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Throughfall kinetic energy and its spatial characteristics under rubber-based agroforestry systems

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A R T I C L E I N F O

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A B S T R A C T

Rubber is usually grown as a monoculture but there have been recent attempts to encourage rubber-based agroforestry systems to reduce adverse environmental impacts, including the reduction of soil erosion in Xishuangbanna, SW China. To estimate the influence of different types of rubber-based agroforestry systems on soil erosion processes, we measured the throughfall kinetic energy (TKE) under different vegetation types by using 640 sand-filled Tübingen splash cups. This study was conducted in Xishuangbanna Tropical Botanical Gardens under natural rainfall conditions. Our results indicated that in both rubber-based agroforestry systems and rubber monocultures, a significant linear positive correlation exists between TKE and rainfall amount. Rainfall amount is a critical factor that contributes to soil detachment in rubber plantations in this region. TKE under rubber plantation conditions was found to be notably higher than under open field conditions (ranging from 1.84 to 2.32 times greater). However, there was no significant difference under multiple canopies compared to monoculture. TKE values under the different rubber-based agroforestry systems were closely related to the canopy structure, and TKE and leaf area index were significantly negatively correlated. The spatial variability of TKE was higher in rubber-based agroforestry systems than in rubber monocultures. In addition, TKE was usually concentrated in 3–4 m bands that did not have the protection of a sub-canopy. The fact that the erosion by TKE under rubber-based agroforestry was still high highlights the importance of selecting intercrops when constructing rubber-based agroforestry systems and of improving planting patterns.

1. Introduction

Due to economic demands, rubber monoculture plantations have undergone substantial expansion and have replaced primary tropical forest in Xishuangbanna, SW China. It is commonly recognized that the change in vegetation to rubber monoculture may result in significant soil erosion (Liu et al., 2015, 2011) and a loss of soil organic matter (Li et al., 2012), posing a major threat to regional water quality (Zhou et al., 2014). Therefore, there is clearly a need to identify the key mechanisms or factors that contribute to soil erosion in rubber plantation forests.

In forests, throughfall kinetic energy (TKE) is a widely used indicator to express the potential of rainfall erosivity and predict soil erosion rates (Goebes et al., 2015a, 2015b; Morgan, 2009; Zhou et al., 2002). Many studies have confirmed that monoculture plantations significantly increased TKE and accelerated soil erosion (Mosley, 1982; Nanko et al., 2008; Zhou et al., 2002). Therefore, TKE might be one of the best indices of the impacts of rubber plantation forests on soil erosion. On the other hand, the rainfall erosivity factor (R), in terms of the widely used methodology for soil loss estimation USLE/RUSLE (Renard et al., 1997; Wischmeier and Smith, 1978), is defined as a product of the rainfall kinetic energy (KE) and the maximum 30-min rainfall intensity (I_{30}). Direct measurements of rainfall kinetic energy are very rare (Mikoš et al., 2006); therefore, an alternative approach is to estimate kinetic energy from widely available rainfall intensity (I) data by implementing empirical kinetic energy-rainfall intensity relationships. Although, this relationship has been used in many locations with different climate conditions, it should be justified prior its implementation in a climatically different environment, such as the rubber plantations in Xishuangbanna.

In recent years, the Xishuangbanna local government has proposed building rubber-based agroforestry systems that aim to reduce water and soil losses. With the different canopy layers, they could increase rainfall interception and reduce TKE (Feng, 2007). In particular, TKE is mainly influenced by forest crown architecture and tree species richness (Geißler et al., 2012, 2010; Goebes et al., 2015a; Hall and Calder, 1993;

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Nanko et al., 2006; Seitz et al., 2015; Wainwright et al., 1999; Wakiyama et al., 2010). Crown cover, plant morphology (Xu et al., 2009), leaf area index (Park and Cameron, 2008) and branch traits (Nanko et al., 2008) are all thought to influence TKE in various ways. In Japan, Nanko et al. (2008, 2011) conducted numerous experiments and observed that decreasing the canopy thickness resulted in increased TKE. Geißler et al. (2010, 2012, 2013) also emphasized the importance of shrubs and herbs in forest ecosystems as protection against soil erosion. Therefore, whether the rubber-based agroforestry system is effective in reducing TKE and soil erosion needs to be studied, but thus far, relatively few studies have investigated this topic (Liu et al., 2016; Zhu et al., 2014).

In addition, compared with the spatial variability of throughfall, TKE has also been demonstrated to have spatial variability (Goebes et al., 2015b; Nanko et al., 2011). TKE variability has important implications for sampling strategies and has important effects on soil physical properties such as bulk density, soil aggregates size, crust thickness and infiltration rate (Cerdà, 2000; Vaezi et al., 2017). Therefore, research on TKE and its spatial variability is a key factor in understanding the hydrological, hydrosedimentological and ecological cycles (Ramon et al., 2017). However, the spatial variability of TKE has rarely been studied. Nanko et al. (2011) showed a distance-to-stem effect, where TKE below a single Japanese cypress (*Chamaecyparis obtusa*) increased as the distance to the stem increased. Goebes et al. (2015b) examined the spatial variability of TKE in mixed-species forest stands and found that TKE showed distinct spatial variability, influenced primarily by neighbourhood tree species richness. By studying the spatial variability of TKE in the rubber-based agroforestry systems, we can analyse the spatial characteristics of splashing in the forest. Such knowledge would provide a reference for the construction of rubber-based agroforestry systems.

In this study, we focused on TKE under different types of rubber-based agroforestry systems and rubber monoculture. Specifically, we investigated (1) how rainfall characteristics and canopy architecture affect TKE and (2) what are the spatial variability features of TKE.

2. Materials and methods

2.1. Study area

The study site was located in the Xishuangbanna Tropical Botanical Gardens (XTBG, 21°55′39″ N, 101°15′55″ E), Yunnan Province, SW China. Observations were conducted in a small catchment (19.3 ha) that consisted of rubber monoculture and different types of rubber-based agroforestry systems. The elevation of the small catchment ranged from 550 m to 680 m with an average slope of 15°. The local climate is dominated by tropical southern monsoons from the Indian Ocean between May and October and by subtropical jet streams between November and April (Zhang, 1988). Therefore, the two apparent seasons in this area are the rainy season (May to October) and the dry season (November to April). Climate records over the past 40 years showed that the mean annual air temperature was 21.7 °C and that the mean annual rainfall was 1487 mm. Most of the precipitation (87%) occurred between May and October, with very little precipitation (13%) occurring between November and April (Fig. 1) (Liu et al., 2015).

