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Are rubber-based agroforestry systems effective in controlling rain splash erosion?

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ABSTRACT

In order to evaluate the influence of different types of rubber-based agroforestry systems on soil erosion processes, rainfall and throughfall erosivity (splash erosion potential) were measured in an open field environment and under different vegetation types using sand-filled Tübingen splash cups. Our results indicate that the splash erosion potential under rubber monoculture was, on average, 3.12 times greater than those in the open environment. Splash erosion potential under agroforestry systems was higher than that of an open environment (ranging from 1.22 to 2.18 times greater), except for the rubber and tea system (0.87 times the open environment). However, in all but one system (the rubber and orange system), there was a significant reduction in splash erosion beneath multiple canopies compared to monoculture, especially for the rubber and tea system (0.27 times the monoculture) where it had high sub-canopy closure and low sub-canopy height. The erosion potential under the forest is closely related to the forest structure, especially height and canopy cover. These results indicate that low canopy height with high sub-canopy coverage is the major control on the amount of splash erosion, regardless of how the splash potential is increased by the canopy above. These results highlight the importance of selecting low near-surface intercrops for constructing rubber-based agroforestry systems. This also accentuates the importance of an intact litter layer in rubber plantations to protect the soil against splash erosion. Disturbance of these forests by latex tapping activities, herbicide application and removal of the litter layer during fertilization, for example, will also lead to higher actual splash erosion rates inside the forests in comparison with the open environment.

1. Introduction

Soil erosion is an important global issue which has ecological and financial implications (Sidle et al., 2006; Zhang, 2000; Zhou et al., 2010). Vegetation has been identified as an important key control on the type and intensity of soil erosion (Morgan, 2005; Su et al., 2010; Wei et al., 2005; Wiersum, 1985), and soil splash is the initial stage in the chain of processes that leads to soil loss and subsequent sediment transportation (Kinnell, 2005; Leguédois et al., 2005; Van Dijk et al., 2002).

In forested landscapes, vegetation canopy cover is one of the most important factors affecting soil splash erosion (Gyssels et al., 2005). Although it is generally accepted that throughfall beneath a forest canopy loses most of its splash erosion potential, the forest canopy does not necessarily protect surface soil from rain splash erosion (Calder, 2001). Although tree foliage can reduce the initial erosive power of rain, if water drops concentrate into larger drops, and if the fall height between the canopy and the soil is great enough, these falling drops can obtain a new erosive power that may exceed the initial erosive power of the original raindrop. For example, Mosley (1982), investigating soil erosion in a New Zealand beech forest, identified that soil splash was 3.1 times greater under the canopy than in the open environment. Brandt (1988) showed that, for a tropical rainforest, soil splash under multiple canopy layers was reduced to a minimum of 0.4 times splash compared to an open environment, but under a single canopy it increased to 6.65 times. Geißler et al. (2012a) showed that the rates of soil splash below the canopy of a subtropical forest were 2.59 times greater than those of open areas. The mechanisms involved in reducing or enhancing splash erosion under different types of vegetation cover, however, are still poorly understood (Nanko et al., 2008).

In areas containing natural forest, splash erosion does not typically occur as the understory vegetation and litterfall forms a protective layer over the soil surface (Wiersum, 1985). In some monoculture plantations, however, splash erosion has become a primary concern for soil conservation (Calder, 2001). Under a high, single forest canopy, the kinetic energy of water drops reaching the ground surface are significantly greater than those of natural rainfall (Mosley, 1982); under a low, single-layered vegetation cover, the kinetic energy of the water drops reaching the ground is believed to be lower (Vis, 1986; Wainwright et al., 1999). Relatively few studies, however, have investigated the throughfall erosivity, or splash erosion potential, under the canopy of

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tropical agroforestry systems (Bruijnzeel et al., 1998; Critchley and Bruijnzeel, 1996).

In Xishuangbanna, SW China, the most important driver of land-use/land-cover change over the past four decades has been the rapid increase in rubber monoculture plantations (*Hevea brasiliensis*). This change has been at the expense of primary and secondary tropical rainforest (Li et al., 2012). Due to economic demands, tropical rainforest in this region have been deforested and replaced with >400000 ha of rubber plantations; this being >20% of the total land area. It is commonly recognized, therefore, that the change in land-cover vegetation to rubber monoculture may result in excessive water loss and soil erosion (Xu et al., 2005b; Ziegler et al., 2009a); soil hardening and crusting (Liu et al., 2015); a loss of soil organic matter (Li et al., 2012); and rapid fluctuation of the microclimatic conditions (Feng, 2007). Some of these effects have already been noted in this region with noticeable, frequent dry season surface water shortages, an event which was rarely recorded prior to the change of vegetation (even during the driest year) (Qiu, 2009). To ensure the long-term sustainability of this plantation system, improving soil quality by developing sustainable land-use practices and reducing the rate of soil degradation is also very important.

Changes to the structure of a forest may arise through a number of different management practices. Changes in the use of forested land can result in changes in the sediment yield over short and long time periods (Brandt, 1988; Xu et al., 2005a; Young, 1990). It is also recognized that association of rubber trees with other cash tree crops can be an attractive practice to reduce competition for land, and at the same time diversifying farmers' income (Snoeck et al., 2013). In recent years, the Xishuangbanna local government has proposed building environmentally friendly rubber plantations (rubber-based agroforestry systems) which aim to reduce water and soil loss. Currently, Chinese scientists have developed a variety of rubber-based agroforestry systems to improve such degraded lands (Feng, 2007). In these agroforestry systems, rubber trees are commonly intercropped with economic plants like tea (*Camellia sinensis*), cacao (*Theobroma cacao*) and coffee (*Coffea arabica*); fruits such as pineapple (*Ananas comosus*), banana (*Musa saoientum*) and mandarin orange (*Citrus reticulata*); and traditional Chinese medicinal plants like *Flemingia macrophylla*, *Alpinia oxyphylla*, *Amomum longiligulare* and *Morinda officinalis*. Such crops, or combinations of crops, are grown under rubber trees to make use of available space at different heights to improve the effective use of the land resource. Currently, rubber and tea systems have replaced about 5% of the total area of rubber monoculture in this region. Other planting systems, such as rubber and coffee and rubber and cacao, have only been popularized by the local government in recent years. Although such systems can be highly effective in fixing carbon (Li et al., 2012), and are thought to be economically viable and ecologically sustainable in this region (Snoeck et al., 2013), little is known about their effects on controlling soil loss, especially on rain splash erosion (Liu et al., 2015).

In this study, we evaluated the influence of different types of rubber-based agroforestry systems and rubber monoculture on soil erosion processes. This study focused on changes in throughfall erosivity and plant characteristics which are related to their effects on splash erosion potential.

