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Characteristics of throughfall kinetic energy under the banana (*Musa nana* Lour.) canopy: The role of leaf shapes

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ABSTRACT

Banana (*Musa nana* Lour.) plants have a distinctive canopy pattern with their extremely long and wide leaves. However, the effects of such distinct leaf shapes on rainfall redistribution and splash erosion are still poorly understood. Here, we investigated the basic characteristics of throughfall (TF) distribution and throughfall kinetic energy (TKE) and clarified the effect of specific leaf shapes on TKE under the individual banana plant (IBP) and the whole banana plantation (WBP) canopies. We found that the TF under the IBP and WBP canopies was 80.2% and 84.7% of the incident rainfall, respectively. The spatial variability of TF was high, which was attributed to the prominent funnelling and shading effects of the banana canopy. The KE at canopy drip points was significantly higher than that at canopy non-drip points and in open fields under both the IBP and the WBP canopies, implying that the negative effect of banana canopy drip points was far greater than the protective effect of non-drip points on splash erosion. In addition, the leaves at canopy drip points were classified as valley (Va), overlap (Ov), leaf tip (Ti), breakage (Br) and complex shapes (Cs). Significant differences in TKE among these leaf shapes were found, and the significantly lower TKE in Ti and the greater TKE in Cs than those in Va, Ov and Br were observed. As a result, these leaf shapes potentially affected TF splash erosion under the banana canopy. Further ecohydrological studies are required to improve heavy TF splash erosion in banana plantation and to create environmental-friendly plantation.

1. Introduction

The process of rainfall redistribution through plant canopies modifies water input to soil layer, thereby affecting soil conditions (Lacombe et al., 2018), runoff generation (Llorens and Domingo, 2007) and water and nutrient cycling (Kimmins, 1973). Throughfall (TF) is a critical component of rainfall redistribution, and it on average contributes to approximately four-fifths of the gross rainfall into floor (Huber and Iroumé, 2001; Levia and Frost, 2006; Siles et al., 2010). Several studies have revealed that canopy dripping can result in larger volumes of water reaching the soil layer and a higher splash erosive power than open rainfall (Mosley, 1982; Zhou et al., 2002; Liu et al., 2018). Agricultural systems such as banana (*Musa nana* Lour.) plantation can have a similar effect on increasing TF volumes and splash erosion through canopy dripping. A field investigation of banana plantations have revealed that the TF volume at some drip points could be up to five times higher than that of open rainfall (Cattan et al., 2007). However, whether such heavy TF has severe negative effects on soil splash erosion remains unknown. Therefore, the study of TF in banana plantations is of great significance for understanding its impacts on soil erosion.

The spatial distribution of TF is determined by multiple canopy characteristics (e.g. leaf traits and canopy species) and meteorological conditions (e.g. rainfall amount and intensity) (Park and Cameron, 2008; Goebes et al., 2015a). For example, canopy could contribute to raindrops coalescing on leaf surface, causing the TF volume of canopy drip points larger than that of open rainfall (Germer et al., 2006). Park and Cameron (2008) revealed that the TF volume of raindrops coalescing is even greater on large leaves than on small leaves. Moreover, the TF volume is greater either at canopy margin (Whelan et al., 1998; Zhang et al., 2016) or near the trunk (Robson et al., 1994; Fan et al., 2015), whereas no such relationship has been found between the TF volume and the distance from the trunk in other studies (Loustau et al., 1992; Keim et al., 2005). In addition, the spatial distribution of TF for low rainfall amounts exhibits high variability due to the relatively

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substantial interactions among canopies, whereas with increasing rainfall amounts, the water storage capacity of the canopy is satisfied and the spatial distribution of TF thus becomes asymptotically homogeneous (Gómez et al., 2002; Vrugt et al., 2003). Overall, the above differences in the spatial distribution of TF appear to be driven by species canopy traits and rainfall event size.

Plant canopies result in variable distributions of TF and can alter the potential power of raindrops falling to the soil surface (Loescher et al., 2002; Nanko et al., 2011). Rainfall kinetic energy (KE) has been widely used for evaluating the potential power of raindrops to detach soil particles. For instance, lower values of throughfall kinetic energy (TKE) compared with an open field have been found under some crop canopies, including wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), oats (*Avena sativa* L.) and beans (*Glycine* max (Linn.) Merr.) (Elwell and Stocking, 1976; Morgan, 1982; Ma et al., 2015) and under the creosote bush (*Larrea tridentata* DC.) canopy (Wainwright et al., 1999). These findings indicate that some canopies indeed can effectively inhibit raindrop splash erosion, and potentially protect soil from erosion. Conversely, TKE is higher under some canopies than in open fields, such as beech (*Nothofagus* spp.), eucalyptus (*Eucalyptus exserta*), rubber (*Hevea brasiliensis*) and some other forest systems (Mosley, 1982; Zhou et al., 2002; Geißler et al., 2013; Liu et al., 2018). As a result, a substantial increase in TKE inevitability aggravates water loss and soil erosion. All these studies provide evidence that species canopies play a role in protecting soil against the splash erosive power of TF.

Rainfall redistribution alters nutrient leaching (Nordén, 1991; Sansoulet et al., 2007) and the amount of water runoff via the soil surface (Charlier et al., 2009). Banana is cultivated in tropical and subtropical regions with high rainfall rates, including several global biodiversity hotspots e.g. Southwest China, East and West Africa. Therefore, there is a pressing need to obtain detailed insights into the rainfall redistribution of banana plantations. Moreover, in Xishuangbanna (Southwest China), banana plants are widely cultivated on hillslopes, and soil erosion frequently occurs during the rainy season, which comprises 6 months each year. However, our knowledge regarding the factors affecting soil erosion in banana plantations in this area is very limited. Preliminary investigations have demonstrated that the extremely long, wide leaves of banana plants substantially modify rainfall redistribution (Harris, 1997), for example, the spatial distribution of TF is variable, and a remarkably large TF has been observed at some drip locations (Bassette and Bussière, 2005). However, no information is available to estimate the splash erosive power of TF in banana plantation and the role of banana leaf traits in splash erosion.

