated in the forest plantation, the grassland and the oil palm plantation tests (p-value > 0.1).

4. Discussion

The combined study of natural rainfall runoff response and in situ rainfall simulation runoff response measurements illustrates more accurately the hortonian overland flow processes of the study site. The runoff responses obtained for the different land cover types by both methods are highly correlated (Fig. 5) although the order of magnitude of runoff is not the same in large and small plots, tending to decrease with increasing plot area, a pattern that has been observed by other authors (Esteves and Lapetite, 2003; Gomi et al., 2008; Joel et al., 2002). This scale effects are usually linked to the spatial variability of the area (Gómez et al., 2001), to the fact that water on long slopes has more opportunity time to infiltrate than water on short slopes and to the temporal variability of rainfall (Van de Giesen et al., 2011).

The response of the two methodologies is not meant to be compared in this study. The response of the runoff plot is interpreted as an average response for the field slope, whereas the rainfall simulator measurements, both runoff and sediment yield, allow us to characterize and understand the runoff response variability within the plot. In addition, the combination of the two methodologies to characterize the runoff process allows a wider range of rain intensities to be tested, from 1 to

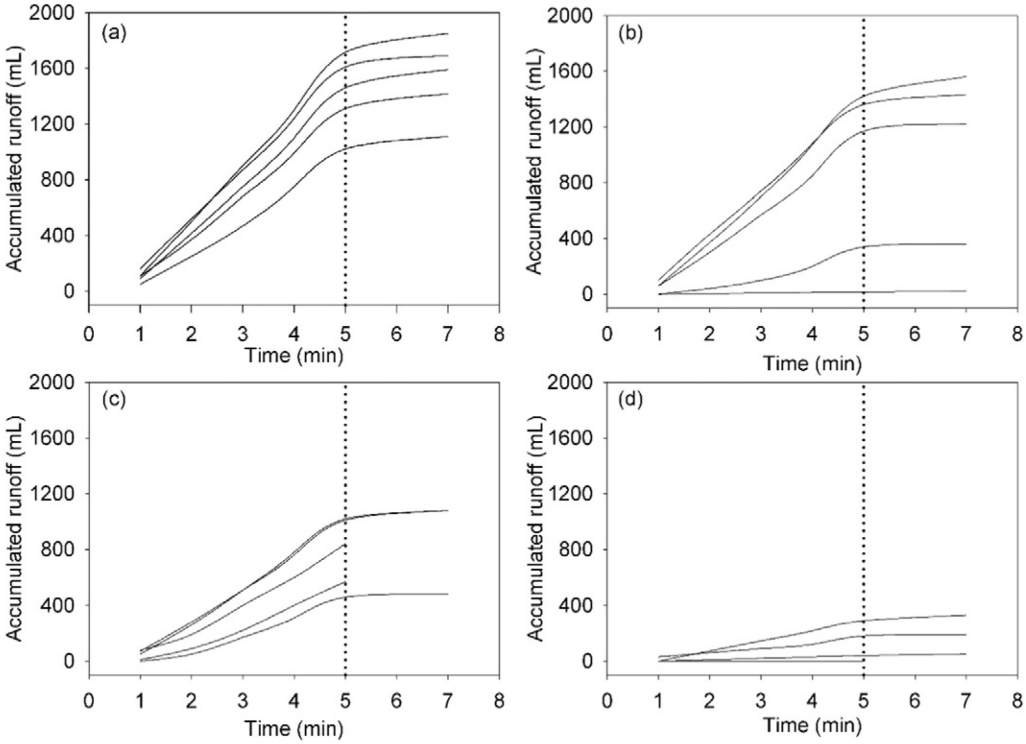

Fig. 4. In situ rainfall simulation runoff responses for the land uses: (a) Oil palm, (b) grassland, (c) forest plantation and (d) secondary forest in Tinoco Catchment (Costa Rica). Each curve represents a repetition of the in situ rainfall simulation tests. Grassland microplots (b) show a high heterogeneity in the responses as a result of differences in soil cover, roughness and eroded degree of the microplots.

