The effects of conversion of tropical rainforest to rubber plantation on splash erosion in Xishuangbanna, SW China

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ABSTRACT

The Xishuangbanna (SW China) landscape has changed dramatically during the past three decades due to the conversion of tropical rainforest to rubber plantations. This study characterized the influence of conversion of tropical rainforest to rubber plantation on potential splash erosion rate and actual splash erosion rate. The average potential splash erosion rate was 2.1 times higher in the rubber plantation than in the open, while for the rainforest it was only 1.2 times higher than in the open, suggesting that the rubber plantation canopy greatly increased the rainsplash erosion. The average actual splash erosion rate was 2.0 times higher in the rubber plantation than in the rainforest, demonstrating that the rainforest was more effective in controlling splash erosion. The actual splash erosion rate was considerably lower in the terrace bench than in the riser bank in the rubber plantation, indicating that the riser bank was more sensitive to raindrop splash. Hence, protection of terrace risers with productive vegetation or litter/mulch layer is of vital importance in this bench-terraced rubber plantation. These results clearly show that conversion of tropical rainforest to rubber plantation had a negative effect on controlling splash erosion.

Key words | rainsplash erosion, rubber plantation, soil erosion, tropical rainforest

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INTRODUCTION

Soil splash erosion is the first stage in the chain of processes leading to soil loss and subsequent sediment transport (Ellison 1947; Morgan 1978; Van Dijk *et al*. 2002; Kinnell 2005; Leguédois *et al*. 2005). In forested landscapes, vegetation canopy cover is one of the most important reasons for soil splash erosion (Gyssels *et al*. 2005). It is commonly accepted that throughfall beneath a forest canopy is deprived of most of its splash erosion potential. Contrary to popular belief, however, forest canopy does not necessarily protect the surface soil from rainsplash erosion (Calder 2001). For example, Mosley (1982) revealed that for a New Zealand beech forest, the amount of sand splashed was 3.1 times greater under the canopy than in the open. Geißler *et al*. (2010) showed that for subtropical forests, the rates of soil splash below the canopies were 2.59 times higher compared to those in the open. However, the mechanisms reducing or enhancing splash erosion under different types of vegetation cover is still poorly understood (Geißler *et al*. 2010).

Splash erosion generally does not occur in natural forest area since litterfall and understory vegetation form a protective layer on the soil surface (Nanko *et al*. 2008). However, in some monoculture plantations, splash erosion becomes a primary concern for soil conservation (Calder 2001). Under high, single forest canopy the kinetic energy reaching the ground surface was significantly greater than that of natural rainfall (Mosley 1982; Nanko *et al*. 2008). Under low, single-layer vegetation cover, the energy reaching the ground is thought to be decreased (Vis 1986; Wainwright *et al*. 1999). However, few studies have investigated the erosivity of throughfall or splash erosion potential under the canopy of tropical forests (Critchley & Bruijnzeel 1996; Bruijnzeel *et al*. 1998).

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In Xishuangbanna, SW China, the most important driver of land-use/land-cover change has been the rapid increase in monoculture rubber plantations at the expense of tropical rainforests during the past several decades (Xu *et al.* 2005; Li *et al.* 2007). The conversion of tropical rainforest to bench-terraced rubber plantation could have a major impact on soil properties, and possibly make the soils more vulnerable to erosion (Zhang *et al.* 1997; Liu *et al.* 2011). In steep areas, terraces are often constructed before planting rubber trees. This causes two important changes in the soil: (1) the soil in the bench terraces is destabilized; and (2) the unvegetated riser faces are more vulnerable to erosion than the original condition (Critchley & Bruijnzeel 1996; Bruijnzeel *et al.* 1998). Unfortunately, few studies have documented the nature and intensity of erosion on bench terraces (Critchley & Bruijnzeel 1996; Van Dijk *et al.* 2002), particularly in bench-terraced rubber plantations (Liu *et al.* 2011; Lu *et al.* 2011). This study evaluates the influence of conversion of tropical rainforest to rubber plantation on potential splash erosion rate and actual splash erosion rate. The main objective of the study is to assess the influence of forest type on the splash erosion of rainwater input after its passage through the canopy.