Therefore, the present study aimed to understand the characteristics of TF and TKE and the effect of leaf shapes on TKE at canopy drip points in a banana plantation in Xishuangbanna. Specifically, the objectives were: (i) to investigate the spatial distribution of TF under individual banana plant (IBP) and the whole banana plantation (WBP) canopies, (ii) to assess how the banana canopy influences soil erosion dynamics and (iii) to understand the influence of leaf shapes on TKE at canopy drip points. The results of this study can be used as reference for further studies on soil erosion in banana plantations and to aid rational decision-making by local governments and farmers regarding banana plantation management.

2. Materials and methods

2.1. Study region

The study was conducted in Xishuangbanna Tropical Botanical Gardens (XTBG, 21.93°N, 101.27°E, 570–600 m a.s.l.), Yunnan Province, southwest China. The climate at this study site is dominated by southwest monsoon carrying Indian Ocean moisture. Thus, XTBG experiences an apparent dry–wet season cycle, including a rainy season from May to October and a dry season from November to April. Meteorological data over the past decade (2010–2019) at the XTBG

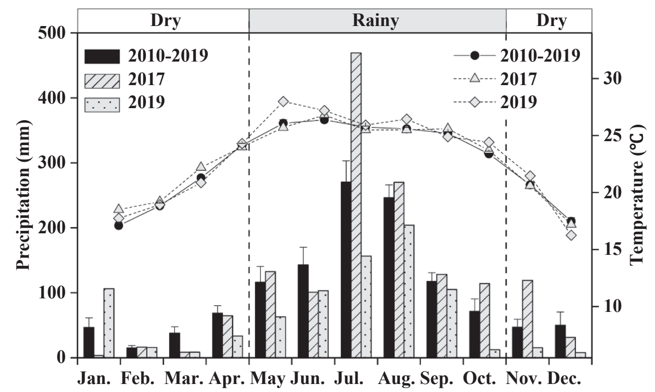

Fig. 1. Monthly distribution of mean precipitation and mean air temperature over the past decade (2010–2019) (mean ± SE) at the study site. Weather data was acquired from the Xishuangbanna Station for Tropical Rainforest Ecosystem, located to our study site.

meteorological station reveal that the mean annual precipitation is 1231.8 mm (Fig. 1). The rainy season has a mean gross rainfall of 965.3 mm, which is approximately 80% of the mean annual precipitation. The mean annual air temperature is 22.7 °C, and the mean monthly temperature ranges from 17.1 °C in January to 26.4 °C in June. The soil depth in this region is approximately 2 m. Based on the classification system of the International Society of Soil Science, the soil has a clay-loam texture (42% coarse sand, 34% silt and 24% clay) (Liu et al., 2016). The soil is classified as a Ferralic Cambisol, which developed from alluvial deposits derived from sandstones and has an ochric A horizon and a cambic B horizon with ferralic properties (Vogel et al., 1995).

The study was conducted in a 4.3-ha banana plantation comprising a banana monoculture planted at a density of 2 × 2 m. The banana trees were planted 6 years before the study was conducted, which was after the land was transformed from a rubber monoculture. Mature banana bunches were harvested between April and May at three growth stages: vegetative, flowering and bunch appearance. After harvest, the pseudostem was chopped down and the new banana seedlings that sprouted from bulbs grew rapidly. The banana plantation was properly irrigated to meet the demand for water during the dry season, whereas it was drained to prevent flooding during the rainy season. The banana plantation was managed through frequent application of fertilisers (10–15 times a year) near the root of each plant, and regular weeding and pest control (pesticide spraying) were performed throughout the year.

2.2. Experimental design

Experiments were conducted under the IBP canopy between June and September 2017 and under the WBP canopy between June and September 2019, respectively. Based on the plant growth conditions, banana plants were randomly selected to conduct field experiments, and an adjacent open field was simultaneously sampled as a reference (control). The general characteristics of banana plants and the banana field are presented in Table 1.

Under the IBP canopy, the TF and TKE experiments were conducted separately for four and six rainfall events, respectively. The TF experimental network comprised 208 TF collectors, which were placed at 25-cm intervals (Fig. 2a). The plot area was 3.75 m × 3 m, with 16 rows (R1 to R16) and 13 columns (C1 to C13) of TF collectors. For TKE experiments, the locations of canopy drip positions firstly need to be marked based on raindrops splash pits or traces. After three rainfall events, soil splash pits or traces clearly appeared beneath the banana plant canopy. On the premise of non-interference among splash cups, we marked as many canopy drip points as possible surrounding the

Table 1
General characteristics of the two sampling sites for the throughfall (TF) and throughfall kinetic energy (TKE) experiments (mean ± SD, n = 18).

Sites	Period	Projects	Events	Height (m)	BD (cm)	DBH (cm)	P (m)	LAI (m^2 m^{-2})	MTA
IBP	2017	TF	4	3.0	19.1	18.1	1.7	3.7	30.7°
		TKE	6						
WBP	2019	TF	16	2.9 ± 0.06	18.1 ± 0.7	16.7 ± 2.1	1.5 ± 0.02	3.6 ± 0.2	27° ± 3.2°
		TKE	16						

IBP: the individual banana plant; WBP: the whole banana plantation.
BD: Basal Diameter; DBH: Diameter of Breast Height; P: Crown Breadth; LAI: Leaf Area Index; MTA: Mean Tilt Angle, leaf orientation.

banana plant and recorded the distance from the banana pseudostem. 48 splash cups were respectively installed on the splash pits for each rainfall event. Meanwhile, ten splash cups were installed in non-drip points beneath the banana canopy and five cups in the open field as control experiment.