2. Materials and methods

2.1. Site description

The study site was located in the Xishuangbanna Tropical Botanical Garden (21°55′39″N, 101°15′55″E) in the Yunnan Province, SW China. Observations were conducted in a small catchment (19.3 ha) which consisted of rubber monoculture and different types of rubber-based agroforestry systems. The catchment spanned an altitudinal range of 560–680 m *a.s.l.* and had a slope of about 16° (Fig. 1). This region has a strongly seasonal climate with two main air masses alternating during the year. Climatologically, the Southwest Monsoon from the Indian Ocean delivers 80–90% of annual rainfall without influence from the Pacific typhoons during the rainy season (May to October), while the southern edges of the subtropical jet stream dominates the climate during the dry season (November to April). Climate records over the past 40 years show that 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 1480 mm, of which most precipitation occurred between May and October, with very little precipitation between November and April (Liu et al., 2015).

The soil depth under the vegetation was about 2 m, and this soil was well drained with a clay loam texture (42% coarse sands, 34% silts, 24% clays). The soil is classified as a Ferralic Cambisol (IUSS Working Group WRB, 2015), 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 consisted of a 30–40 cm thick layer of gravel deposited by the Luosuo River, a side branch of the Mekong River. Soil bulk density was 1.2 g cm^{-3} with an organic matter content of 25.9 g kg^{-1} (0–20 cm), and a pH of 5.4 (Li et al., 2012).

Rubber trees in this catchment were intercropped with five vegetation species commonly cultivated in this area: tea (*C. sinensis*), cacao (*T. cacao*), coffee (*C. arabica*), orange (*C. reticulata*) and *F. macrophylla*. For the rubber monoculture, rubber trees were planted in a traditional planting system with 2.1 m × 4.5 m spacing. For rubber-based intercropping systems, double rows of rubber trees were also planted with 2.1 m × 4.5 m spacing; the rows of rubber trees were then separated by 14 m wide inter-rows to allow intercropping. The associated crops were planted in the 14 m inter-rows in different arrangements to form five types of rubber-based agroforestry systems. These systems consisted of a rubber and tea system: six rows of tea planted in the middle of the inter-row at a density of 0.5 m × 2.0 m; rubber and cacao system: four rows of cacao planted with 3 m × 4 m spacing; rubber and coffee system: five rows of coffee planted with 2.5 m × 2.5 m spacing; rubber and orange system: four rows of orange planted with 1.5 m × 2.0 m spacing; and rubber and *Ficus macrophylla* system: eight rows of *F. macrophylla* planted with 0.5 m × 1.5 m spacing. In addition, a 1.5 m gap along each side of the rubber trees was kept for the convenience of tending, fertilizing and rubber latex tapping. All rubber trees were planted on the catchment slopes after deforestation of the native rainforest in 1989. The plantations subsequently received uniform agro management and were tapped for latex for 16 years. The crowns of the rubber trees were recorded to be between 11 and 18 m above the ground. The associated crops were planted in different years: tea and orange in 1997, and the others in 2005. In these forests, herbaceous plants were rarely present on the ground surface due to regular herbicide application. Comparison of the rubber trees in each of the treatments (monoculture *vs.* intercropping system) showed that there was no significant difference in their morphological characteristics (Table 1). More detailed information about the stands is provided by Liu et al. (2015).

Table 2 provides the morphological characteristics of the understory plant species in the different types of rubber-based agroforestry systems. The canopy closure rate and the crops' leaf area index (LAI) were determined by using a plant canopy analyzer (LAI-2200; Li-Cor Inc., USA). The canopy thickness and the height of the canopy center were visually estimated.

2.2. Rainfall, throughfall and splash erosion measurements

An open site and six throughfall observation sites (each 20 m × 20 m) were established in the different rubber plantations in the catchment. A tipping-bucket data-logging rain gauge (3554WD; Spectrum Technologies Inc., USA) with a 0.2 mm resolution was installed in the open. This rain gauge recorded rainfall volume and intensity, and the tip time was recorded at 10-min intervals. Three V-shaped

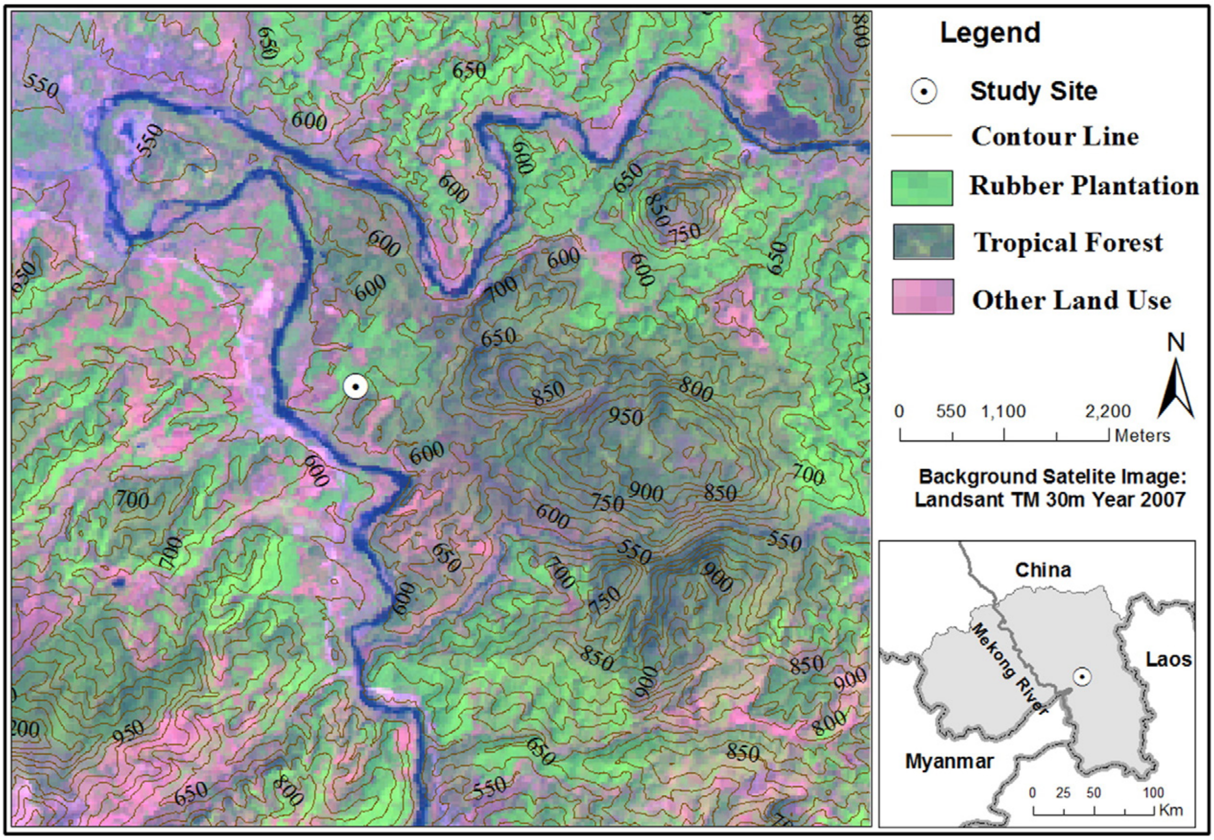

Fig. 1. Map showing location of the study site (21°55′39″N, 101°15′55″E) in Yunnan Province, southwest China.