Rubber trees in this catchment were intercropped in the following four planting patterns: rubber (*H. brasiliensis*) monoculture (R), rubber-cocoa (*T. cacao*) agroforestry system (RC), rubber-*F. macrophylla* agroforestry system (RF), and rubber-tea (*C. sinensis*)-orange (*C. reticulata*) agroforestry system (RTO). We selected these four planting patterns to conduct the field experiments and an area without trees to measure rainfall kinetic energy for comparison. In the rubber plantation, rubber trees were planted in a traditional spatial arrangement: double rows spaced 2 m apart on level bench terraces. Within the rows, the trees were spaced 4 m apart, and each set of double rows was separated by a 12 m-wide gap. The intercrops were planted in the 12 m-wide gaps, and

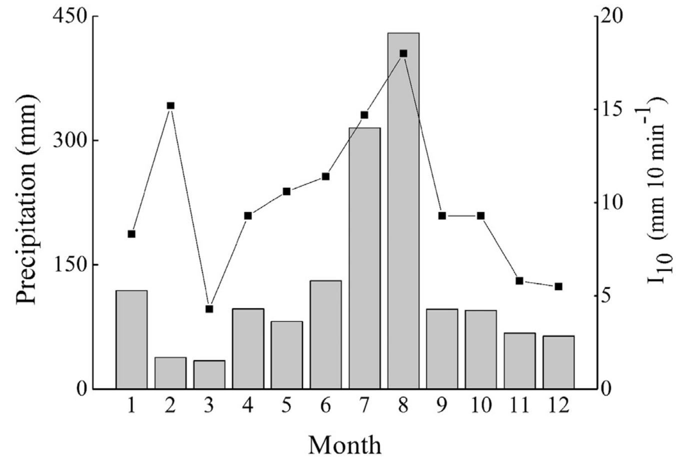

Fig. 1. Monthly precipitation distribution (grey bar) and monthly maximum 10 min rainfall intensity (I_{10}, black square) during 2015.

there was no understory vegetation in the rubber monoculture (Fig. 2d).

In RF, the *F. macrophylla* was planted in seven rows, each spaced 1 m apart and with 0.7 m between the plants in each row (Fig. 2a). In RC, the cocoa trees were planted in four rows, each spaced 3 m apart and with 1.5 m between the plants in each row (Fig. 2b). In RTO, the intercropping system was planted with two species: the tea trees were planted in two rows, and the orange trees were planted in one row between tea trees, each spaced 2 m apart and with 0.5 m between the tea trees plants in each row. The spacing between the orange and tea trees was 4 m, with 2 m between orange trees (Fig. 2c). The planting strategies of the intercrops were designed based on prior planting experience and on the suitability of the terrain for the growth of the intercrops (Feng, 2007). The crown heights of the rubber trees ranged between 11 and 18 m above the ground. The mean diameters of the rubber trees at breasted height in the RF, RC, RTO and R systems were 32.47 ± 5.23 cm, 30.77 ± 5.81 cm, 24.89 ± 4.18 cm, and 22.56 ± 3.33 cm (mean ± SD), respectively. The distance between the rubber monoculture and the three rubber-based agroforestry systems was approximately 500 m; consequently, there was no significant difference in rainfall characteristics or geological properties.

2.2. Experimental design

A total of four plots were used for TKE measurements during the rainy season in 2015: one in the rubber monoculture, and the other three in the various rubber-based agroforestry systems. The plots were sampled in the inter-rows. Each plot's area was 108 m^2, which was divided into nine sections (3 m × 4 m grids). In the nine sections, each corner was located at a specified TKE measurement, and rain gauges were placed in the centre of each section (Fig. 2). Each plot included sixteen TKE measurement positions and nine rain gauges. The splash cup positions remained constant during the experiment. To collect reference measurements under open field conditions, a set of five splash cups was positioned in a pentagonal shape at equal distances of 60 cm from the rain gauge. The 60-cm distance was sufficient to avoid interference between the splash cups (Geißler et al., 2012). All the splash cups were firmly attached to steel stakes inserted vertically into the ground, and their rims were level with the ground surface. After each sampling rainfall event, all cups were replaced.

TKE was measured using Tübingen splash cups (4.6 cm in diameter) designed by Scholten et al. (2011). In general, splash cups allow a high number of replications at low cost and are easy to handle in the field. Previous experiments indicated that TKE can be easily and accurately estimated in the field using this type of sand-filled splash cup (Geißler et al., 2012). The splash cups used in our investigation consisted of a