Under the WBP canopy, the TF and TKE experiments were conducted simultaneously. The experimental network comprised 32 TF collectors and 32 TKE splash cups (Fig. 2b). The plot area was 14 m × 6 m, with eight rows (R1 to R8) and four columns (C1 to C4) of TF collectors and splash cups. Both splash cups and TF collectors were separately placed at 2-m spacings. The spacing distance between each splash cup and TF collector was 15 cm in order to prevent the sand from splashing into the TF collector. Because leaf dripping corresponds to drip points and the absence of leaf dripping to non-drip points, the 32 splash cups were classified as either drip points or non-drip points. Moreover, three replications of TF collectors and splash cups were used as control in the open field.

2.3. Measurements of rainfall and throughfall

Rainfall data was measured using a tipping-bucket rain gauge (0.254 mm resolution; Model 3554WD; Spectrum Technologies, Inc., USA), which was located in an open field 300 m away from the study stand. The tipping-bucket rain gauge was placed 50 cm above the ground surface to prevent droplet splash effect. The bucket tipping time was recorded using a data logger (0.5 s resolution; Model 115; Spectrum Technologies, Inc., USA). The time interval of rainfall data recording in this study was set to 10 min. In total, we recorded 26 rainfall events during the sampling period. For each incident rainfall event, the gross rainfall and peak 30-min rainfall intensity were recorded.

TF was collected using artificial funnel-type water collectors that comprise a short-stemmed funnel (6 cm diameter) at the top and a valve bag at the bottom. We used binder clips to clamp each valve bag to the neck of a short-stemmed funnel. All the funnel rims were placed at the

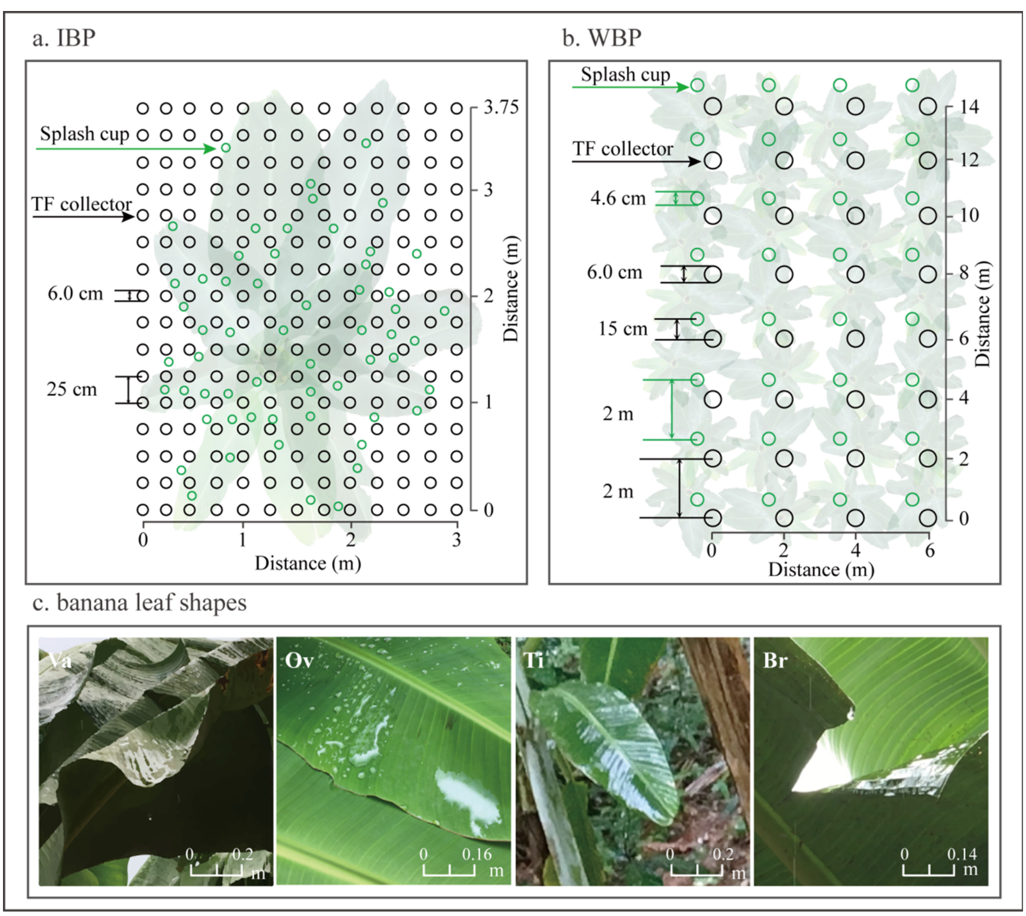

Fig. 2. (a) Diagrammatic representation of throughfall (TF) and throughfall kinetic energy (TKE) experiments under an individual banana plant (IBP) canopy, (b) under the whole banana plantation (WBP) canopy and (c) leaf shapes of banana canopy drip points, namely valley shape, Va; overlap shape, Ov; leaf tip, Ti; breakage shape, Br. Moreover, some intermingled leaf shapes, such as Va-Ov, Ov-Br, Va-Br, and even Va-Ov-Br appeared, which was uniformly considered them as complex shapes (Cs).

ground level with the ground to avoid any incline. After every rainfall event, we sealed the valve bags instantly, cleaned off the outside soil and water, weighed the water inside the valve bags and calculated the TF using Eq. (1):

$$TF = 10 \times (m_2 - m_1)/\rho \pi r^2 \quad (1)$$

where TF denotes the measured TF per m^2 in mm precipitation; m_1 denotes the net weight (g) of the valve bag; m_2 denotes the gross weight (g) of the valve bag reserving TF; r denotes the funnel semi-diameter (cm) and ρ denotes the density of water (1.0 g/cm^3).