troughs (each 0.15 m × 2.0 m), placed in a random pattern in each vegetation site, were used to collect throughfall. Each trough, connected to a plastic closed bottle, was mounted about 0.3 m above ground level beneath the canopy. Water levels were measured daily and any litterfall present in the troughs was discarded. Throughfall was measured during the rainy season from June to October 2013.

Rainfall and throughfall erosivity (the splash erosion potential) were measured in the open field environment and under vegetation using sand-filled Tübingen splash cups which were developed by Scholten et al. (2011), based on the archetype of the Ellison splash cup. These splash cups provided apparatus which were easy to install and use in the mountainous and remote areas, as well as ensuring a high number of replicates could be undertaken (Geißler et al., 2012a). Previous experiments have indicated that rainfall and throughfall kinetic energy can be easily and accurately estimated in the field by using this kind of sand-filled splash cup which has been calibrated in the laboratory (Geißler et al., 2012b). The splash cups used in our investigation, consisting of a plastic flask to which a carrier system was attached, had a diameter of 4.6 cm and a surface area of 16.62 cm^2. The splash cups were filled with quartz sand with a particle size of 125–200 μm. A constant soil moisture level was maintained in the splash cups over a reasonable period of time; soil moisture was actively constant under natural rainfall and evaporation conditions, and it had acceptable uniformity over a wide range of rainfall intensities and durations. The splash cup method has also been noted to be sensitive to very low rainfall intensities (Geißler et al., 2012b). Before field measurements, the cups were filled with sand and weighed to calculate the amount of sand added to each cup. The splash cups were then exposed to different natural rainfall events. After a single rainfall event the cups were removed from the carrier system and returned to the laboratory where they were oven dried at 105 °C for 24 h. After cooling, the cup and sand were re-weighed. The weight difference was used to calculate the sand loss per unit area (g m^{-2}). More detailed information about the calibration results of the splash cups is provided by Geißler et al. (2012a) and Scholten et al. (2011).

Ten to thirty splash cups were positioned on the floor in each vegetation site according to a 1 m wide grid. Consequently, the splash cups had a minimum separation distance of 1 m (Fig. 2). When a tree or an obstacle was encountered at the allocated position, the splash cup was positioned at the next possible position. The splash cups' positions remained constant during the experiment. To get reference measurements under open field conditions, nine splash cups were positioned

Table 1
Morphological characteristics of rubber trees in the rubber monoculture (Rm) and different types of rubber-based agroforestry systems.

Type of plantation	Rm	R-tea	R-cof	R-cac	R-mac	R-ora
Plant height (m)	17.4 ± 1.5a	17.1 ± 1.3a	16.9 ± 2.2a	18.2 ± 1.3a	18.6 ± 1.1a	17.0 ± 1.7a
Height of 1st branch (m)	6.5 ± 0.8a	6.4 ± 1.0a	6.6 ± 0.5a	6.9 ± 0.4a	7.0 ± 0.3a	6.7 ± 0.8a
Leaf area index (m^2 m^{-2})	2.2 ± 0.7a	2.1 ± 0.8a	2.0 ± 0.6a	1.9 ± 1.1a	1.8 ± 0.8a	2.3 ± 0.4a
Canopy thickness (m)	6.5 ± 0.5a	6.9 ± 0.3a	6.5 ± 0.6a	7.1 ± 0.5a	6.4 ± 0.6a	6.9 ± 0.8a
Canopy closure rate (%)	67 ± 11a	72 ± 5a	65 ± 9a	68 ± 6a	64 ± 12a	71 ± 7a

R-tea represents rubber and tea (*C. sinensis*) system; R-cof, rubber and coffee (*C. arabica*) system; R-cac, rubber and cacao (*T. cacao*) system; R-mac, rubber and *F. macrophylla* system; and R-ora, rubber and orange (*C. reticulata*) system. Values are mean ± 1 SD (n = 9–12). Values in the same line followed by different normal letters are significantly different (P < 0.05).

Table 2
Morphological characteristics of understory species in the different types of rubber-based agroforestry systems.

Species	*Camellia sinensis* (tea)	*Coffea arabica* (coffee)	*Theobroma cacao* (cacao)	*Flemingia macrophylla*	*Citrus reticulata* (orange)
Plant height (m)	1.2 ± 0.3a	1.9 ± 0.2ab	2.5 ± 0.3ab	2.2 ± 0.2ab	4.0 ± 0.2b
Height of 1st branch (m)	0.2 ± 0.1a	0.2 ± 0.1a	0.6 ± 0.2a	0.2 ± 0.1a	1.7 ± 0.2b
Leaf size (cm^2)	61 ± 5a	84 ± 3a	296 ± 13c	134 ± 11b	78 ± 6a
Leaf area index ($m^2\ m^{-2}$)	2.4 ± 0.4a	0.9 ± 0.2b	0.9 ± 0.4b	1.8 ± 0.2a	0.7 ± 0.3b
Height of canopy center (m)	0.7 ± 0.3a	1.5 ± 0.1ab	1.8 ± 0.1b	1.2 ± 0.1ab	3.2 ± 0.2c
Canopy thickness (m)	0.9 ± 0.2ab	0.5 ± 0.3a	1.1 ± 0.6b	1.4 ± 0.2b	1.6 ± 0.5b
Canopy closure rate (%)	79 ± 9a	35 ± 6b	33 ± 6b	68 ± 12a	21 ± 9b

Values are mean ± 1 SD ($n = 9$–12). Values in the same line followed by different normal letters are significantly different ($P < 0.05$).

at equal distances in a 60 cm wide grid close to the rain gauge. A distance of 60 cm was used to avoid interference between the splash cups (Geißler et al., 2012a; Poesen and Savat, 1981). The open site had the same topography as the cropped areas. All splash cups were firmly attached to steel sticks that were vertically inserted into the ground with their rims being level with the ground surface. After each sampling rainfall event all cups were replaced.