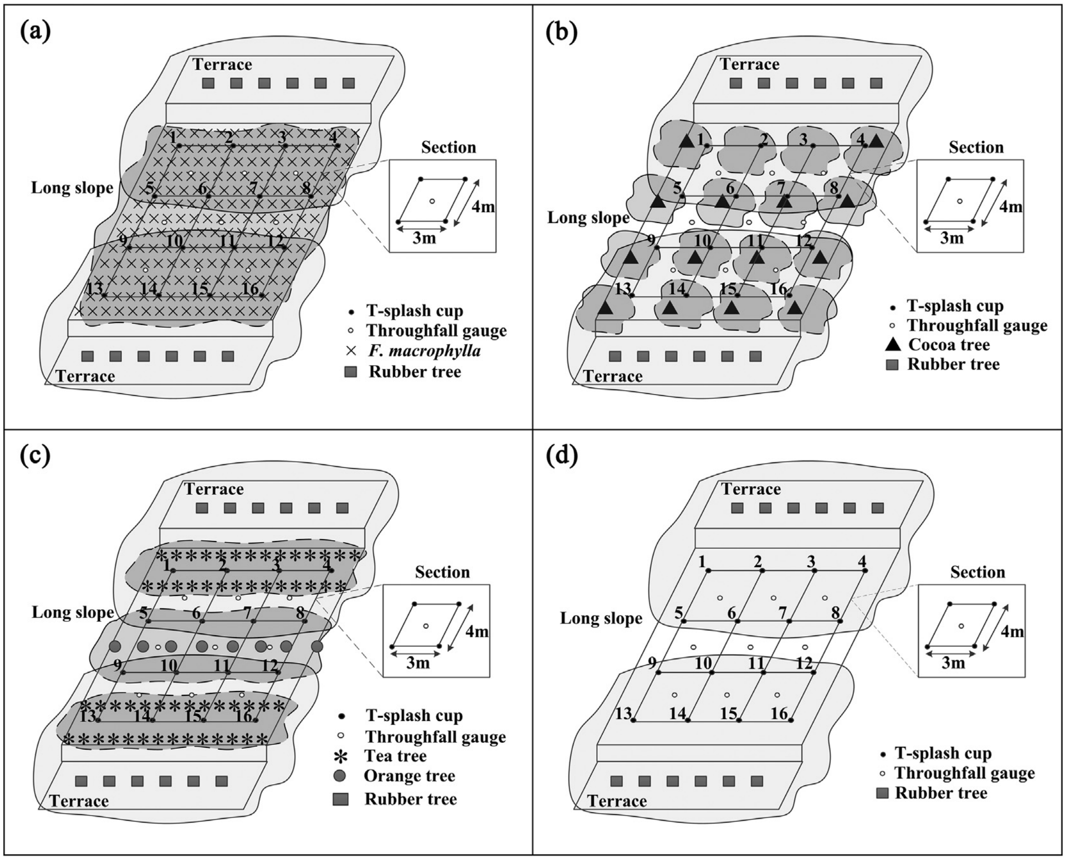

Fig. 2. Schematic diagram of sampling design with sixteen measurement positions. Black dots represent the measurement positions (P1-P16) as they were set in 3 m × 4 m grids along the long slope between the rubber trees in the three rubber-based agroforestry system plots and one rubber monoculture plot. White dots represent throughfall gauges, and grey squares represent the rubber trees planted in terraces. (a) Rubber-*F. macrophylla* agroforestry system; (b) Rubber-cocoa agroforestry system; (c) Rubber-tea-orange agroforestry system; (d) Rubber monoculture.

plastic flask attached to the carrier system, with 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 and had acceptable uniformity over a wide range of rainfall intensities and durations. The splash cup method is also sensitive to very low rainfall intensities (Geißler et al., 2012). 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 each 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 kinetic energy of rainfall and throughfall. More detailed information about the calibration results of the splash cups and the provided functions can be found in Goebes et al. (2015b). In total, 640 splash cups were used and measured from July to October 2015 (i.e., 4 plots × 16 measurement positions × 10 rainfall events).

In total, ten rainfall events were recorded from July to October 2015 (Table 1). A tipping-bucket data-logging rain gauge (3554 WD; Spectrum Technologies Inc., USA) with a 0.2 mm resolution was installed in the open field. This rain gauge recorded both rainfall amount and intensity, and the tip time was recorded at 10-min intervals. The rain gauge in the open field was adjacent to the sampled plots. To obtain a higher spatial resolution, 9 rainfall gauges (4.6 cm in diameter, the same size as the splash cups) were placed in the core of each section to measure the throughfall amount. The throughfall was measured immediately after each rainfall event.

To evaluate the influence of vegetation on TKE, tree height (H_1, rubber tree height; H_2, second canopy height; and H_3, third canopy height), stem diameter 5 cm above ground (GD_1, stem diameter of the high sub-canopy and GD_2, stem diameter of the low sub-canopy), leaf area index (LAI), mean tilt angle (MTA), diameter at breast height of the rubber trees (DBH), and first branch height (FB_1, first branch height of the rubber trees; FB_2, first branch height of the high sub-canopy; and FB_3, first branch height of the low sub-canopy) were measured as co-variables. Tree height was measured using a measuring pole as the length from stem base to apical meristem. Stem diameter was measured with a calliper to the nearest millimeter along two directions. First, branch height was measured with tape as the height from the ground to the first branch. In addition, LAI and MTA were determined above every splash cup position in the late evening using a plant canopy analyser (LAI-2200; Li-Cor Inc., USA).

2.3. Statistical analysis

IBM SPSS statistics 22.0 (IBM Inc.) software was used for the statistical analyse. The significance of rainfall amount, rainfall intensity and throughfall amount effects on TKE was determined using a general linear model ($\alpha = 0.05$). We used regression analysis to calculate the relationship between TKE and the three different rainfall intensity types (I_{10}, I_{30} and I_{60}). Four common empirical functions, including the linear function, power-law function, exponential function, and logarithmic function, were used for curve fitting. Principal components analysis (PCA) was performed to analyse the effects of canopy traits on TKE, and included the LAI, MTA, H_1, H_2, H_3, DBH, GD_1, GD_2, FB_1, FB_2 and FB_3 measurements from each plot during the ten rainfall events. The PCA was calculated using Canoco version 4.5. To express the distribution of TKE at various locations under the different agroforestry system canopies, the contour maps shown in this paper were drawn using the

Table 1
Characteristics of the ten rainfall events registered from July to October 2015 with additional information on throughfall. Rainfall amount and rainfall intensity refer to the measurements of the standard tipping-bucket rain gauges with 0.2 mm accuracy; the measurement interval was 10 min in the open field. Throughfall amount refers to field measurements using rainfall gauges.

Event	Periods	Number of storms[a]	Rainfall amount (mm)	Rainfall intensity (mm 10 min^{-1})	Rainfall intensity (mm 30 min^{-1})	Rainfall intensity (mm h^{-1})	Mean throughfall amount (mm)			
							RF	RC	RTO	R
Event 1	5–6 Jul	2	58.8	14.7	28.0	31.9	49.3	54.3	46.5	54.5
Event 2	16–18 Jul	2	108.4	5.0	10.8	11.3	80.4	101.1	74.7	98.6
Event 3	26–27 Jul	2	19.5	7.6	12.9	14.9	18.4	16.7	15.4	18.6
Event 4	10–11 Aug	1	7.3	4.5	5.7	6.7	4.2	6.2	4.7	6.0
Event 5	13–14 Aug	1	20.3	1.5	3.4	5.4	17.1	20.3	17.0	21.6
Event 6	20 Aug	1	94.5	18.0	43.5	66.7	80.9	91.6	75.6	94.1
Event 7	29 Aug–1 Sep	4	185.6	17.7	35.2	37.8	137.6	124.2	127.9	148.3
Event 8	9–12 Sep	3	30.8	8.6	12.3	14.0	24.4	29.3	23.4	33.7
Event 9	9–10 Oct	2	34.7	5.3	7.3	8.6	25.0	30.4	25.9	31.1
Event 10	12–13 Oct	1	12.7	0.5	1.5	2.1	9.1	12.0	9.6	13.6

[a] An individual rainfall event was defined as a period of continuous rainfall that was isolated from the subsequent rainfall event by at least six uninterrupted hours without precipitation.

ordinary kriging feature of the Surfer program (Version 10.0, Golden Software Inc.). Ordinary kriging is a method of interpolation deriving from regionalized variable theory. It uses a linear function of the data based on spatial autocorrelation and assumes that the data has a normal distribution. More detailed information about ordinary kriging can be found in Cressie (1988).