2.4. Measurement of throughfall kinetic energy

Raindrop splash erosive power—KE—was measured using Tübingen splash cups with a 4.6-cm diameter. The cups were filled with 125–200 μm standard sand parallel to the cup rim (Scholten et al., 2011). Before field monitoring, splash cups were preprocessed; they were oven-dried at 105 °C for 24 h in the laboratory; weighed using an electronic weighing scale, with an accuracy of ± 0.01 g; placed onto trays with water to absorbed water saturation and then taken to the field. When the rainfall episodes ended, the splash cups were removed from the field and brought to the laboratory, where they were oven-dried at 105 °C for 24 h. Then, the dried cups with sand were re-weighed. KE was calculated as described previously (Goebes et al., 2015b) using Eq. (2):

$$KE = m \times 0.1455 \times (10,000/\pi r^2) \quad (2)$$

where KE denotes the rainfall kinetic energy per area (J m^{-2}), m (g) denotes the weight of the standard sand quantity loss per splash cup and r (cm) denotes the radius of the splash cup.

2.5. Leaf shapes classification

Banana plants grow large and flexible leaves that can easily deform to appear as concave and breakage shapes. Thus, the pits on the leaf margin are uniformly defined as 'valleys' (Va) in our study. The 'overlap' (Ov) of concave areas sometimes appears where raindrops are intercepted by the upper leaf, then accepted by the lower leaf and finally drained away. In fact, the Va and Ov shapes are both micro-catchments on the leaves. Moreover, the leaf 'tip' (Ti) and the 'breakage' (Br) approximate the triangular geometrical morphology, in which the water is intercepted and drained away based on the slope. Thus, we classified leaves at canopy drip points into four shapes: Va, Ov, Ti and Br (Fig. 2c). Moreover, some leaf shapes such as Va–Ov, Ov–Br, Va–Br and even Va–Ov–Br were also observed, and we uniformly defined them as complex shapes (Cs). After every rainfall event, we summed up the leaf shapes vertically corresponding to the splash cups and the number of each leaf shape. Generally, the number of each leaf shape and the leaf shape of each point always varied among different rainfall events because of leaf waggling. Thus, for the reliable and scientific data, seven rainfall events (Table 2) in which the number of each leaf shape was not less than three were selected to calculate the TKE values of the different leaf shapes.

2.6. Statistical analysis and calculations

The normal distributions of TF and TKE were evaluated using the Kolmogorov–Smirnov test. Log transformation or square-root transformation was conducted for non-normally distributed data. Contour maps were created using the Golden Software Surfer10 (Golden Software Inc.). The spatial variability of TF was indicated using the coefficients of variation of (CV_{TF}). All statistical analyses were conducted using the IBM SPSS Statistics 22.0 software (IBM Inc.). The effect of leaf shapes on TKE was statistically evaluated using one-way analysis of variance (ANOVA), whereas the interaction effect of leaf shapes and rainfall events on TKE was statistically evaluated using two-way ANOVA.

Table 2
Descriptive statistics of the gross rainfall (GR) and throughfall (TF) for the recorded rainfall events.

Events	*GR* (mm)	I_{30}	*TF* (mm)	Max_{TF}/GR	*CV* (%)	*n*
A1	14.7	10.0	13.6	8.0	32.2	208
A2	24.8	5.9	21.4	4.4	30.0	208
A3	52.5	8	36.8	2.4	27.8	208
A4	70.5	12.7	58.7	1.8	33.9	208
B1	0.9	0.5	0.6	3.8	45.7	32
B2	1.2	0.4	0.7	2.4	66.6	32
B3	2.6	2.2	2.1	2.6	32.4	32
B4*	5.9	2	4.9	3.8	36.3	32
B5*	10.7	5.7	10.1	8.6	31.0	32
B6	14	2.2	11.1	1.8	20.5	32
B7	16.5	13.6	14.0	2.8	33.4	32
B8*	17.2	2.2	13.5	3.5	68.1	32
B9	18.2	5.9	14.7	2.4	39.5	32
B10*	33.8	15.1	26.3	6.3	53.9	32
B11	39.8	17.7	35.1	2.4	39.1	32
B12	42.6	14.3	35.1	2.5	47.8	32
B13*	51.4	10.2	42.1	4.1	32.7	32
B14*	55.8	19.4	50.9	2.2	32.6	32
B15	61.8	20.5	52.4	1.7	11.6	32
B16*	69.4	30.6	60.4	3.1	28.7	32

A1 ~ A4: rainfall events under the individual banana plant canopy; B1 ~ B16: rainfall events under the whole banana plantation canopy. The sign'*' indicates the rainfall event of leaf shape record.
GR: gross rainfall (mm); I_{30}: the peak 30 min rainfall intensity (mm 30 min^{-1}); Max_{TF}/GR: maximum TF volume divided by gross rainfall; *CV*: coefficient of variation (%); *n*: the number of TF collectors.

Significant differences in TKE were found using least significant difference tests ($P < 0.05$). The relationships among TF, TKE and rainfall parameters were determined using linear/nonlinear correlation analysis.