Splash erosion observations were conducted from the 6th June to the 28th October 2013. During the monitoring period 29 rainfall events were recorded. Quality control of all soil splash measurements in the open field, and under each vegetation site, enabled nine rainfall events with effective precipitation (ranging from 5.4 to 55.9 mm) to be selected for this study (Table 3).

2.3. Statistical analysis

Statistical analyses were conducted using SPSS 13.0 (SPSS Inc., Chicago, USA). Significant differences among sand losses between vegetation types and the open field were detected using one-way analysis of variance (ANOVA) followed by post hoc Fisher's least significant difference test. Student's *t*-test was used to detect the differences between species within plant morphological variables. For correlating rainfall characteristics to sand loss, a simple linear regression and the coefficient of determination was used. One-way analysis of covariance (ANCOVA) was used to determine if the regression line slopes were statistically different.

3. Results

3.1. Rainfall and throughfall

The percentage of gross rainfall which reached the ground surface as throughfall ranged from 71% to 94% under the rubber monoculture canopy, with a mean of 85% (Table 4). For the agroforestry systems, throughfall varied from 26% to 92% of gross rainfall, with a maximum mean of 83% for the rubber and orange system, and a minimum mean of 73% for the rubber and tea system. The percentage of throughfall had a wide variation which was dependent on the volume and intensity of the incident rainfall event.

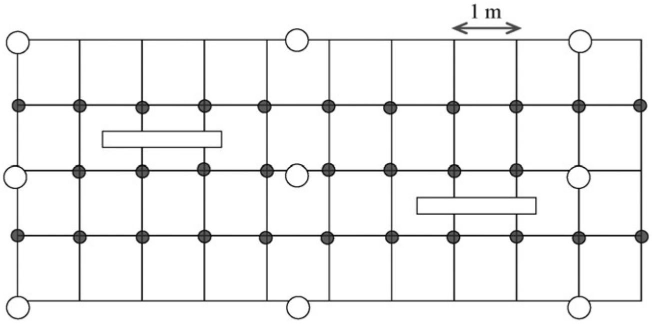

Fig. 2. Schematic design for the splash erosion and throughfall measurements under the rubber monoculture plantation. Stems are represented by cycles, splash cups by black dots, and throughfall troughs by rectangles.

Fig. 3 shows throughfall and gross rainfall for the rubber monoculture. Using a linear regression to determine the point of intersect with the axes (Brandt, 1988), a canopy interception capacity of 0.4 mm for the rubber monoculture was determined. As expected, this result was consistently lower than those of the agroforestry systems (Table 5), with the rubber and tea system having the greatest canopy capacity (1.01 mm) and the rubber and orange system having the lowest canopy capacity (0.49 mm). This result suggests that multiple-layered canopies of the agroforestry system intercepted more water during each incident rainfall event.

Stemflow was not measured in this experiment, but previous field observations in this rubber plantation indicated that stemflow amounts reached around 5% of the annual rainfall (Liu et al., 2008).

3.2. Sand loss from splash cups in the open environment and under vegetation

Simultaneous measurements in the open environment and under the rubber monoculture showed a significant difference in sand loss from the splash cups, with the mean value being 3.12 times greater under the rubber monoculture (5028 ± 2661 $g\ m^{-2}$) than in the open environment (1611 ± 628 $g\ m^{-2}$, Table 4). It was also found that during small sized storms, the difference in sand loss was much more distinct (up to 9.33 times more than in the open environment). For the agroforestry systems, the ratio of sand loss to that in the open environment ranged from 0.87 (rubber and tea system) to 2.18 (rubber and orange system); the rubber and tea system was the only system to have a ratio < 1.

Results for mean sand loss under the agroforestry systems (except for the rubber and orange system) were all significantly lower when compared with the rubber monoculture ($P < 0.05$, Table 4). This indicates that throughfall erosivity beneath these multiple-layered canopies was greatly reduced. Among the five types of agroforestry systems, the rubber and tea system was shown to be the most effective in controlling splash erosion potential (0.27 times the monoculture system), with the rubber and *F. macrophylla* system being the second most effective (0.39 times the monoculture system).

The variability between pseudo-replicates (*i.e.*, those within a single rainfall event) was high under all vegetation types, and this increased with the amount of sand mobilized; the difference in the open environment was lower (Table 4). As expected, events with low sand loss

Table 3
Rainfall characteristics of the nine rain events measured during June and October 2013.

Event	1	2	3	4	5	6	7	8	9
Date	6 Jun.	19 Jul.	22 Jul.	28 Jul.	22 Aug.	25 Aug.	21–22 Oct.	24 Oct.	28 Oct.
Duration (h)	7.5	5.4	1.5	4.1	0.4	5.2	10.4	5.8	2.0
Max. rainfall intensity (mm 10 min^{-1})	1.5	3.3	2.5	1.5	1.0	3.8	7.1	0.8	5.1
Rainfall amount (mm)	21.1	19.4	25.7	21.4	6.5	12.7	55.9	5.4	26.2

Table 4
Gross rainfall (Rg), throughfall (TF) and sand loss (SL) from splash cups for the open environment (Open), rubber monoculture (Rm), and different types of rubber-based agroforestry systems for nine rain events measured during June and October 2013.