3. Results

3.1. Throughfall kinetic energy and rainfall characteristics

TKE under different rubber-based agroforestry systems was compared to the recordings of rainfall characteristics (Figs. 3 and 4; Table 2). Fig. 3 presents the relationship between rainfall amount and TKE based on a 10-min dataset. Although rainfall amount was measured during the ten rainfall events under different meteorological conditions, rainfall amount had strong linearity with TKE in the different rubber-based agroforestry systems (the coefficients of determination for RF, RC, RTO, and R were 0.971, 0.921, 0.857 and 0.927, respectively, at $P < 0.0001$). In addition, TKE under the different rubber-based agroforestry systems was strongly linearly correlated with throughfall amount (Fig. 4, the coefficients of determination for RF, RC, RTO, and R were 0.965, 0.964, 0.895 and 0.947, respectively, at $P < 0.0001$).

The coefficients of determination for the relationships between throughfall kinetic energy and rainfall intensity are shown in Table 2. The different functions resulted in differences in the significant correlations with the different peak rainfall intensity values. In all the

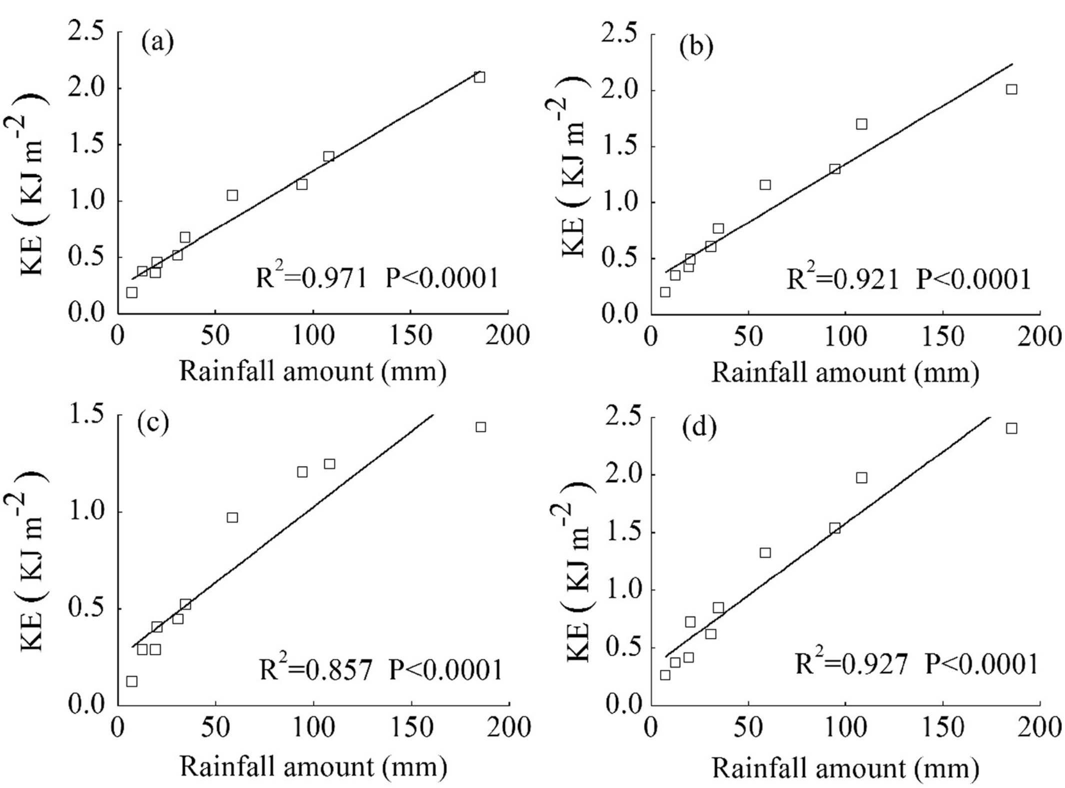

Fig. 3. The relationship was between rainfall amount and TKE in the three different rubber-based agroforestry systems and one rubber monoculture. The black solid line represents the regression line. (a) Rubber-*F. macrophylla* agroforestry system; (b) Rubber-cocoa agroforestry system; (c) Rubber-tea-orange agroforestry system; (d) Rubber monoculture.