3. Results

3.1. Gross rainfall and throughfall characteristics

Under the IBP canopy, a total rainfall amount of 162.5 mm was measured for four rainfall events, and a total TF of 130.4 mm (or 80.2% of the incident rainfall) was collected (Table 2). The recorded maximum TF volume was 1.8–8.0 times higher than the gross rainfall. The values for CV_{TF} were approximately 30% during all rainfall events. The TF ratio was > 100% at some sampling points, which were mainly close to the middle and margin regions of the canopy (Fig. 3). In particular, several extremely high TF ratios were observed, for example TF ratio was > 200% at (C4, R11). However, the TF ratios were relatively small (< 40%) near the banana pseudostem. The lowest TF ratios (< 20%) were observed at (C5, R6), (C8, R6) and (C8, R8).

Under the WBP canopy, for the 16 monitored rainfall events, the recorded gross rainfall ranged from 0.9 to 69.4 mm, and the peak 30-min rainfall intensity ranged from 0.4 to 30.6 mm 30 min^{-1} (Table 2). A total rainfall amount of 455.7 mm was measured, and a total TF of 374.0 mm (or 84.7% of the incident rainfall) was collected. The recorded maximum TF volume was 1.7–8.6 times greater than the gross rainfall. The TF volumes showed a linear increase with increasing gross rainfall ($R^2 = 0.98$, $P < 0.001$) and peak rainfall intensity ($R^2 = 0.82$, $P < 0.001$) (Fig. 4). Differently, the TF ratio showed a nonlinear increase with gross rainfall ($R^2 = 0.44$, $P < 0.001$) and peak rainfall intensity ($R^2 = 0.57$, $P < 0.001$), following power functions. Moreover, the CV_{TF} of TF ranged widely from 10% to 70%, concentrating between 30% and 40% at high levels. An extremely weak correlation was found between CV_{TF} and gross rainfall ($R^2 = 0.08$, $P < 0.001$) and peak rainfall intensity ($R^2 = 0.06$, $P < 0.001$). For the four typical events—B5, B10, B14 and B16—in Table 2, which were selected from the 16 total events, the spatial distribution of the cumulative mean TF

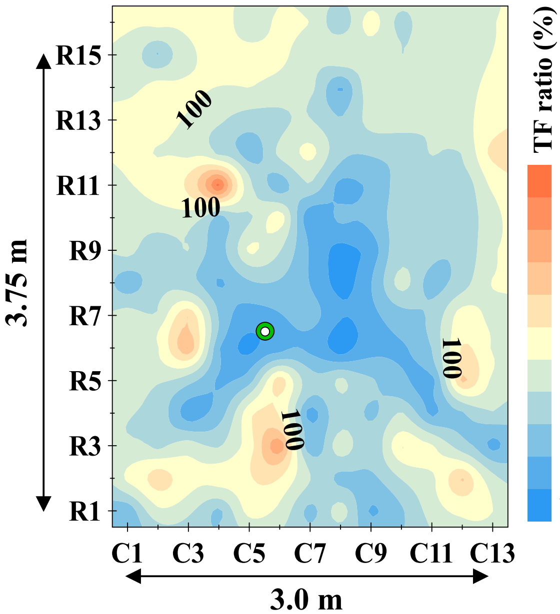

Fig. 3. The spatial distribution of cumulative mean throughfall (TF) ratio under the individual banana plant (IBP) canopy for total rainfall events (gross rainfall 162.5 mm). The plot area was 3.75 m × 3 m with 16 rows (R1 ~ R16) and 13 columns (C1 ~ C13) of TF collectors. The contour with "100" label means TF volume = gross rainfall. The green ring indicates the experimental banana plant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

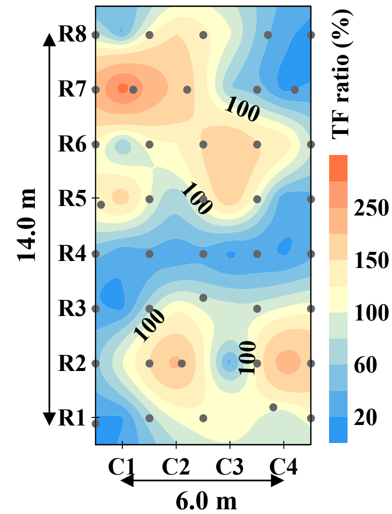

Fig. 5. The spatial distribution of cumulative mean throughfall (TF) ratio under the whole banana plantation (WBP) canopy for typical rainfall events (gross rainfall 169.7 mm). The plot area was 14 m × 6 m with eight rows (R1 ~ R8) and four columns (C1 ~ C4) of TF collectors. The contours with "100" label indicate TF volume = gross rainfall. The black cirles indicate the locations of bananna plant pseudostems.

ratio is plotted in Fig. 5. The individual points close to the pseudostem showed a relatively high TF ratio at (C1, R7), (C2, R7) and (C2, R2). The highest TF ratio was > 300% at (C1, R7), and the lowest TF ratio was < 20% at (C1, R1), (C1, R3) and (C4, R7).