MATERIALS AND METHODS

Site description

The study was conducted near Menglun (21°55′39″N, 101°15′55″′E), Yunnan province, SW China. In this region, during the last 40 years, the mean annual air temperature was 21.7 °C with a maximum monthly temperature of 25.7 °C for the hottest month (June) and a monthly minimum of 15.9 °C for the coldest month (January). The mean annual rainfall was 1,487 mm, of which 87% occurs in the rainy season (between May and October) vs. 13% in the pronounced six-month dry season (between November and April).

The soil is classified as a Ferralic Cambisol (FAO/UNESCO) developed from alluvial deposits derived from sandstone, with an ochric A horizon and a cambic B horizon with ferralic properties (Vogel *et al.* 1995). The parent material, at a depth of 2 m, consists of a 30–40 cm thick layer of gravel deposited by a side branch of the Upper Mekong River. Soil bulk density is 1.2 g cm^{-3} with a pH of 5.4 (Lu *et al.* 2009).

The tropical rainforest (dominated by *Pometia tomentosa* and *Terminalia myriocarpa*) and rubber plantation (*Hevea brasiliensis*) were selected to conduct the field experiment. Splash erosion rate was monitored in the control and rubber plantation stands within a 5 m × 20 m plot. The distance between the two stands was about 500 m and there was no significant difference in rainfall characteristics or geological properties between the stands (Liu *et al.* 2011). The rubber trees were planted at 2.1 m × 4.0 m spacing on level bench terraces on the catchment slopes after complete clear-cutting of native rainforest in 1988. The management of the plantation has included control of understory growth, fertilization and latex extraction. The rubber plantation plot is composed of a terrace bench and a riser bank. The slope angle of the terrace bench and riser bank were 2° and 23°, with a width of 2 and 3 m, respectively. There was no understory vegetation in the rubber plantation. More detailed information about the two stands is provided by Liu *et al.* (2011).

Data collection and analysis

A tipping-bucket rain gauge of 0.2 mm resolution was installed in the open approximately 500 m west of the tropical rainforest stand. To monitor throughfall, four V-shaped troughs (0.3 m × 2.0 m) were randomly installed in both the tropical rainforest and rubber plantation, respectively. Throughfall was measured between 10 August and 15 November 2010 at 5 min intervals using a HOBO water-level logger (U20-001-04, Onset Corp., USA). Based on this dataset, the maximum value of rainfall and throughfall intensity over different time periods were calculated. These data were used to determine how the potential splash erosion rate changed in the open field depending on total rainfall and maximum rainfall intensity over different time scales (i.e., 24, 3 and 1 h).

Potential splash erosion rate is defined as the amount of the disturbed soil per unit source area that was mobilized by rainsplash. It was measured by using disturbed soil samples highly susceptible to rainsplash erosion, and therefore it can be appropriate for examining the difference in kinetic energy of natural rainfall or throughfall. Soils were collected from the top 5 cm of the soil layer in the rubber plantation and tropical rainforest, and dried at 105 °C for 24 h and pre-screened using a 2 mm aperture square-hole sieve. The disturbed soil is poorly aggregated, with great susceptibility to splash erosion (Gao & Bao 2001). Ellison-type splash cups (Geißler *et al*. 2010) were used to measure splash erosion rates and to estimate throughfall and rainfall erosivity. The soil was saturated by placing the splash cup inside a shallow pan with water for 8 h. The initially saturated soil was then allowed to drain for 24 h so that the humidity could be adjusted to the field capacity. At the beginning of the observation, 18 splash cups filled with soil were randomly installed in the tropical rainforest, while 3 were installed in the open, and 9 in the terrace bench and 12 in the riser bank in the rubber plantation.

Actual splash erosion rate is defined as the amount of the undisturbed soil per unit source area that was mobilized by rainsplash. It was evaluated by use of Morgan-type splash cups (Nanko *et al*. 2008; Mizugaki *et al*. 2010). Three splash cups were randomly installed in the tropical rainforest and nine in the rubber plantation (three in terrace bench and six in riser bank). The minimum distance between the splash cups within each site was 1.5 m (Figure 1). The splashed soil materials were dried at 105 °C for 24 h and then weighed. The actual splash erosion rate for a given observation period was calculated by averaging the actual splash erosion rate from all splash cups installed. Observations were conducted during six periods (see Table 1) between 10 August and 15 November 2010. The splash cups were re-installed after each observation period.