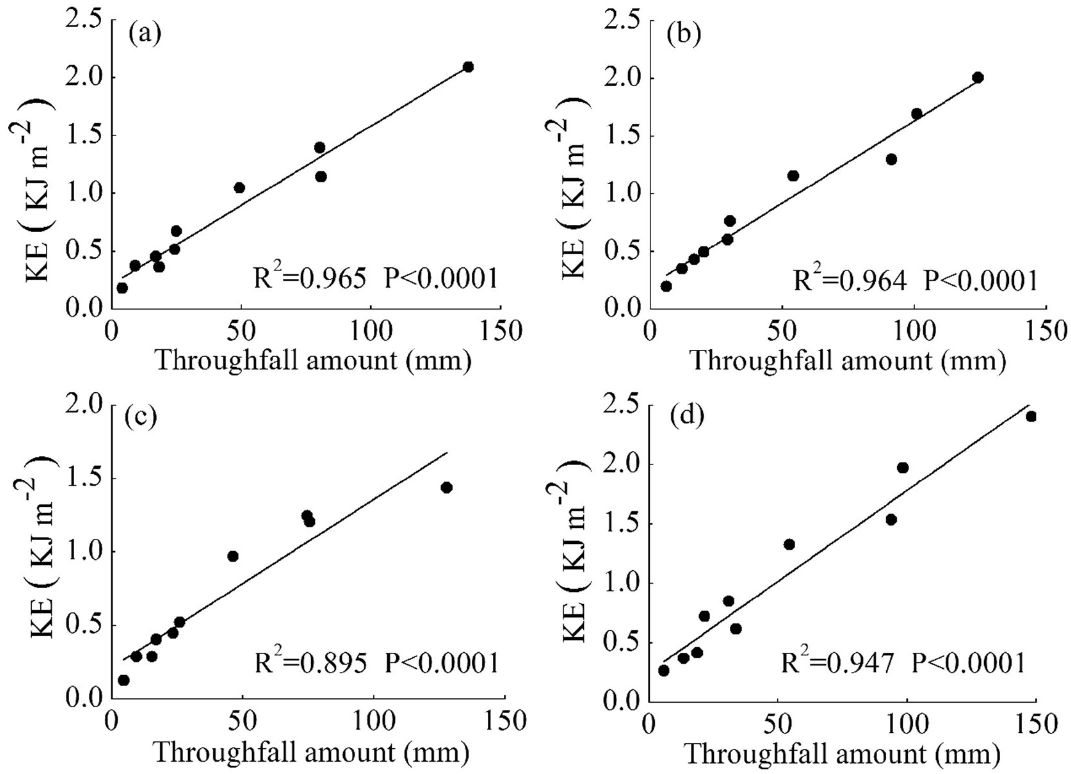

Fig. 4. TKE in the three different rubber-based agroforestry systems and one rubber monoculture in relation to throughfall amount. The black solid line represents the regression line. (a) Rubber-*F. macrophylla* agroforestry system; (b) Rubber-cocoa agroforestry system; (c) Rubber-tea-orange agroforestry system; (d) Rubber monoculture.

rubber-based agroforestry systems, there were significant correlations between the TKE and I_{10} (10 min peak rainfall intensity) using the exponential and linear functions ($P < 0.05$). TKE correlated significantly with I_{30} (30 min peak rainfall intensity) using the linear, power-law, exponential and logarithmic functions ($P < 0.05$). TKE correlated significantly with I_{60} (60 min peak intensity) using the power-law and logarithmic functions ($P < 0.05$).

3.2. Throughfall kinetic energy under different canopy characteristics

As reported by Kinnell (1981) and Rosewell (1986), the kinetic energy of rain can be expressed in two ways: volume-specific and time-specific kinetic energy. The kinetic energy of rain is usually expressed as the amount of rain kinetic energy expended per unit volume of rain (volume-specific kinetic energy, KE_{mm}). Because some of the observation periods included more than one storm, KE_{mm} was an appropriate index in our experiments. KE_{mm} was derived from kinetic energy divided by rainfall or throughfall amount. The results for mean KE_{mm} under the rubber-based agroforestry systems and rubber monoculture were all significantly higher than those of the open field ($P < 0.05$, Fig. 5). Although there were no significant differences among the rubber-based agroforestry systems and the rubber monoculture, the results showed that average TKE_{mm} was lowest in RTO and was highest in R during the ten rainfall events (except in events 3 and 10, where RC and RF were highest, respectively). Across all rainfall events, the average volume-specific TKE was 20.24 ± 5.38 (mean ± SD) $J\,m^{-2}\,mm^{-1}$ under RTO, 22.49 ± 5.77 $J\,m^{-2}\,mm^{-1}$ under RC, 24.67 ± 10.18 $J\,m^{-2}\,mm^{-1}$ under RF and 24.93 ± 8.67 $J\,m^{-2}\,mm^{-1}$ under R. The average of volume-specific kinetic energy was only 12.90 ± 5.02 $J\,m^{-2}\,mm^{-1}$ under the open field.

To describe the integrated effects of the canopy characteristics shown by the crown architecture parameters (H_2, H_3, GD_1, GD_2, LAI, MTA, DBH, FB_2 and FB_3) in response to TKE, principal components analysis of the crown architecture was performed (Fig. 6). PCA showed significant effects of canopy properties on TKE. The first axis of the PCA explained 48.2% of the variance in the TKE data, and the second axis explained 33.6%. The TKE under rubber monoculture was separated from that of the other rubber-based agroforestry systems. The TKE under RF and RC was strongly affected by the sub-canopy, especially LAI. The TKE under RTO was mainly affected by the second sub-canopy characteristics.

Table 2
Coefficient of determination (R^2) for the relationships between throughfall kinetic energy and rainfall intensity of the ten events in the four different rubber-based agroforestry systems.

	I_{10}				I_{30}				I_{60}			
Plots	Lin	Pow	Exp	Log	Lin	Pow	Exp	Log	Lin	Pow	Exp	Log
RF	0.422*	0.22	0.392*	0.238	0.439*	0.393*	0.433*	0.389*	0.266	0.376*	0.300	0.351*
RC	0.386*	0.274	0.387*	0.261	0.418*	0.441*	0.422*	0.416*	0.267	0.420*	0.300	0.375*
RTO	0.478*	0.217	0.389*	0.286	0.555**	0.406*	0.456*	0.481*	0.431*	0.411*	0.358*	0.470*
R	0.362*	0.239	0.355*	0.226	0.407*	0.401*	0.408*	0.380*	0.264	0.394*	0.295	0.351*

Lin represents the linear function, Pow represents the power-law function, Exp represents the exponential function, and Log represents the logarithmic function. I_{10} indicates a 10 min peak intensity ($mm\ 10\ min^{-1}$), I_{30} indicates a 30 min peak intensity ($mm\ 30\ min^{-1}$), and I_{60} indicates a 60 min peak intensity ($mm\ h^{-1}$).

* $P < 0.05$.

** $P < 0.01$.

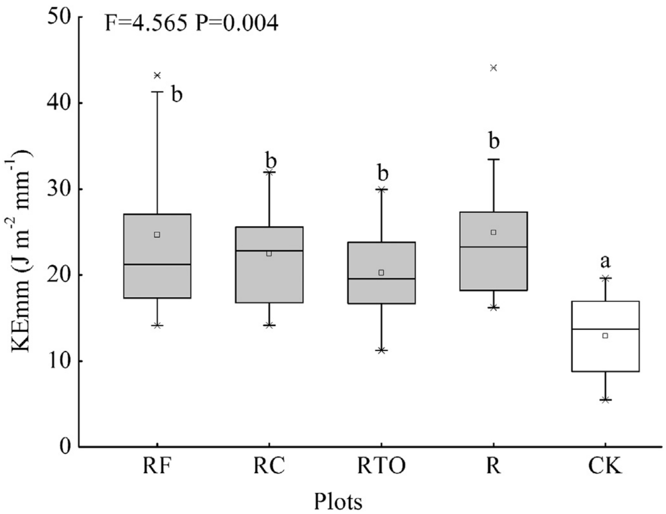

Fig. 5. Throughfall kinetic energy of per volume (TKE_{mm}) in the different rubber-based agroforestry systems and kinetic energy per volume in the open field were calculated across all ten events on the box plot. RF, rubber-*F. macrophylla* agroforestry system; RC, rubber-cocoa agroforestry system; RTO, rubber-tea-orange agroforestry system; R, rubber monoculture; CK, open field. Different normal letters are significantly different at $P < 0.05$.