38 mm h^{-1} in selected natural storms (Table 2) to 384 mm h^{-1} under rainfall simulation. Runoff responses follow a similar pattern (secondary forest < grassland < oil palm), but the differences between land uses are even bigger when rainfall intensity reaches values as high as those obtain by rainfall simulation tests in the study. Hence, under this extremely high rainfall intensity, the oil palm plantation reaches runoff values higher than 75% while secondary forest shows moderate runoff values of around 5% (Fig. 5).

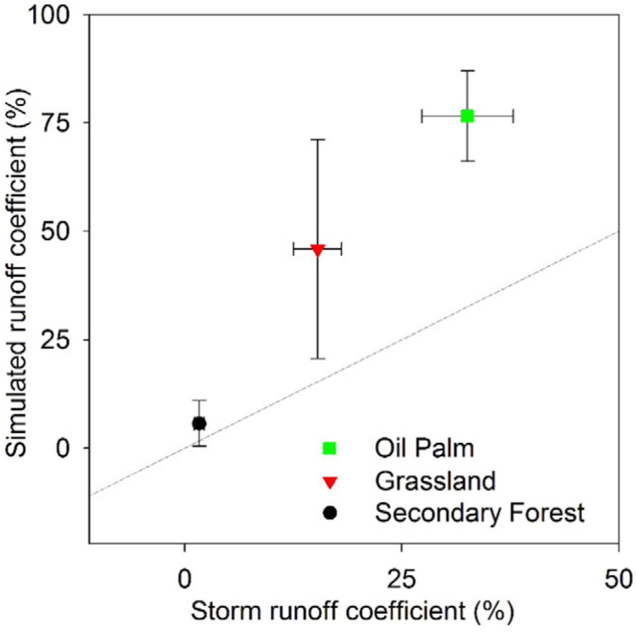

Fig. 5. Mean natural storm rain-runoff coefficient versus mean rainfall simulation runoff coefficient for the different land uses in Tinoco Catchment (Costa Rica).

Storm events selected are representative of a wide range of intensities and duration (Table 2) and represents the typical conditions in the study site, with tropical climatic characteristics, such as daily rain event occurrences and high rain intensities during first moments of the event (Fig. 3). However, no clear relation can be seen between runoff coefficients or peak flow or runoff volume and rainfall for any of the land covers (Fig. 2).

Secondary forest shows a significantly lower runoff response than grasslands and oil palm plantations both under natural rainfall (Figs. 2 and 3) and during rainfall simulation tests (Fig. 4). This pattern agrees with the general theory put forward by most authors (Brauman et al., 2007). However, this lower runoff under secondary forests occurs even though the Ks (saturated hydraulic conductivity) values obtained for the plots are not significantly different (Table 1). Ks has been described as a very sensitive parameter to soil degradation and it is considered a key indicator of the effects of land use change on the hydrological processes in the soil (Alegre and Cassel, 1996; Hassler et al., 2011; Ziegler et al., 2004; Zimmermann and Elsenbeer, 2008; Zimmermann et al., 2006, 2010). This lack of relationship between the observed runoff coefficients and Ks values might be caused by the high spatial variability of this variable in the study plots. This high spatial variability of Ks has been reported by other authors (Zimmermann and Elsenbeer, 2008). In addition, local factors such as land use history and the intensity of former cattle grazing have been reported to strongly influence the results (Hassler et al., 2011).

The runoff coefficient found in the study plots was 10-fold greater in grassland than in secondary forest, which is lower than reported in most of the studies of land use change from forest to pasture in tropical areas (Biggs et al., 2006; Chandler and Walter, 1998; De Moraes et al., 2006; Germer et al., 2009, 2010). However, the comparison of this type of results is complex due to differences in soil type, vegetation cover and above all, the level of degradation and overgrazing of the plot. Grasses can directly benefit surface runoff by enhancing rainfall interception and improving the development of macropores with their intricate rooting system (Pellant, 2000). However, degradation due to overgrazing and the lack of soil conservation measures reduce soil infiltration and increase surface runoff at different levels (Molina et al., 2007; Vanacker et al., 2005).