3.2. Throughfall kinetic energy characteristics

Under the IBP canopy, significant differences ($P < 0.001$) in KE values among the three treatments (canopy drip points, non-drip points and open field) were tested, though no such differences were tested according to rainfall or the interaction between rainfall and treatments ($P > 0.05$). The KE values in the open field (KE_{CK}) ranged from 1.8 to 222.4 J m^{-2} and the cumulative mean KE_{CK} was 82.3 J m^{-2} (Fig. 6a). The KE values at the non-drip points (KE_{ND}) ranged from 0.9 to 70.0 J m^{-2} and were mostly concentrated between 0.9 and 30.0 J m^{-2}. The cumulative mean value of KE_{ND} was 19.2 J m^{-2}, which was significantly smaller than that in the open field. In contrast, the KE values at the canopy drip points (KE_D) had a wider range from 5.3 to 5877.3 J m^{-2} and had a significantly higher cumulative mean value of 858.5 J m^{-2} than KE_{CK} and KE_{ND}. The KE_D values were 3.3–123.5 times (44.7 times for accumulative events) and 3.8–60.5 times (10.4 times for accumulative events) higher than the KE_{ND} and KE_{CK} values, respectively. The combined TKE (canopy drip points plus non-drip points) under the individual banana canopy was 2822.5 J m^{-2}, which is 5.3 times higher than that in the open field.

Under the WBP canopy, the results of ANOVA in KE values were similar to those under the IBP canopy (Table 3). In detail, significant differences ($P < 0.001$) in KEs among the three treatments were found, whereas no such differences were found according to rainfall or the interaction between rainfall and treatments ($P > 0.05$). By comparison, the cumulative mean KE_D of 903.8 J m^{-2} was significantly higher than the KE_{CK} of 28.1 J m^{-2} and KE_{ND} of 316.9 J m^{-2} (Fig. 6b). The mean values of KE_D were 3.3–119.3 times (23.7 times for accumulative events) and 1.2–14.6 times (2.7 times for accumulative events) higher than those of KE_{ND} and KE_{CK}, respectively. Furthermore,

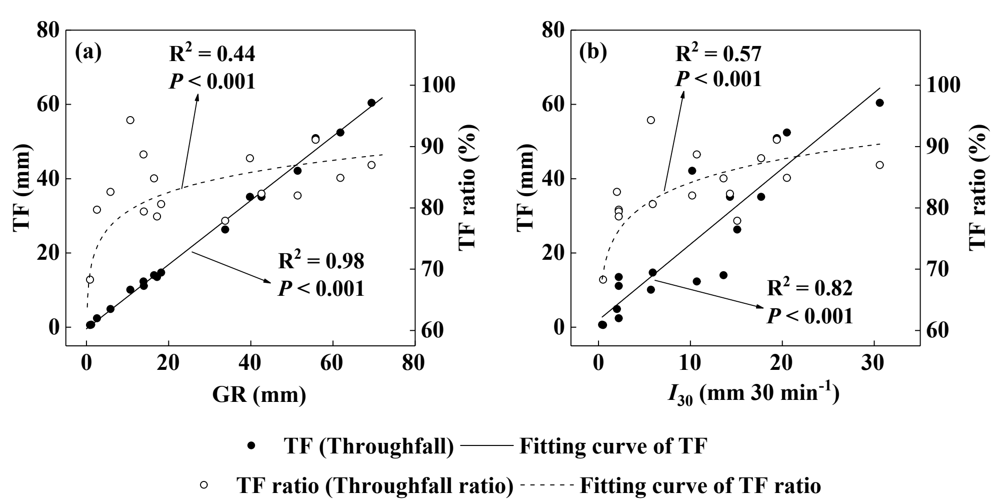

Fig. 4. Throughfall (TF) and TF ratio plotted against (a) gross rainfall (GR) and (b) peak 30 min rainfall intensity (I_{30}).

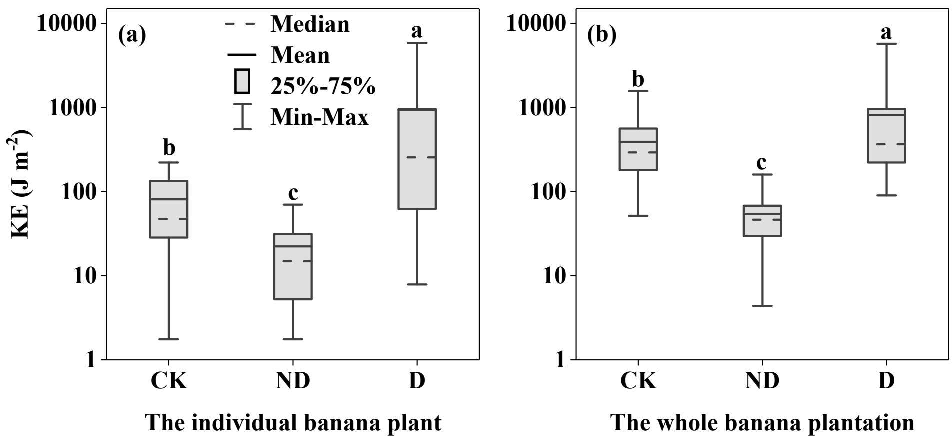

Fig. 6. Box-plots of rainfall kinetic energy (KE) for three treatments (CK, open field; ND, canopy non-drip points; D, canopy drip points) (a) in the individual banana plant canopy and (b) in the whole banana plantation. Different lower-case letters (a, b and c) indicate significant differences among the three treatments at $P < 0.05$.

the mean values of combined TKE (canopy drip points plus non-drip points) were 1.3–11.7 times higher than those in the open field. The combined value of TKE in the banana plantation was 15505.2 J m^{-2}, which was 2.6 times higher than that in the open field. Besides, the KE_D was significantly affected by gross rainfall, rainfall intensity and TF volume via nonlinear correlations with correlation coefficients of 0.87, 0.62 and 0.79, respectively ($P < 0.001$) (Fig. 7). The KE_{ND} was dependent on the TF volume with a correlation coefficient of 0.48 ($P < 0.001$).