Student's *t*-test was used to detect the differences in potential splash erosion rate and actual splash erosion rate between the rubber plantation and the open, and between the tropical rainforest and the open. All statistics were conducted using the program SPSS 13.0 (SPSS Inc., Chicago, IL).

RESULTS

Over the total period of observation, the rainfall amount was 497.5 mm. As expected, the throughfall amount was higher in the rubber plantation (396.5 mm) than in the tropical rainforest (366.4 mm), which indicates that interception in the canopy of the tropical rainforest was significantly higher than that for the rubber plantation. The amount of rainfall varied between the six observation periods, with a maximum of 143.5 mm in period 3 and a minimum of 43.0 mm in period 6.

The average potential splash erosion rate in the rubber plantation (3,729 ± 1,235 g m^{-2}) was 2.1 times higher than that in the open (1,763 ± 612 g m^{-2}; Table 1). As expected, there were significant differences in potential splash erosion rate in each splash cup between the rubber plantation and the open ($P < 0.001$). The ratio of potential splash erosion rate to that of the open ranged from 1.6 to 2.8 in the rubber plantation during the six observation periods. It was also found that the average potential splash erosion

Figure 1 | Morgan-type splash cups installed on the floor to collect soil sediment splashed from the ground surface in the bench-terraced rubber plantation (*left*) and the tropical rainforest (*right*).

Table 1 | Potential splash erosion rate (g m^{-2}) in the rubber plantation and the open during each observation period

Periods		Open			Rubber plantation			Rubber plantation/ Open
		Terrace bench	Riser bank	Average	Terrace bench	Riser bank	Average	
Period 1 (10–18 August)	Erosion rate	1,672	1,745	1,708	2,950	3,710	3,385	2.0
	SD	111	226	164	977	1,091	1,089	
	n	3	3	6	9	12	21	
Period 2 (19–28 August)	Erosion rate	2,156	2,362	2,259	4,784	4,761	4,770	2.1
	SD	290	149	235	1,251	1,057	1,114	
	n	3	3	6	9	12	21	
Period 3 (29 August–20 September)	Erosion rate	2,462	2,992	2,727	4,240	4,560	4,423	1.6
	SD	169	070	313	962	954	947	
	n	3	3	6	9	12	21	
Period 4 (21 September–5 October)	Erosion rate	1,174	1,526	1,350	3,534	4,044	3,825	2.8
	SD	199	80	236	1,087	1,225	1,168	
	n	3	3	6	9	12	21	
Period 5 (6–22 October)	Erosion rate	1,387	1,533	1,460	2,899	3,540	3,265	2.2
	SD	140	215	181	1,104	634	902	
	n	3	3	6	9	12	21	
Period 6 (23 October–2 November)	Erosion rate	969	1,174	1,072	2,176	3,098	2,703	2.4
	SD	267	119	217	647	994	964	
	n	3	3	6	9	12	21	
Overall	Erosion rate	1,637	1,889	1,763	3,431	3,952	3,729	2.1
	SD	571	641	612	1,313	1,132	1,235	
	n	18	18	36	54	72	126	

rate in the riser bank (3,952 ± 1,132 g m^{-2}) was 1.2 times as large as that in the terrace bench (3,431 ± 1,313 g m^{-2}).

The potential splash erosion rate in the tropical rainforest (2,552 ± 1,357 g m^{-2}) was 1.2 times higher than that in the open (2,090 ± 845 g m^{-2}; Table 2). There were no significant differences in potential splash erosion rate between the tropical rainforest and the open ($P = 0.061$). The ratios of potential splash erosion rate in the tropical rainforest to that in the open varied from 0.9 to 1.9.

The actual splash erosion rate was highest in the riser bank, followed by the terrace bench in the rubber plantation, while the lowest was in the tropical rainforest (Table 3). The average actual splash erosion rate in the rubber plantation (2,258 ± 1,547 g m^{-2}) was 2.0 times as large as that in the tropical rainforest (1,144 ± 996 g m^{-2}). There were significant differences in actual splash erosion rate between the tropical rainforest and the rubber plantation ($P < 0.05$).

The potential splash erosion rate was much larger than the actual splash erosion rate in the three forest sites. The ratio of actual splash erosion rate to potential splash erosion rate was 0.5 for both the terrace bench and the riser bank, and 0.3 for the tropical rainforest, suggesting that the splash erosion rate of the undisturbed soil was much lower than that of the disturbed soil.