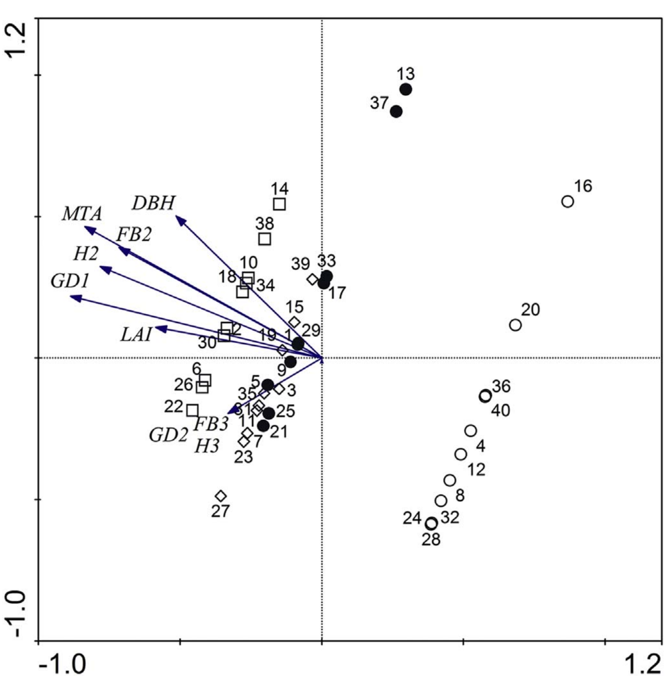

Fig. 6. Correlation biplot based on a PCA of the all canopy characteristics in the different agroforestry systems and rubber monoculture sites. The eigenvalues of the first four axes are 0.482, 0.336, 0.154, and 0.028, respectively. All rainfall events are included in the analyses. Arrows indicate tree characteristics. Abbreviations of tree characteristics are as follows: H_2, second canopy height; H_3, third canopy height; GD_1, stem diameter of the high sub-canopy; GD_2, stem diameter of the low sub-canopy; LAI, leaf area index; MTA, mean tilt angle; DBH, diameter at breast height of the rubber trees; FB_2, first branch height of the high sub-canopy; and FB_3, first branch height of the low sub-canopy. Abbreviations of samples names are as follows: Filled circle, average TKE_{mm} of RF; square, average TKE_{mm} of RC; diamond, average TKE_{mm} of RTO; and hollow circle, average TKE_{mm} of R.

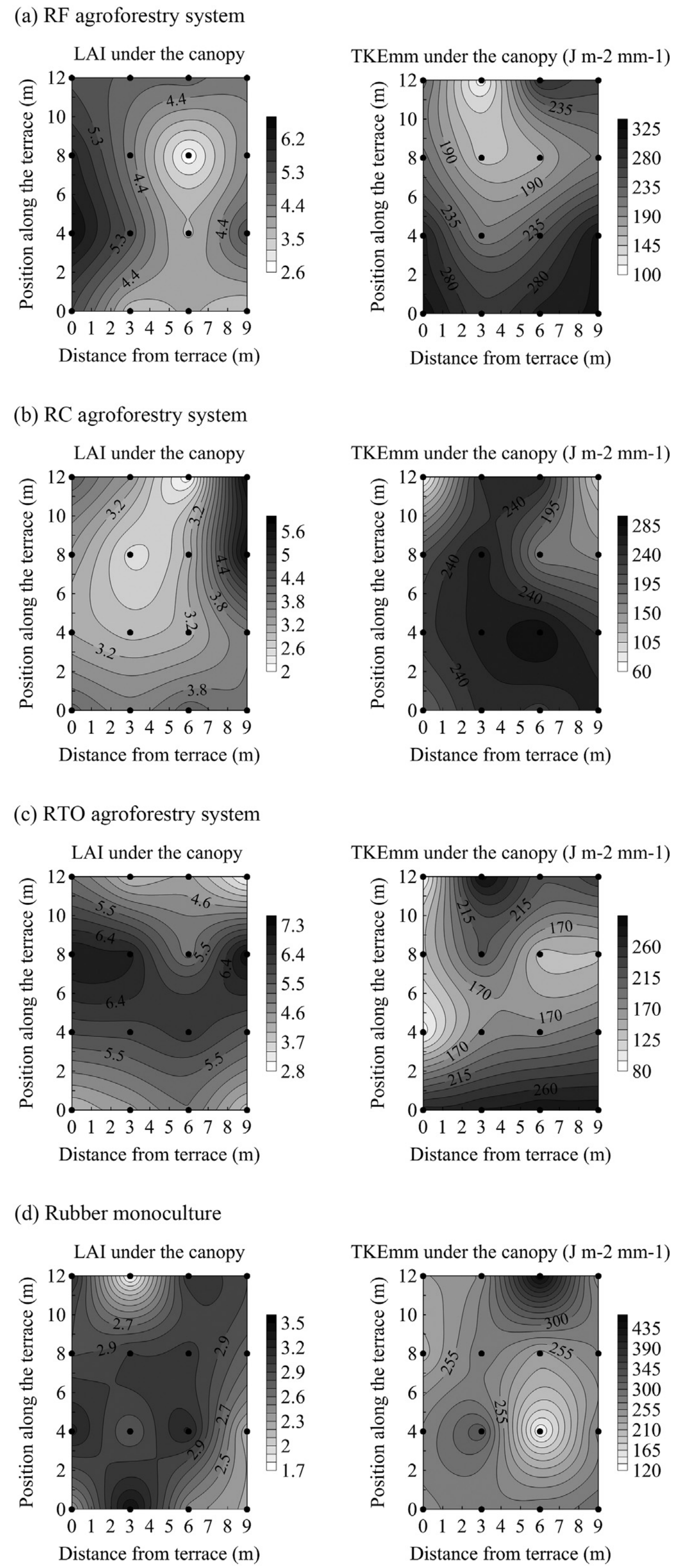

Fig. 7. Spatial distribution of the sum of TKE_{mm} and LAI under the different rubber-based agroforestry systems and rubber monoculture across ten events. (a) Rubber-*F. macrophylla* agroforestry system; (b) Rubber-cocoa agroforestry system; (c) Rubber-tea-orange agroforestry system; (d) Rubber monoculture. The black dots were the position of sixteen splash cups and they remained constant during the experiment.