3.3. Throughfall kinetic energy–leaf shapes relationships

Under the IBP canopy, ANOVA results showed that the TKEs differed according to rainfall, leaf shape and their interactions ($F_{rainfall} = 7.01, P < 0.001; F_{leaf\ shapes} = 3.41, P < 0.01; F_{rainfall\ *\ leaf\ shapes} = 35, P < 0.001$) (Table 3). The cumulative mean TKEs of different leaf shapes are presented in Fig. 8a. On average, TF in the leaf shapes released considerably higher KE than that in the open field. The cumulative mean TKE of Cs (TKE_{Cs}) was significantly higher at 1121.0 J m^{-2} than that of other leaf shapes. The cumulative mean TKE of Ti (TKE_{Ti}) was 200.87 J m^{-2}, which is significantly lower than that of the other leaf shapes ($P < 0.05$). Accordingly, the decreasing order of cumulative mean TKEs was $TKE_{Cs} > TKE_{Ov} > TKE_{Va} > TKE_{Br} > TKE_{Ti}$, though no significant differences were found among Va, Ov and Br.

Under the WBP canopy, the TKEs differed according to rainfall ($F_{rainfall} = 3.65, P < 0.01$) but did not differ according to leaf shape or the interaction between the leaf shape and rainfall ($F_{leaf\ shapes} = 1.97, P = 0.1; F_{rainfall\ *\ leaf\ shapes} = 0.35, P = 0.99$) (Table 3). The cumulative mean TKE of the different leaf shapes is shown in Fig. 8b. TKEs in each leaf shape (excluding Ti) had significant higher values than KE in open field. TKE_{Ti} was significantly lower than the TKE of the other leaf shapes ($P < 0.05$). Accordingly, the cumulative mean TKE followed a decreasing order of $TKE_{Cs} > TKE_{Ov} > TKE_{Br} > TKE_{Va} > TKE_{Ti}$, though no significant differences were found among Cs, Ov, Br and Va.

4. Discussion

4.1. Effects of rainfall events on throughfall

According to the recorded weather data, rainfall intensity fluctuates widely in Xishuangbanna, which is accompanied by the variation of ecohydrological patterns (Wang and Zhang, 2005). In our study, the fluctuation range of rainfall intensity was caught with 0.4–30.6 mm 30 min^{-1}. Thus, the recorded rainfall events could moderately show the climate features of the rainy season in this region. For banana plantations in this region, the TF under the banana canopy was approximately 60%–85% of the incident rainfall, which is consistent with the 80% and 70%–90% reported by Harris (1997) and Cattan et al. (2007), respectively. In general, higher gross rainfall produces a larger TF value, following a linear correlation between the two (André et al., 2011; Liu et al., 2019). Our study results showed that the TF volumes were expected to increase linearly with increasing gross rainfall. In addition, the greater amount of recorded rainfall had a higher peak intensity ($R^2 = 0.80, P < 0.001$, n = 16) (Fig. 4a). As a consequence, a significant linear relationship was also found between the TF volume and the peak rainfall intensity, a finding different from those reported by other studies (Zhang et al., 2016; Liu et al., 2019). The reason for this difference could be the various rainfall types in different climatic regions. In addition, significant power correlations between the TF ratio

Table 3
The results of a general linear model testing the effects of rainfall events and drip treatments on rainfall kinetic energy (KE) and the effects of rainfall events and leaf shapes on throughfall kinetic energy (TKE), respectively. *F*-values and significance *P* are given.

Scale	KE				TKE			
	Source	d.f.	F	P	source	df	F	P
IBP	Rainfall	5	0.60	0.7	Rainfall	5	7.01	< 0.001
	Treatments	2	10.74	< 0.001	Leaf shapes	4	3.41	< 0.01
	Rainfall × Treatments	10	0.73	0.69	Rainfall × Leaf shapes	20	35	< 0.001
WBP	Rainfall	15	1.48	0.12	Rainfall	6	3.65	< 0.01
	Treatments	2	27.72	< 0.001	Leaf shapes	4	1.97	0.1
	Rainfall × Treatments	30	1.17	0.26	Rainfall × Leaf shapes	24	0.35	0.99

IBP: the individual banana plant; WBP: the whole banana plantation.
The three treatments include open field, canopy non-drip points and canopy drip points.
The five leaf shapes include valley, overlap, tip, breakage and complex shapes.