Linear regression analysis showed that for each forest site, the potential splash erosion rate was strongly correlated with the 1-h maximum throughfall intensity ($R^2 = 0.824$), but weakly correlated with the total throughfall amount ($R^2 = 0.487$). While for each open site, the potential splash erosion rate was highly correlated with the total rainfall amount ($R^2 = 0.861$) but weakly correlated with the maximum rainfall intensity over the short time scales, such as 3 h ($R^2 = 0.767$).

DISCUSSION

In a forested area, erosive power of throughfall drops is the single most important cause of soil splash detachment (You *et al.* 2003). Mizugaki *et al.* (2010) proposed that throughfall

Table 2 | Potential splash erosion rate (g m^{-2}) in the tropical rainforest and the open during each observation period

Periods		Open	Tropical rainforest	Tropical rainforest/ Open
Period 1 (10–18 August)	Erosion rate	1,864	2,930	1.6
	SD	171	1,422	
	N	3	18	
Period 2 (19–28 August)	Erosion rate	2,740	2,395	0.9
	SD	252	1,261	
	N	3	18	
Period 3 (29 August–20 September)	Erosion rate	3,530	3,364	1.0
	SD	110	1,400	
	N	3	18	
Period 4 (21 September–5 October)	Erosion rate	1,553	2,622	1.7
	SD	249	1,275	
	N	3	18	
Period 5 (6–22 October)	Erosion rate	1,738	1,863	1.1
	SD	160	1,076	
	N	3	18	
Period 6 (23 October–2 November)	Erosion rate	1,115	2,139	1.9
	SD	111	1,289	
	N	3	18	
Overall	Erosion rate	2,090	2,552	1.2
	SD	845	1,357	
	N	18	108	

intensity is a critical factor contributing to soil detachment under forest canopy. Nanko *et al*. (2008) and Mizugaki *et al*. (2010) stated that the soil splash detachment rates in a Japanese cypress plantation were weakly correlated with the total amount of rainfall, but strongly correlated with the maximum value of rainfall over short time scales, such as 1 h. These findings were also confirmed by the data presented here, which showed that the potential splash erosion rate was highly correlated with the 1-h maximum throughfall intensity, but weakly correlated with the total throughfall amount. This is principally because of the continuous and concentrative raindrop impacts over a short time duration (Nanko *et al*. 2008).

The potential splash erosion rate was strongly correlated with the total rainfall amount, but tended to be weakly correlated with the maximum rainfall intensity over short time scales (Table 4). This also confirms the conclusions of Al-Durrah & Bradford (1982) and Morgan (1978). The main reason may be related to the fact that heavy torrential rain was dominant during the observational periods (Liu *et al*. 2011), which can result in soil splash erosion in most of the observation events.

Table 3 | Actual splash erosion rate (g m^{-2}) in the tropical rainforest and the rubber plantation during each observation period

Periods		Rubber plantation			Tropical rainforest	Rubber plantation/Tropical rainforest
		Terrace bench	Riser bank	Average		
Period 1 (10–18 August)	Erosion rate	1,386	1,946	1,760	879	2.0
	SD	844	692	745	640	
	N	3	6	9	3	
Period 2 (22 August–3 September)	Erosion rate	1,240	1,658	1,518	798	1.9
	SD	646	649	642	504	
	n	3	6	9	3	
Period 3 (4 September–23 October)	Erosion rate	3,386	4,720	4,275	2,270	1.9
	SD	1,423	1,740	1,686	1,394	
	n	3	6	9	3	
Period 4 (24 October–15 November)	Erosion rate	997	1,717	1,477	628	2.4
	SD	450	742	724	515	
	n	3	6	9	3	
Overall	Erosion rate	1,752	2,510	2,258	1,144	2.0
	SD	1,266	1,638	1,547	996	
	n	12	24	36	12	

Table 4 | Coefficient of determination between the potential splash erosion rate and the total rainfall amount, and maximum rainfall intensity over different time scales

Sites	Rainfall								*n*
	Total		Max. 24 h		Max. 3 h		Max. 1 h		
	R^2	*P*	R^2	*P*	R^2	*P*	R^2	*P*	
Riser bank	0.101	0.007	0.208	0.000	0.207	0.000	0.223	0.000	54
Terrace bench	0.146	0.004	0.368	0.000	0.374	0.000	0.399	0.000	72
Tropical rainforest	0.066	0.007	0.082	0.003	0.110	0.000	0.111	0.000	108
Open	0.868	0.000	0.664	0.000	0.597	0.000	0.651	0.000	18