Event		Open	Rm	R-tea	R-cof	R-cac	R-mac	R-ora
1	Rg *or* TF (mm)	21.1	19.8 (94%)	16.7 (79%)	17.2 (82%)	17.9 (85%)	15.8 (75%)	18.3 (87%)
	SL (g m^{-2})	987 ± 60a	3227 ± 703b	1306 ± 692a	2155 ± 1499c	1938 ± 1379bc	1800 ± 915 ac	1631 ± 596a
2	Rg *or* TF (mm)	19.2	17.2 (90%)	15.8 (82%)	16.1 (84%)	15.3 (80%)	16.3 (85%)	17.7 (92%)
	SL (g m^{-2})	2607 ± 277a	5412 ± 1198b	1583 ± 1144a	3702 ± 807c	1553 ± 1439a	2914 ± 933 ac	3305 ± 1228c
3	Rg *or* TF (mm)	25.7	22.5 (88%)	20.2 (79%)	21.7 (84%)	22.8 (89%)	20.5 (80%)	20.4 (79%)
	SL (g m^{-2})	1963 ± 771a	3173 ± 656b	1511 ± 1162a	2866 ± 1692b	1938 ± 2113a	2227 ± 771ab	1565 ± 722a
4	Rg *or* TF (mm)	21.4	17.9 (84%)	18.3 (86%)	18.5 (86%)	19.1 (89%)	18.4 (86%)	17.6 (82%)
	SL (g m^{-2})	572 ± 60a	1427 ± 626b	710 ± 70a	1270 ± 620b	1300 ± 1072b	1234 ± 501b	1126 ± 638b
5	Rg *or* TF (mm)	6.5	4.6 (71%)	1.7 (26%)	3.3 (51%)	4.1 (63%)	3.2 (49%)	4.2 (65%)
	SL (g m^{-2})	668 ± 84a	1993 ± 704b	506 ± 235a	1854 ± 548b	1156 ± 445c	825 ± 175 ac	1752 ± 807b
6	Rg *or* TF (mm)	12.7	9.3 (73%)	7.9 (62%)	8.1 (64%)	8.9 (70%)	10.5 (83%)	9.1 (72%)
	SL (g m^{-2})	1102 ± 385a	2679 ± 1427b	620 ± 163c	2516 ± 1421b	2221 ± 1355b	1511 ± 626a	2203 ± 1222b
7	Rg *or* TF (mm)	55.9	46.2 (84%)	45.0 (82%)	45.5 (83%)	46.7 (85%)	48.4 (89%)	46.3 (84%)
	SL (g m^{-2})	3702 ± 144a	8904 ± 3407b	2270 ± 1138a	5912 ± 1734c	6941 ± 3967b	3474 ± 1535a	7362 ± 3919b
8	Rg *or* TF (mm)	5.4	4.1 (76%)	1.5 (28%)	2.9 (54%)	3.1 (57%)	2.2 (41%)	3.7 (69%)
	SL (g m^{-2})	54 ± 18a	506 ± 132b	66 ± 54a	138 ± 78c	102 ± 66c	78 ± 24a	295 ± 169d
9	Rg *or* TF (mm)	26.2	22.3 (85%)	20.5 (78%)	21.9 (84%)	20.1 (77%)	19.7 (75%)	21.5 (82%)
	SL (g m^{-2})	2847 ± 813a	6929 ± 3696b	2149 ± 692c	4082 ± 1270b	3227 ± 1433a	2360 ± 753 ac	5400 ± 1884b
Overall	Rg *or* TF (mm)	193.5	163.2 (85%)	141.3 (73%)	155.2 (80%)	158.0 (82%)	157.0 (81%)	160.6 (83%)
	SL (g m^{-2})	1611 ± 628a	5028 ± 2661b	1401 ± 765a	3203 ± 1692c	2543 ± 1950c	1964 ± 1053 ac	3511 ± 2270bc

R-tea represents rubber and tea (*C. sinensis*) system; R-cof, rubber and coffee (*C. arabica*) system; R-cac, rubber and cacao (*T. cacao*) system; R-mac, rubber and *F. macrophylla* system; and R-ora, rubber and orange (*C. reticulata*) system. Values for SL are mean ± 1 SD (n = 9 for open and n = 10-30 for vegetation). Values in parentheses are percentages of incident rainfall. Values in the same line followed by different normal letters are significantly different (P < 0.05).

showed a smaller variability between pseudo-replicates at all observation sites.

Sand loss from the splash cups in the open environment and under the vegetation canopies were closely correlated with rainfall volume and maximum intensity (Fig. 4). For each vegetation site, the correlated sand loss with maximum rainfall intensity was consistently higher than the correlations found with rainfall volume (P < 0.05). Results from the open field experiment showed sand loss to be strongly correlated with rainfall volume (R^2 = 0.817, P < 0.01), but not as strongly correlated with rainfall intensity (R^2 = 0.602, P < 0.05). ANCOVA showed that the slopes of regression for sand loss *vs.* maximum rainfall intensity under canopies were statistically higher than those for sand loss *vs.* rainfall volume ($F_{1,\ 122}$ = 60.705, P < 0.001). It was identified that among the open environment, the rubber and tea system and the rubber and *F. macrophylla* system, the slopes of the regression lines for sand loss *vs.* maximum rainfall intensity were not significantly different ($F_{2,\ 21}$ = 0.806, P = 0.460). Similarly, it was also found that there were no significant differences in the regression line slopes for the open environment, the rubber and tea system and the rubber and *F. macrophylla* system for sand loss *vs.* rainfall volume ($F_{2,\ 21}$ = 1.604, P = 0.225). Additionally, it was identified that sand loss had a better correlation with the maximum rainfall intensity under the vegetation canopies than in the open environment (P < 0.05). This indicates that the tree canopies eliminated rainfall variables which determine the erosive power of rainstorms.

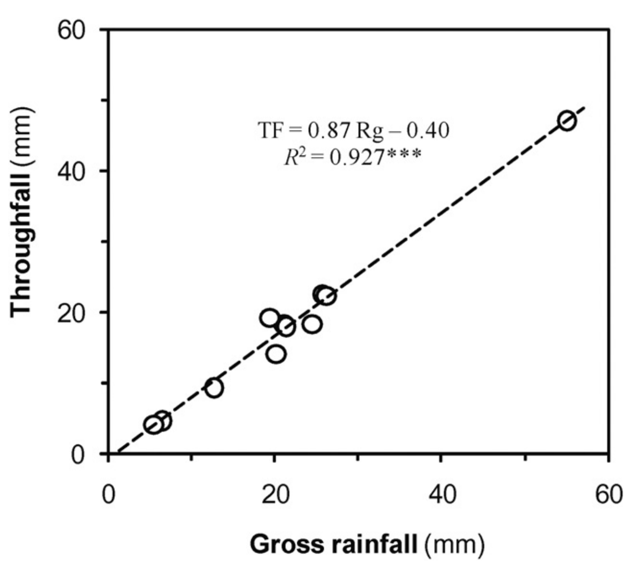

Fig. 3. Throughfall (TF) plotted against gross rainfall (Rg) to determine canopy interception capacity for the rubber monoculture. ***P < 0.001.

3.3. Canopy characteristics and their effect on splash erosion potential

With the exception of *F. macrophylla*, tea showed a significantly higher value in leaf area index (LAI) and canopy closure rate (CR) among the understory intercrops in the five types of agroforestry systems (Table 2). For *C. reticulata* (orange), the height of canopy center (HC) and the height of the 1st branch were significantly higher than those of the other intercrops (P < 0.05). *T. cacao* also had a notably bigger leaf size (296 ± 13 cm^2) than the other vegetation types (P < 0.05).

Sand loss from splash cups was plotted against HC, CT (canopy thickness), CR and LAI of the understory crops in each agroforestry system (Fig. 5). It can be seen that sand loss from the splash cups obtained under these multiple-layered canopies was positively correlated with HC (P < 0.05) and negatively correlated with CR (P < 0.05) and LAI (P < 0.01), but it was not correlated with CT. This demonstrates that lower HC, higher CR and higher LAI of the sub-canopy layer in the rubber-based agroforestry system prevented the potential increase in splash erosion. Sand loss was not found to be correlated with leaf size. Again, variability in sand loss increased with increases in HC and

Table 5
Regression functions between throughfall (TF) and gross rainfall (Rg) under the different types of rubber-based agroforestry systems.