3.3. Spatial distribution of throughfall kinetic energy

The coefficients of variance of TKE_{mm} (CV_{TKEmm}) under different canopies were calculated using data for the sixteen positions for each event. CV_{TKEmm} ranged from 16.97% to 52.16% in RF rubber-based agroforestry, from 16.30% to 56.25% in RC rubber-based agroforestry, from 36.07% to 58.86% in RTO rubber-based agroforestry and from 9.80% to 39.06% in rubber monoculture (Fig. 8). Furthermore, a one-way analysis of variance indicated that the CV_{TKEmm} of the four groups were significantly different ($F = 5.104$, $P < 0.01$). The CV_{TKEmm} in RTO rubber-based agroforestry changed the most, and the CV_{TKEmm} in rubber monoculture changed the least. The CV_{TKEmm} was higher in the rubber-based agroforestry systems than in the monoculture. There was no significant difference between the RF and RC rubber-based agroforestry systems.

The spatial distribution of TKE_{mm} was different under the different rubber-based agroforestry system canopies (Fig. 7). The contour map shows sixteen positions in a total of ten rainfall events. In RF, TKE_{mm} gradually decreased along the slope (Fig. 7a). In RC, the value of TKE_{mm} was similar to that in RF. However, the spatial distribution of TKE_{mm} had some extreme points at the middle position of the terrace (Fig. 7b). In RTO, the spatial distribution of TKE_{mm} was more even, homogeneous, and smaller in the middle position along the terrace and larger near the rubber trees (Fig. 7c). Furthermore, the cumulative per volume of TKE was the smallest among all four rubber-based agroforestry systems. Compared with the other three rubber-based agroforestry systems, TKE_{mm} commonly increased in the rubber monoculture, and its value was the largest. The spatial distribution of TKE_{mm} was non-uniform and some extreme points existed, most of which were assembled on both sides of the terrace (Fig. 7d). The smaller values of TKE_{mm} were in the middle of the terrace, and the larger values were on both sides of the terrace. The positions with the largest TKE_{mm} were almost at the same points under the different rubber-based agroforestry systems, concentrated in 3–4 m bands. In addition, we also analysed the spatial distribution of LAI under the different rubber-based agroforestry system canopies. The spatial distributions of LAI and TKE were opposite. Where the LAI was high, TKE_{mm} was relatively low. This is consistent with the result that the relationship between TKE and LAI was significantly negatively correlated ($r = -0.4$, $P < 0.0001$) in the four study plots.

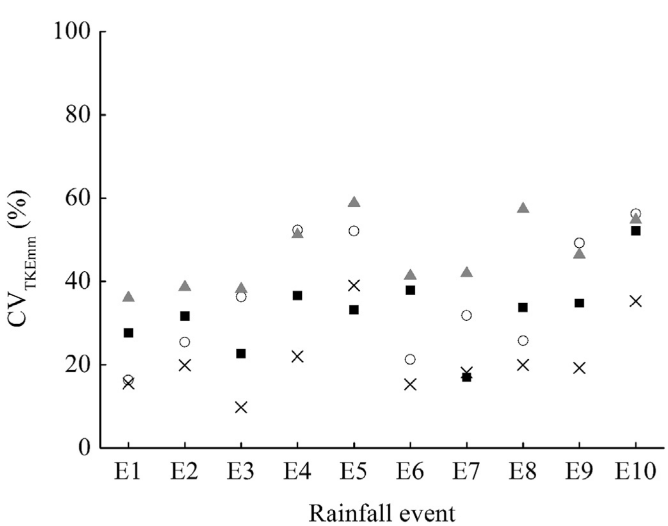

Fig. 8. Relationships between the rainfall event and the coefficient of variation of TKE_{mm} (CV_{TKEmm}). CV_{TKEmm} in Rubber-*F. macrophylla* agroforestry system (squares), Rubber-cocoa agroforestry system (circles), Rubber-tea-orange agroforestry system (up triangles), and Rubber monoculture (crosses).

4. Discussion

4.1. Throughfall kinetic energy and rainfall characteristics

The relationship between kinetic energy and rainfall intensity is the most widely used, and kinetic energy and rainfall intensity relationships have already been established in several countries (Petan et al., 2010; Ramon et al., 2017; Van Dijk et al., 2002). However, these may be not applicable in other countries because different locations have different origins and types of rainfall. In some of the kinetic energy-rainfall intensity results obtained from different researchers in different countries, the empirical constants differed from one place to another, and these differences were notable. The differences can be attributed not only to the errors introduced during measurements and interpretation but also to differences in rainfall characteristics inherent to the various geographic locations (Fornis et al., 2005; Kinnell, 1981; McIsaac, 1990; Van Dijk et al., 2002). For these reasons, Fornis et al. (2005) warned that a relationship between kinetic energy and rainfall intensity that performs well in one location may perform poorly in another location.

Even though previous results showed that rainfall intensity is a critical factor contributing to soil detachment under forest canopies (Mizugaki et al., 2010; Nanko et al., 2008), these findings did not apply to the data presented here. Considering the different possibilities of expression of KE from different interval rainfall intensities, four different widely used regression functions were used to examine the relationship between TKE and rainfall intensity. However, TKE tended to be more weakly correlated with rainfall intensity than with rainfall amount (Table 2). Compared with other regions, the main reason for this result may be that the rainfall characteristics in Xishuangbanna had large fluctuations in rainfall intensity, along with higher wind speeds and other complex meteorological factors, but this result needs confirmation by further studies using simulated rainfall. The results indicate that there is a close relationship between precipitation and TKE, which emphasizes the importance of measuring the rainfall amount. Under rubber-based agroforestry systems and rubber monoculture, an extremely significant linear relationship was found between TKE and rainfall amount (as well as throughfall amount). These results agree with the results of previous studies (Geißler et al., 2013; Liu et al., 2015; Nanko et al., 2011).