The oil palm plantation plot presented the highest runoff coefficient in the catchment (32.6%). The intensive management of this crop system, with labor and cattle ranging, generates a compact layer in the soil. This fact, combined with the compacted subsoil resulting from former grazing practices leads to a decline in macroporosity and high susceptibility to erosion (Allen, 1985). Furthermore, the lack of soil conservation measures on the hillsides and the widely spaced planting pattern of the crop, favor longer slope lengths, which increase the generation of overland flow. The effect of this land use change from grassland to oil palm plantation has not yet been explored sufficiently. In part, this is due to the fact that most of the research on oil palm has been conducted in Asia, where the species is generally planted in areas of former tropical forests (Meijerink et al., 2008; Müller et al., 2008). However, some studies in Malaysia do reported runoff coefficients measured in plots of up to 44% (Banabas et al., 2008) and in oil palm watersheds of up to 44%–56.6% of the total rainfall in the catchment (James Gerusu, 2013; Yusop and Katimon, 2007). These values are difficult to compare with our data since scale effects and several plot parameters would be affecting in big proportion. Although it is not clear what processes are responsible for this greater runoff, important hortonian overland flow during short-term high intensity rainfall events is linked in this studies to the high intrinsic variability in soil infiltrability in the plots (Banabas et al., 2008) which is in line with the measurements in the microplots tests (Fig. 4). Additional documented effects of this deforestation process are a decrease in soil porosity and Ks (Firdaus et al., 2010) and an increase in surface runoff of about 13% (Babel et al., 2011). Our results support the hypothesis that soil physical properties are worsened by land use change from grassland to oil palm plantation. Although grasslands have been converted to oil palm plantations in large areas of Latin America (Castiblanco et al., 2013; Höbinger et al., 2012) over recent decades, studying the effect of this land use change on hydrological processes has not been considered a priority in the region, as oil palm was mainly established on alluvial plains, where soil erosion is very low due to the topographic conditions. However, these dynamics have been changing in recent years and oil palm is expanding and it is planting on slopes, with the consequent hydrological risks.

As a direct response to the runoff produced, the sediment yield was also consistently lower in the secondary forest sites than in the other land uses. Indeed, there is a significant correlation between runoff and sediment production at the microplot scale (Fig. 6). Rainfall simulation experiments reveal the high variability of runoff and sediment responses in the grassland plot (Fig. 4), associated with different slope positions and variable vegetation cover. Sediment yield in oil palm plantations follows the same tendency as the runoff response. Since sediment yield was measured only at the microplot scale, it is not the aim of this study to discuss about erosion rates, more over if it is generally considered that the sediment delivery decreased sharply from the microplot to the plot scale (Chaplot and Poesen, 2012) and no reference data is available at the runoff plots by now. However, taking into account the significant correlation between runoff and sediment production obtained, it is possible to hypothesis about moderate rates of surface erosion from mature oil palm plantations as it have been documented as well in some studies before (Hartemink, 2006; Lim, 1990; Maene, 1979). However, there are no conclusive results as most of the areas in Asia where this crop is currently cultivated do not face the same problems as in the Latin American sites and our limited data is not sufficient to support this point.

Several studies conducted in tropical regions (Honduras, Ecuador, Panama or Amazonia) have documented the effect of land cover changes and secondary forest regrowth on the hydrological properties of the soil (De Moraes et al., 2006; Godsey and Elsenbeer, 2002; Hanson et al., 2004; Zimmermann and Elsenbeer, 2008; Zimmermann et al., 2006, 2010). Ks values rapidly decrease following forest to grassland conversion while the recovery of Ks values after the abandonment of pasture is slow and may take more than 10 years, although as yet there have been no conclusive findings (Hassler et al., 2011; Zimmermann et al., 2010). The results presented in this study of the Tinoco Experimental Catchment help to further our understanding of this issue, providing evidence of the effect of secondary forest recovery over the last 15 years on rain runoff response at plot scale.