Agroforestry system	Regression function	*R2*	*P*
R-tea	TF = 0.87 Rg – 1.01	0.974	<0.001
R-cof	TF = 0.88 Rg – 0.57	0.940	<0.001
R-cac	TF = 0.87 Rg – 0.60	0.954	<0.01
R-mac	TF = 0.90 Rg – 0.81	0.912	<0.001
R-ora	TF = 0.92 Rg – 0.49	0.881	<0.05

R-tea represents rubber and tea (*C. sinensis*) system; R-cof, rubber and coffee (*C. arabica*) system; R-cac, rubber and cacao (*T. cacao*) system; R-mac, rubber and *F. macrophylla* system; and R-ora, rubber and orange (*C. reticulata*) system.

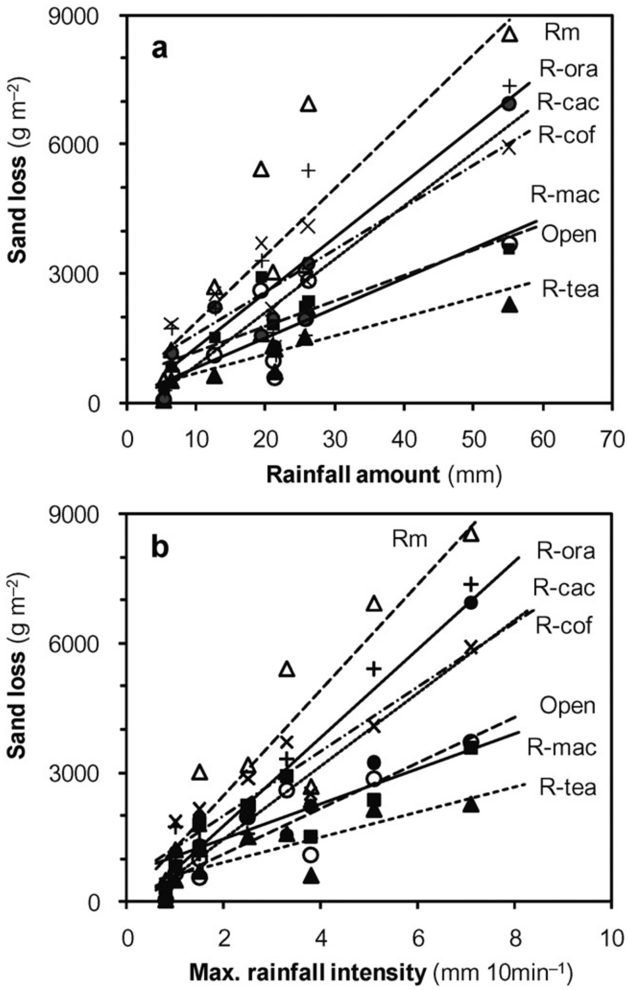

Fig. 4. Sand loss from splash cups in the open environment and under the different types of rubber plantations in relation to rainfall amount (a) and intensity (b) during each event. Linear regression equations and coefficients of determination are not shown for the sake of clarity. See Table 1 for abbreviations.

decreases in CR and LAI, as indicated by the magnitude of its standard deviation (Fig. 5).

4. Discussion

4.1. Splash erosion potential under single and multiple canopies

The base of the rubber tree foliage was at least 10 m above the ground; hence it is considered that the assumption of terminal velocity is acceptable for most throughfall drops to reach the forest floor (Mosley, 1982). The measurements under the rubber monoculture showed sand loss from splash cups being, on average, 3.12 times greater than in the open field environment. This suggests that splash erosion would be the dominant erosion process in this plantation due to the high percentage of exposed mineral soil on the plantation floor (nearly 90%; Liu et al., 2015), coupled with high throughfall kinetic energies. This is consistent with previous studies. Mosley (1982), for example, measured splash erosion to be 3.1 times greater in a beech forest compared to open field conditions and Nanko et al. (2008) recorded the kinetic energy of rainfall under *Chamaecyparis obtusa* to be 2.7 times greater than in the open field. Similarly, Geißler et al. (2012a) noted that the ratio of sand loss under vegetation to that of an open field environment ranged from 2.37 to 3.38, with a mean of 2.59. Brandt (1988) highlighted that splash erosion under a single canopy in a tropical rainforest can increase to 6.65 times greater than splash erosion in the open environment. In relation to differences between rainfall and throughfall erosivity, however, Vis (1986) measured the kinetic energy in a Colombian forest to be 1.4 times greater than that in the open field environment. The difference in magnitude compared to results from this study may be due to the larger cup size used by Vis (1986). Larger sized cups have their central area further away from the cup edge, thus it is more difficult for the sand to be expelled from the cup (Poesen and Torri, 1988). Furthermore, coarser and therefore less erodible sand was used in the experiment by Vis (1986). As highlighted by Geißler et al. (2012a) and Scholten et al. (2011), both differences have resulted in an underestimation of erosion potential compared to this study where much finer sand and smaller sized cups have been used.

The data obtained in this study under the five types of agroforestry systems showed that in all but one system (rubber and tea system; 0.87 times the open value) there was more sand loss beneath multiple-layered canopies than in the open environment ($P < 0.05$). However, in all but one system (rubber and orange system) there was a significant reduction in sand loss beneath the multiple-layered canopies compared to single-layered monoculture ($P < 0.05$), especially for the rubber and tea system (0.27 times the monoculture). These differences in throughfall erosivity between the agroforestry systems can be explained by height differences for the throughfall drops from the canopies, and different canopy closure rates (*e.g.*, Geißler et al., 2012a). Brandt (1988) and Vis (1986) suggested that, as the thin sub-canopy increased the incidence of large drops from the upper canopy, and that the sub-canopy was not low enough, its protective effect for the ground soil would be limited. Similarly, Dohrenwend (1977) simulated the effects of different canopies on the kinetic energy of throughfall and showed that ground cover crops, growing within 25 cm above the ground surface, would provide excellent protection for the underlying soil. He stated that water drops falling over short distances move an amount of sand proportionately less than their contribution to the total kinetic energy of the rainfall. Low vegetation has been reported to lower kinetic energy, even up to 0.1 times that of natural rainfall, although under some circumstances it appeared that an increase in soil splash occurred despite a decrease in kinetic energy (Brandt, 1988; Noble and Morgan, 1983). These findings were also confirmed by our data for the rubber and tea system which showed a high sub-canopy closure (79%) and a low sub-canopy height (1.2 m), and consequently a significant reduction in splash erosion potential (0.27 times the monoculture, Table 4). Data for the rubber and *F. macrophylla* system also showed an immediate effect in reducing splash erosion potential (0.39 times the monoculture) because it had a high sub-canopy closure (68%) and a low sub-canopy height (2.2 m). This finding is consistent with results from ANCOVA analysis which showed that among the open environment, the rubber and tea system and the rubber and *F. macrophylla* system, the regression line slopes for sand loss *vs.* rainfall intensity or volume were not significantly different. However, the rubber and orange system would be more susceptible to splash induced erosion (0.71 times the monoculture) since it had a low sub-canopy closure (21%) and a high sub-canopy height (4 m).