Accordingly, the relationship between TKE and rainfall intensity was not suitable for the local rubber plantation. TKE dependence on rainfall amount (throughfall amount) is a convenient way to estimate soil erosion. Therefore, we developed a suitable equation to link TKE and rainfall amount (P) via a linear relationship. The calculated functions were as follows:

$$TKE_{RF} = 232.927 + 10.322\ P\ (P < 0.0001) \quad (1)$$

$$TKE_{RC} = 04.167 + 10.384\ P\ (P < 0.0001) \quad (2)$$

$$TKE_{RTO} = 245.548 + 7.801\ P\ (P < 0.0001) \quad (3)$$

$$TKE_{R} = 332.663 + 12.460\ P\ (P < 0.0001) \quad (4)$$

4.2. Throughfall kinetic energy and tree characteristics

Simultaneous measurements under open environments and rubber monoculture showed a significant difference in kinetic energy; the value was 2.32 times greater under rubber monoculture than under the open environment. For the agroforestry systems, the ratios of TKE to the open environment were 2.19 (RF), 2.01 (RC) and 1.84 (RTO). None of the rubber-based agroforestry systems had a ratio of < 1, but that of the RTO was the lowest. The data obtained in this study showed that there was a higher TKE beneath the canopies than in the open environment. These results are consistent with those of previous studies (Liu et al., 2016). On average, the ratios of TKE in agroforestry systems were less than that in rubber monoculture. The construction of agroforestry had an effect on reducing soil erosion by TKE.

In this experiment, RTO generally had the lowest average TKE among the observed agroforestry systems. The second sub-canopy (H_3, GD_2 and FB_3) contributed the most to the reduction in TKE (Fig. 6). RF also had a low TKE among the observed agroforestry systems. The sub-canopy (H_2, GD_1, FB_2 and LAI) also contributed to the reduction of TKE. However, as other studies reported, GD and FB may change as an indirect effect of tree characteristics (Goebes et al., 2015a). R generated a relatively high TKE below its crown. Because rubber trees have the highest crown, there are very low numbers of branches and higher first branches, both of which lead to a low canopy storage capacity (Herwitz, 1985). In addition, high canopies allow large raindrops to reach their terminal velocity (Laws and Parsons, 1943). Morgan (2009) suggested that the maximum distance a raindrop must fall to reach terminal velocity is 8 m. Because the canopy height of rubber trees can reach 20 m (Liu et al., 2011), it was proposed that all throughfall drops in the rubber monoculture could reach terminal velocity. Although the effect of agroforestry systems in reducing TKE was limited, we have shown that the crown traits affect TKE under different rubber-based agroforestry systems. In all rainfall events, TKE and LAI were significantly negatively correlated. These results are consistent with those of other studies (Geißler et al., 2013; Ma et al., 2015). Generally, throughfall amount decreases with increasing LAI, as interception is enhanced at higher LAI values (Crockford and Richardson, 2000; Gómez et al., 2001; Levia and Frost, 2006).

4.3. Implications

A number of studies have shown that the crown architecture of trees influences TKE (Geißler et al., 2010; Goebes et al., 2015a). Therefore, we assumed that agroforestry systems would reduce soil erosion more effectively than monocultures. In our study, however, the values of TKE under the rubber-based agroforestry systems did not show a significant reduction compared with the values observed in the monoculture. The reason for this may be the planting density of intercropping plants, because their planting density was sparse, and the crown area was low. When throughfall was heavy, the raindrops not only reached terminal velocity but also were able to combine with droplets from intercropping plants, generating larger raindrops with higher velocity. At the low planting density, the intercropped plants did not have canopy closure, and high TKE could be observed (Bochet et al., 2002; Stogsdill et al., 1989). Generally, the variability of TKE was higher in low-density planting areas than in high-density planting areas (Geißler et al., 2012; Raat et al., 2002). This result agrees with an earlier study, which found that shrubs had little effect on reducing soil erosion (Wiersum, 1985). Further research is required to explain how the canopies affect TKE.

For most rainfall events, the spatial distribution of TKE under canopies tended to be concentrated in certain spots in 3–4 m bands. One possible explanation is that these points were near rubber trees with no sub-canopy. The intercropping plants did not cover or only barely covered the edges of these points. Larger drops that formed at the leaf margins and apex produced more splash erosion in these areas, albeit by only a narrow margin. Coalescing drops from leaves and branches were responsible for a notable spatial heterogeneity of throughfall erosivity (Geißler et al., 2012). Therefore, TKE tended to be extreme in certain areas, and the spatial distribution was uneven. These conditions were obvious in RC because cocoa cultivation was more scattered, and the canopy traits led to larger droplets. To improve intercropping patterns, further research is needed to understand how planting patterns and density affect TKE.

5. Conclusions

Rubber plantations have resulted in excessive water loss and soil erosion. To evaluate the effects of rubber-based agroforestry on soil erosion processes in a local rubber plantation, this study experimentally measured TKE and its spatial variability under three different rubber-based agroforestry systems and under rubber monoculture. The results showed that there were significant linear positive correlations between TKE and rainfall amount. Therefore, we suggest that rainfall was an appropriate and accessible factor for predicting soil loss under rubber plantations in Xishuangbanna. Although there was no significant difference in TKE under multiple canopies compared to that under monoculture, on average, the ratios of TKE in agroforestry systems were less than that of rubber monoculture. Therefore, to some extent, the construction of agroforestry does reduce soil erosion by TKE. Consequently, we highlight the importance of selecting intercrops and improving intercropping planting patterns for plantation management. TKE under the different rubber-based agroforestry systems was closely related to the LAI and increased with decreasing LAI. The intercropping plants should be selected to increase the LAI and thus reduce the splash erosion by TKE. In addition, the spatial distribution of TKE was usually concentrated in 3–4 m bands that enjoyed no protection from the sub-canopy, meaning that planting patterns should consider the positions with high TKE to prevent soil erosion when constructing rubber-based agroforestry systems. Further studies need to evaluate additional types of rubber-based agroforestry to propose appropriate intercropping systems with complex meteorological conditions.

Competing financial interests

The authors declare no competing financial interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2017.10.014.

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