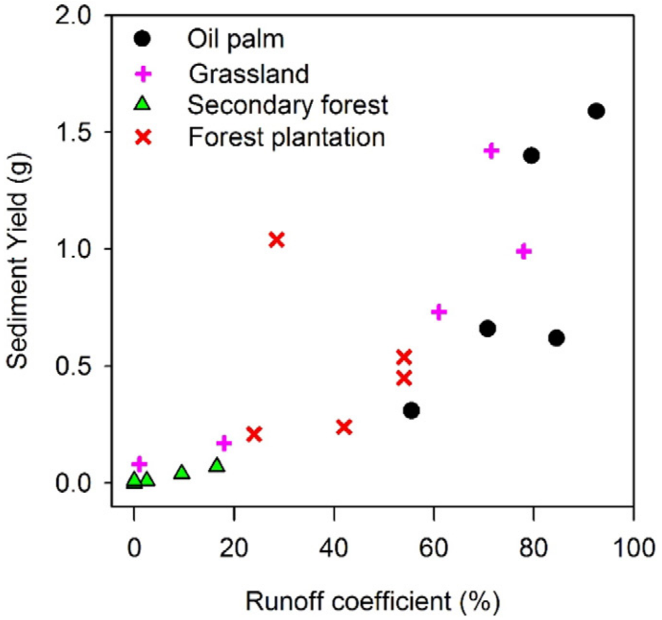

Fig. 6. Relation between sediment yield and runoff response under in situ rainfall simulation tests in the different land uses of Tinoco Catchment (Costa Rica).

The observed runoff coefficients can be used in landscape and hydrological planning as well as in the evaluation of the environmental response to changes in both land use and climate (differences in rain intensity) under the current context of global change. In addition, these results can be used to evaluate the Payments for Environmental Services (including hydrological services). Further research is needed in order to improve these estimations using more extensive records and analyzing the patterns on greater temporal and spatial scales.

5. Conclusions

Land use changes have a significant impact on overland flow generation as evidenced by the analysis of runoff plots in Tinoco Experimental Catchment in the Southern Pacific area of Costa Rica. Secondary forests, which have developed over a 12–15 year period following the abandonment of pastureland, generate very low runoff in normal and high intensity rain events. Grasslands show a 10-fold higher runoff than secondary forests. Oil palm plantations present the highest runoff response, 20-fold that of secondary forests under natural storm conditions and reaching 75% runoff coefficient under extreme rainfall intensity (384 mm h^{-1}) which was measured using a portable rainfall simulator.

The observed runoff coefficients were obtained at plot scale and the upscaling of these results should be done carefully. However, these results can be taken into account in the evaluation of the environmental response to land cover and use changes. In addition, these results can be useful to evaluate the Payments for Environmental Services (including hydrological services) and other environmental management instruments.

Acknowledgments

This research was funded by MACOSACEN project (A2/037794/11), financed by PCI-AECID (Agencia Española de Cooperación Internacional) and CAB project financed by CONARE (Costa Rica). The authors are very grateful to the Natural Resource Laboratory at CIA-UCR for their support and assistance in Costa Rica.

References

Alegre, J.C., Cassel, D., 1996. Dynamics of soil physical properties under alternative systems to slash-and-burn. Agric. Ecosyst. Environ. 58, 39–48.

Allen, J.C., 1985. Soil response to forest clearing in the United States and the tropics: geological and biological factors. Biotropica 17, 15–27.

Babel, M., Shrestha, B., Perret, S., 2011. Hydrological impact of biofuel production: a case study of the Khlong Phlo Watershed in Thailand. Agric. Water Manag. 101, 8–26.

Banabas, M., Turner, M.A., Scotter, D.R., Nelson, P.N., 2008. Losses of nitrogen fertiliser under oil palm in Papua New Guinea: 1. water balance, and nitrogen in soil solution and runoff. Soil Res. 46, 332–339.

Biggs, T.W., Dunne, T., Muraoka, T., 2006. Transport of water, solutes and nutrients from a pasture hillslope, southwestern Brazilian Amazon. Hydrol. Process. 20, 2527–2547.

Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. Annu. Rev. Environ. Resour. 32, 67–98.

Castiblanco, C., Etter, A., Aide, T.M., 2013. Oil palm plantations in Colombia: a model of future expansion. Environ. Sci. Pol. 27, 172–183.

Ceballos, A., Schnabel, S., 1998. Hydrological behaviour of a small catchment in the dehesa landuse system (Extremadura, SW Spain). J. Hydrol. 210, 146–160.

Chandler, D., Walter, M., 1998. Runoff responses among common land uses in the uplands of Matalom, Leyte, Philippines. Trans. ASAE 41, 1635–1641.

Chaplot, V., Poesen, J., 2012. Sediment, soil organic carbon and runoff delivery at various spatial scales. Catena 88, 46–56.

Comte, I., Colin, F., Whalen, J.K., Grünberger, O., Caliman, J., 2012. 3 Agricultural practices in oil palm plantations and their impact on hydrological changes, nutrient fluxes and water quality in Indonesia: a review. Adv. Agron. 116, 71.

De Moraes, J.M., Schuler, A.E., Dunne, T., Figueiredo, R.d.O, Victoria, R.L., 2006. Water storage and runoff processes in plinthic soils under forest and pasture in Eastern Amazonia. Hydrol. Process. 20, 2509–2526.

Esteves, M., Lapetite, J.M., 2003. A multi-scale approach of runoff generation in a Sahelian gully catchment: a case study in Niger. Catena 50, 255–271.

FAOSTAT, 2014. FAOSTAT Database. 2014.

Firdaus, M.S., Gandaseca, S., Ahmed, O.H., Majid, N.M.A., 2010. Effect of converting secondary tropical peat swamp forest into oil palm plantation on selected peat soil physical properties. Am. J. Environ. Sci. 6.

Germer, S., Neill, C., Vetter, T., Chaves, J., Krusche, A.V., Elsenbeer, H., 2009. Implications of long-term land-use change for the hydrology and solute budgets of small catchments in Amazonia. J. Hydrol. 364, 349–363.

Germer, S., Neill, C., Krusche, A.V., Elsenbeer, H., 2010. Influence of land-use change on near-surface hydrological processes: undisturbed forest to pasture. J. Hydrol. 380, 473–480.

Godsey, S., Elsenbeer, H., 2002. The soil hydrologic response to forest regrowth: a case study from southwestern Amazonia. Hydrol. Process. 16, 1519–1522.

Gómez, J., Nearing, M., Giráldez, J., Alberts, E., 2001. Analysis of sources of variability of runoff volume in a 40 plot experiment using a numerical model. J. Hydrol. 248, 183–197.

Gomi, T., Sidle, R.C., Miyata, S., Kosugi, K., Onda, Y., 2008. Dynamic runoff connectivity of overland flow on steep forested hillslopes: scale effects and runoff transfer. Water Resour. Res. 44.

Hanson, D., Steenhuis, T., Walter, M., Boll, J., 2004. Effects of soil degradation and management practices on the surface water dynamics in the Talgua river watershed in Honduras. Land Degrad. Dev. 15, 367–381.

Hartemink, A.E., 2003. Soil Fertility Decline in the Tropics: With Case Studies on Plantations. Cabi.

Hartemink, A.E., 2006. Soil erosion: perennial crop plantations. Encyclopedia of Soil Sciencepp. 1613–1617.

Hassler, S.K., Zimmermann, B., van Breugel, M., Hall, J.S., Elsenbeer, H., 2011. Recovery of saturated hydraulic conductivity under secondary succession on former pasture in the humid tropics. For. Ecol. Manag. 261, 1634–1642.

Höbinger, T., Schindler, S., Seaman, B.S., Wrbka, T., Weissenhofer, A., 2012. Impact of oil palm plantations on the structure of the agroforestry mosaic of La Gamba, southern Costa Rica: potential implications for biodiversity. Agrofor. Syst. 85, 367–381.