4.2. Factors influencing splash erosion potential

In forested areas, the erosive power of throughfall drops is the single most important cause of soil splash detachment (Gyssels et al., 2005). Mizugaki et al. (2010) proposed that throughfall intensity is a critical factor contributing to soil detachment under a forest canopy. Nanko et al. (2008) showed that soil splash detachment in a Japanese cypress plantation was 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. Results from this study also confirmed these findings as they showed splash erosion potential under the vegetation canopies to be strongly correlated with maximum rainfall intensity, but not as strongly correlated with rainfall volume. This indicates that

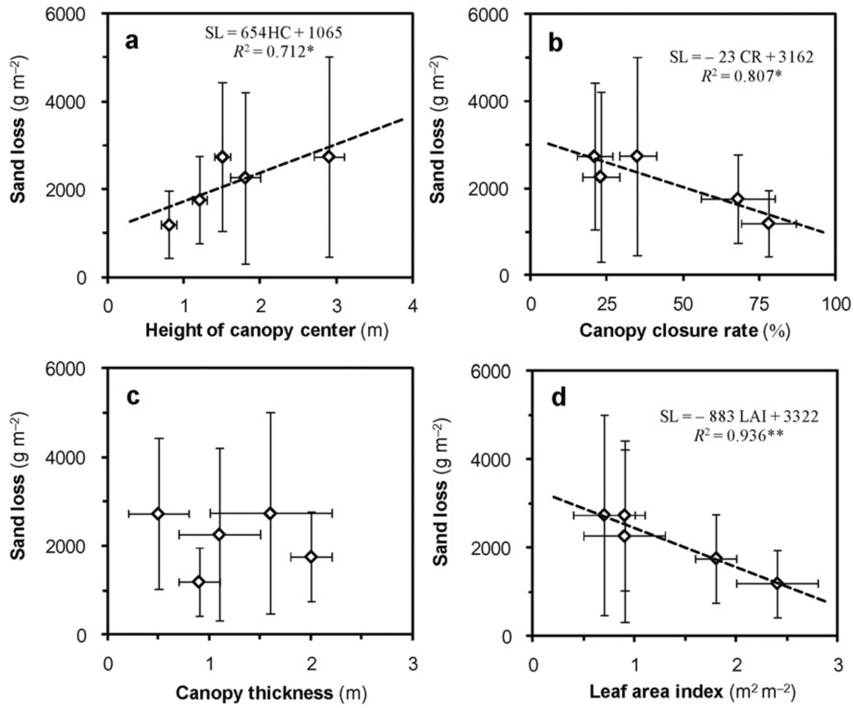

Fig. 5. Relationships between sand loss (SL) and (a) height of canopy center (HC), (b) canopy closure rate (CR), (c) canopy thickness (CT), and (d) leaf area index (LAI) of understory crops in the different types of rubber-based agroforestry systems. Crossed bar represents ±1 SD (n = 9–12). *P < 0.05. **P < 0.01.

continuous and concentrated raindrop impacts over a short duration can cause splash detachment on the forest floor, as suggested by Nanko et al. (2011). This also suggests that maximum rainfall intensity was a more important factor in causing rain splash erosion under the vegetation canopies. The stronger correlations and steeper regression line slopes between sand loss and maximum rainfall intensity demonstrated that the tree canopies eliminated rainfall variables which determine the erosive power of rain storms.

Previous studies have shown that the canopy does not only change the kinetic energy of rainfall by reducing the depth of water; it also changes the drop size distribution, especially for low rainfall intensities (Brooks and Spencer, 1995; Mosley, 1982; Nanko et al., 2011). Previous studies (for example Brandt, 1988; Frasson and Krajewski, 2011; Quinn and Laflen, 1983; Vis, 1986) have also reported drop sizes under different vegetation canopies, results of which have shown that throughfall drops under the majority of canopies have a normal distribution, with a mean between 4.52 and 4.95 mm. The drop size distribution is not affected by the shapes and sizes of the leaves in the canopies; whether the canopy are crops or trees; or by the rainfall intensity (Brandt, 1990). Whether or not the energy of the whole storm is greater under the canopy than in the open environment depends on the balance between energy lost by intercepted water and the splitting of raindrops, and energy gained through the formation of larger drops (Brandt, 1988). Zhu et al. (2014) measured the throughfall drop size distribution from different types of rubber-based agroforestry systems and reported that a much greater percentage of the total volume of water fell in the form of drops larger than those found in rainfall in the open environment, especially in a rubber monoculture. Zhu et al. (2014) also recorded lower throughfall kinetic energy under multiple canopies than under a rubber monoculture (ranging from 0.27 to 0.69 times the monoculture), findings that were confirmed with the results from our splash measurement data (Table 4). It was also found that during small sized storms, the difference in sand loss was much more distinct (up to 9.33 times more than in the open environment; Table 4). Similarly, Zachar (1982) found that small rainfall intensities also caused greater erosion if the duration of rainfall was long enough.

The throughfall erosivity was much more diverse in time and space than rainfall in the open environment, as demonstrated by the magnitude of its standard deviation (Table 4). Again, the variability in throughfall erosivity increased with increasing canopy height and decreasing canopy coverage and LAI (Fig. 5). Results from investigations on a Japanese cypress plantation (Mizugaki et al., 2010) were similar to the results from this study; the results were linked to spatial variability in raindrop impact which led to variations in soil splash erosion. This highly spatial variability in the quantities of sand splashed from the cups under single and multiple-layered canopies can be attributed to the greater spatial variation in throughfall drop sizes that are controlled by the architecture of the canopy, *i.e.*, the concentrating effect (Vis, 1986; Brooks and Spencer, 1995; Calder, 2001; Nanko et al., 2008). Previous studies have shown that coalescing drops from leaves and branches may be responsible for the notable spatial heterogeneity of throughfall erosivity compared to open rainfall, although the amount of throughfall in forests is generally about 10–40% less when compared to the open field (Brandt, 1988; Nanko et al., 2008; Wei et al., 2005; Ziegler et al., 2009b). Geißler et al. (2012b) reported that throughfall characteristics are strongly influenced by traits of the vegetation species, *e.g.*, height, thickness, leaf size and LAI (canopy coverage). Results from this study also highlighted that throughfall erosivity under multiple-layered canopies was positively correlated with the sub-canopy height and negatively correlated with the sub-canopy coverage; but it was not correlated with the sub-canopy thickness (Fig. 5). This indicates that rubber-based agroforestry systems with a low height, high coverage (and therefore high LAI) of sub-canopy faces a low risk of splash-induced erosion. Canopy storage (canopy interception capacity) also appears to be an important factor as it controls the amount of water available to fall from the leaves as drips (Brandt, 1990; Geißler et al., 2012b), as shown in Table 5.