It is worth noting that for the forest site, the coefficient of determination derived from the amount of potential splash erosion for all the cups was considerably lower than that from the average amount of potential splash erosion (Table 4); however, this trend did not occur in the open. Mizugaki *et al*. (2010) found a similar result in a Japanese cypress plantation and explained that spatial variability in raindrop impact and actual soil conditions may lead to variation in soil splash erosion. However, their results did not involve open fields. Clearly, the throughfall under the canopy varied spatially, primarily due to differences in forest canopy structure (e.g., height, thickness, species and leaf area index: Mosley 1982; Vis 1986; Nanko *et al*. 2008; Geißler *et al*. 2010), which directly affect components of throughfall (free throughfall and canopy drip).

The average potential splash erosion rate was 2.1 times higher in the rubber plantation than in the open, suggesting that the rubber tree canopy greatly increased the rainsplash erosion. As expected, there were significant differences in potential splash erosion rate between the rubber plantation and the open, which is consistent with the previous studies of Mosley (1982), Vis (1986) and Geißler *et al*. (2010) who found that the erosivity of throughfall under a single layer canopy was higher compared to that of the rainfall.

High and single layer canopies (e.g., plantations) allow large drops to reach terminal velocity (Laws & Parsons 1943). Wang & Pruppacher (1977) suggested that the maximum distance a raindrop must fall to reach 99% terminal velocity is 12.8 m. Since the canopy height of the rubber plantation can reach to 20 m (Liu *et al*. 2011), it was proposed that all throughfall drops in the rubber plantation could reach terminal velocity. Although no detailed measurements of the throughfall drop-size distribution and kinetic energy were made, visual observations of the imprints of waterdrops in the splash cups showed that both the rubber plantation and tropical rainforest canopies could concentrate small drops into larger sizes. The diameter of the ten largest imprints in splash cups that were measured indicated a twofold increase in diameter of throughfall drops compared to raindrops.

The potential splash erosion rate in the tropical rainforest was slightly higher (1.2 times) than that in the open during the overall observation period (Table 3), suggesting that the tropical rainforest canopy was also ineffective in decreasing rainsplash erosion. This result is consistent with the previous work of Vis (1986), who reported that the amounts of sand splashed from the splash cups under the natural forest canopies were between 15 and 44% higher than in the open. It was proposed that the increased potential splash erosion rate in the tropical rainforest might have resulted from the increased throughfall kinetic energy, as shown by Mosley (1982).

Compared to any form of land use in the humid tropics, the relatively undisturbed soil properties in tropical rainforest are less sensitive to erosion (Critchley & Bruijnzeel 1996; Van Dijk *et al*. 2002). Geißler *et al*. (2010) pointed out that the actual splash erosion in forest floor is strongly affected by the throughfall erosivity, soil properties and leaf litter. In this study, the average actual splash erosion rate in the rubber plantation was considerably higher (2.0 times) than that in the tropical rainforest, demonstrating that surface soil in the rubber plantation was more susceptible to splash erosion and conversion of tropical rainforest to rubber plantation had a negative effect on controlling splash erosion. Also, the actual splash erosion rate was higher in the riser bank than in the terrace bench by a factor of 1.4. This indicates that the riser bank was more vulnerable to raindrop splash, as shown by Critchley & Bruijnzeel (1996) in upland West Java, Indonesia. This difference in actual splash erosion rate is likely due to the different soil properties between the riser bank and the terrace bench. Soil compaction was higher on the terrace bench compared with the riser bank (Liu *et al.* 2011), which results in higher soil bulk density and a decrease in splash detachment rate (Mouzai & Bouhadef 2011). Similarly, Bruijnzeel *et al.* (1998) also pointed out that terracing a hillside may make one section of the new landscape, namely terrace benches, less prone to erosion than the original slope, but this is only achieved at the cost of increasing the erosion potential in the risers. A simple way to reduce erosion would be to plant vegetation or add a litter/mulch layer to the highly vulnerable terrace risers in these bench-terraced rubber plantations.

Clearly, further researches are essential to investigate the erosion processes and the relationships of raindrop size distribution, rainfall intensity and kinetic energy of rainfall on these bench terraces.

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