Iserloh, T., Ries, J., Cerdà, A., Echeverría, M., Fister, W., Geisharpler, C., Kuhn, N., León, F., Peters, P., Schindewolf, M., 2013. Comparative measurements with seven rainfall simulators on uniform bare fallow land. Z. Geomorphol. (Supplementary Issues 57), 11–26.

James Gerusu, G., 2013. Partitioning of rainfall and flowpath processes in small oil palm catchments.

Janssen, R., Rutz, D.D., 2011. Sustainability of biofuels in Latin America: risks and opportunities. Energ Policy 39, 5717–5725.

Joel, A., Messing, I., Seguel, O., Casanova, M., 2002. Measurement of surface water runoff from plots of two different sizes. Hydrol. Process. 16, 1467–1478.

Lestariningsih, I.D., Widianto, Hairiah, K., 2013. Assessing soil compaction with two different methods of soil bulk density measurement in oil palm plantation soil. Procedia Environ. Sci. 17, 172–178.

Lim, K., 1990. Soil Erosion Control Under Mature Oil Palms on Slopes. pp. 191–198.

Maene, L., 1979. Surface Wash Under Mature Oil Palm. Jabatan Pertanian Malaysia.

Meijerink, G.W., Langeveld, J., Hellegers, Petra, Gerarda Johanna, Jacoba, 2008. Biofuels and Water: an Exploration, Wageningen UR.

Mingorría, S., Gamboa, G., Martín-López, B., Corbera, E., 2014. The oil palm boom: socio-economic implications for Q'eqchi'households in the Polochic valley, Guatemala. Environ. Dev. Sustain. 1–31.

Molina, A., Govers, G., Vanacker, V., Poesen, J., Zeelmaekers, E., Cisneros, F., 2007. Runoff generation in a degraded Andean ecosystem: interaction of vegetation cover and land use. Catena 71, 357–370.

Müller, A., Schmidhuber, J., Hoogeveen, J., Steduto, P., 2008. Some insights in the effect of growing bio-energy demand on global food security and natural resources. Water Policy 10.

Pellant, M.L., 2000. Interpreting Indicators of Rangeland Health.

Price, M.F., 1999. Global Change in the Mountains: Proceedings of the European Conference on Environmental and Societal Change in Mountain Regions: Oxford, Uk, 18–20 December 1997. Informa Healthcare.

R Development Core Team, 2006. R 2.4. 0.

Soil Survey, S., 2010. Keys to Soil Taxonomy. 11th Ed. .

Van de Giesen, N., Stomph, T., Ajayi, A.E., Bagayoko, F., 2011. Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: field data and models. Agric. Ecosyst. Environ. 142, 95–101.

Vanacker, V., Molina, A., Govers, G., Poesen, J., Dercon, G., Deckers, S., 2005. River channel response to short-term human-induced change in landscape connectivity in Andean ecosystems. Geomorphology 72, 340–353.

Viviroli, D., Weingartner, R., Messerli, B., 2003. Assessing the hydrological significance of the world's mountains. Mt. Res. Dev. 23, 32–40.

Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses—a Guide to Conservation Planning.

Yusop, Z., Katimon, A., 2007. Runoff characteristics and application of HEC-HMS for modelling stormflow hydrograph in an oil palm catchment. Water Sci. Technol. 56, 41–48.

Ziegler, A.D., Giambelluca, T.W., Tran, L.T., Vana, T.T., Nullet, M.A., Fox, J., Vien, T.D., Pinthong, J., Maxwell, J., Evett, S., 2004. Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: evidence of accelerated overland flow generation. J. Hydrol. 287, 124–146.

Zimmermann, B., Elsenbeer, H., 2008. Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance. J. Hydrol. 361, 78–95.

Zimmermann, B., Elsenbeer, H., De Moraes, J.M., 2006. The influence of land-use changes on soil hydraulic properties: implications for runoff generation. For. Ecol. Manag. 222, 29–38.

Zimmermann, B., Papritz, A., Elsenbeer, H., 2010. Asymmetric response to disturbance and recovery: changes of soil permeability under forest–pasture–forest transitions. Geoderma 159, 209–215.