Mosley (1982) highlighted that the difference in sand loss between splash cups is disproportionately greater than the difference between their corresponding kinetic energy. Since the increase in kinetic energy with drop size is nonlinear (Brandt, 1990), the energy per unit volume of throughfall on some specific dripping points containing large drops can be considerably greater than those containing free throughfall and splash droplets (Calder, 2001; Kinnell, 2005; Nanko et al., 2008). Visual observations from this study indicated that there were specific locations where large drops fell continuously and that the sand surface in splash cups which recorded large losses were deeply pockmarked, especially under the rubber monoculture. This sort of preferential fall path could permit drops in excess of 5 mm in diameter to fall free of interaction with other drops, therefore reaching the forest floor with considerably high potential energy, and high spatial variability (Dohrenwend, 1977; Zhu et al., 2014).

4.3. Implications

The throughfall erosivity under the vegetation canopies was, except for the rubber and tea system, always higher than that of rainfall in the open environment. However, compared to the single-layered monoculture, throughfall erosivity beneath these multiple-layered canopies was significantly reduced, except for the rubber and orange system where it had a low sub-canopy closure and a high sub-canopy height, and consequently a lower reduction in throughfall erosivity. These results indicate that very low height and high sub-canopy coverage ultimately controls the occurrence of splash erosion, regardless of how the splash potential is increased by the canopy above, highlighting the importance of selecting low intercrops for constructing agroforestry systems. Hence, planting low, shade-loving plant species under rubber trees is potentially the most effective way to protect the surface soil against splash erosion. Among the five types of agroforestry systems, the rubber and tea system and the rubber and *F. macrophylla* system were shown to be the most effective in controlling splash erosion potential. Not only that, these two agroforestry systems can also facilitate the diversification of agricultural products, promote faster returns on investment and reduce the breakeven point since fluctuations in rubber prices have been a serious problem for producers (Feng, 2007; Snoeck et al., 2013). For example, economic analyses showed that the rubber and tea system generated a significantly higher land expectation value than rubber and tea monoculture under current socio-economic circumstances (Guo et al., 2006). As a traditional Chinese medicine with various therapeutic purposes (Ko et al., 2010), *F. macrophylla* is widely used in agriculture, for crop improvement, and as fodder. Due to its low rate of leaf decomposition, dense growth, moderate drought tolerance, ability to withstand occasional flooding and coppicing ability, it is commonly used for erosion and weed control, nitrogen fixing and moisture conservation (Orwa et al., 2009; Wu et al., 2016). Solely from the perspective of soil erosion control and economic profitability, tea and *F. macrophylla* are recommended for constructing rubber-based agroforestry systems in this area.

However, as highlighted by Brooks and Spencer (1995), there are two important factors which affect the amount of splash erosion that will actually take place under forest canopies. Firstly, the forest floor is covered by litterfall which can offer further protection to the surface soil. Although splash erosion is found to be high in some localized spots, the overall rate of splash erosion is likely to be low (Zhu et al., 2014). Secondly, rainfall is concentrated beneath drip points, with areas between the drip points having either zero rainfall or receiving direct throughfall which have the characteristics of rainfall in an open environment. High throughfall kinetic energy leading to the occurrence of splash erosion in the rubber plantations mainly depends on the presence of litter cover on the floor, or on the percentage of exposed mineral soil (Vis, 1986; Blanco and Aguilar, 2015; Villatoro-Sánchez et al., 2015). Litter cover as a key control on the type and intensity of soil erosion has previously been highlighted by Miyata et al. (2009). The litter layer not only protects the soil from direct splash erosion, it also acts to filter splashed soil particles, thus preventing the clogging of soil pores which can decrease infiltration and increase surface runoff (Wiersum, 1985). As the litter layer gradually decomposes, it also results in increased humus in forest soils and decreases erodibility (Nanko et al., 2008); a direct soil cover of leaf litter has therefore been identified to be the most important vegetation factor protecting soil from erosion (Brandt, 1988). Wiersum (1985) has shown that a litter layer can reduce splash erosion by up to 0.05 times that of an unprotected soil. Miyata et al. (2009) noted that mineral soil erosion in plots without a litter layer was 5.6 times greater than that in plots with a litter layer in a Japanese cypress plantation. Similarly, Nishiyama (2003) reported that erosion in plots without a litter layer was 5.1 times greater than that of plots with a litter layer. However, in these rubber plantations, human disturbance, for example by latex tapping activities, herbicide application and removal of the litter layer during fertilization, increased the percentage of exposed mineral soil and this, in combination with the high throughfall kinetic energies, may result in higher actual splash erosion rates inside the forests than in the open field, as confirmed by our previous study (Liu et al., 2015). Further field investigations are required to examine the effects of litter on practical soil conservation activities in these rubber plantations, and further research on erosion processes should be centered on the properties and dynamics of the litter layer and the organic fraction in the surface horizons of the forest soils.

5. Conclusions

Rainfall and throughfall erosivity (splash erosion potential) was measured in an open environment and under different types of rubber-based agroforestry systems and rubber monoculture by using sand-filled Tübingen splash cups. Results indicate that the splash erosion potential under rubber monoculture was, on average, 3.12 times greater than those in the open environment. Splash erosion potential under agroforestry systems was higher than that of an open environment (ranging from 1.22 to 2.18 times greater), except for the rubber and tea system (0.87 times the open environment). However, in all but one system (the rubber and orange system), there was a significant reduction in splash erosion beneath multiple canopies compared to monoculture, especially for the rubber and tea system (0.27 times the monoculture) where it had high sub-canopy closure and low sub-canopy height. The erosion potential under the forest is closely related to the forest structure, especially height and canopy cover. The variability in throughfall erosivity increased with increasing canopy height and decreasing canopy coverage and LAI. These results indicate that low canopy height with high sub-canopy coverage is the major control on the amount of splash erosion, regardless of how the splash potential is increased by the canopy above. These results highlight the importance of selecting low near-surface intercrops for constructing rubber-based agroforestry systems. This also accentuates the importance of an intact litter layer in rubber plantations to protect the soil against splash erosion. Disturbance of these forests by latex tapping activities, herbicide application and removal of the litter layer during fertilization, for example, will also lead to higher actual splash erosion rates inside the forests in comparison with the open environment.

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