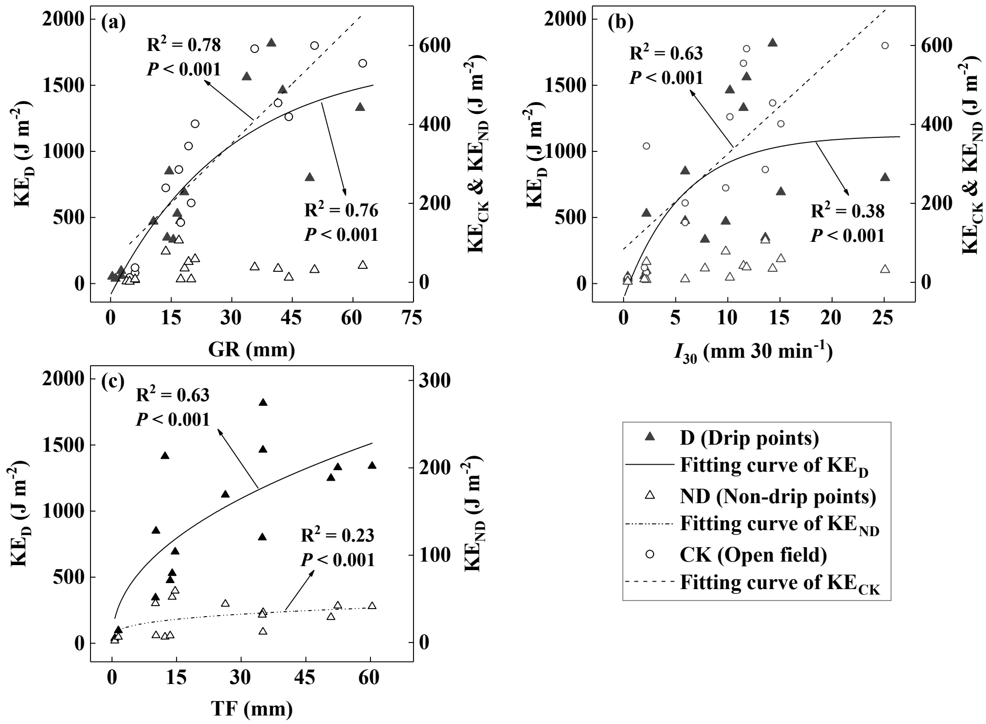

Fig. 7. Relationships between rainfall kinetic energy (KE) for three different treatments (KE_{CK} in the open field, KE_D in the canopy drip points and KE_{ND} in the canopy non-drip points) and rainfall parameters, (a) gross rainfall (GR), (b) peak 30 min rainfall intensity (I_{30}) and (c) TF volume.

and the two rainfall parameters were found, a finding similar to the result reported by Liu et al. (2019), wherein the TF ratio tended to stay constant for higher gross rainfalls and rainfall intensities. Therefore, TF was affected by more complex rainfall parameters than individual ones due to the interactions among gross rainfall, rainfall intensity and other parameters (Zhang et al., 2016). Besides, for all the recorded rainfall events, most CV_{TF} values remained at a relatively high level (CV_{TF} > 30%) in the banana plantation compared with those reported in some forest ecosystems (Liu et al., 2019; Carlyle-Moses et al., 2004; Fan et al., 2015). Such a result clearly demonstrates that TF has distinctly evolved to a high spatial variability in banana plantations. Generally, the spatial variability of TF is inconsistent during the relatively small rainfall events, whereas it is consistent during the relatively large rainfall events (Vrugt et al., 2003; Carlyle-Moses et al., 2004; Shachnovich et al., 2008). However, our results showed that CV_{TF} was almost independent of the gross rainfall and rainfall intensity. This result indirectly implies that the banana canopy may be the dominant factor determining the spatial variability of TF, and the influence of rainfall event size on the spatial variability of TF pales in comparison with the canopy effect.

Soil erosion is associated with heavy rainfall, in which the raindrops release considerable power by splashing soil particle (Levia et al., 2017). In the banana plantation, the effect of rainfall on TKE showed different results for drip points and non-drip points. KE_D was significantly affected by the gross rainfall and peak rainfall intensity. Meanwhile, KE_D also increased with increasing TF volumes. Differently, KE_{ND} was independent of the rainfall event size and was only dependent on the TF volume. This finding suggests that the raindrops splash erosion potential at canopy drip points could be more responsive to rainfall contribution than those at canopy non-drip points. Thus, rainfall factors are expected to be important driving factors affecting splash erosion in banana plantations. These findings are consistent with the results of other studies (Goebes et al., 2015; Liu et al., 2018), indicating that TKE was influenced by gross rainfall, peak intensity and TF volume. However, there is no general consensus. For example, Nanko et al. (2008) showed that TKE is strongly correlated with peak rainfall intensity and

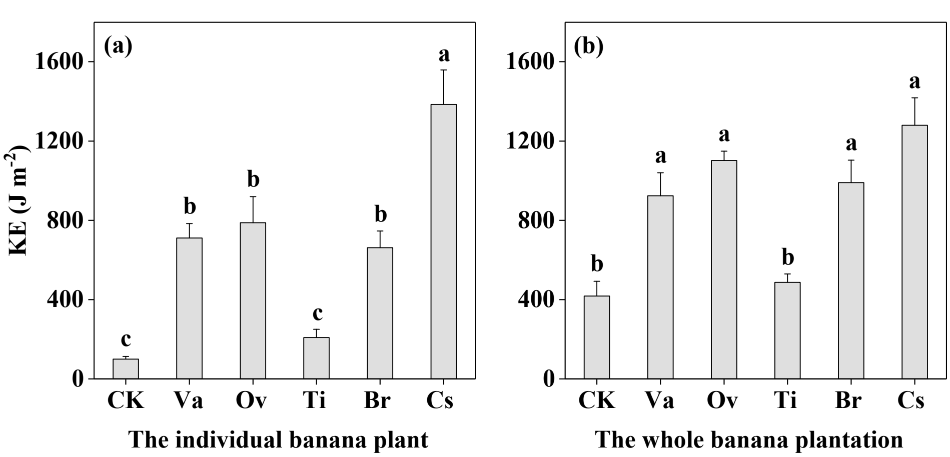

Fig. 8. The cumulative mean throughfall kinetic energy (KE) (mean ± SE) among five leaf shapes (valley, Va; overlap, Ov; leaf tip, Ti; breakage, Br; complex shapes, Cs), (a) in the individual banana plant and (b) in the whole banana plantation. The rainfall KE in open field (CK) was used as a control. Error bar with different lower-case letters (a, b and c) indicate significant differences among five leaf shapes at P < 0.05.

weakly correlated with gross rainfall. This indicates that canopy species potentially influence the differences in the relationships between TKE and rainfall factors. Meanwhile, the difference in rainfall effects on KE_D and KE_{ND} also indicated the mediating effects of banana canopy and rainfall events in the banana plantation. Additionally, given that the rainy season lasts for a long period of 6 months each year and storm events occur frequently at our study site, heavy rainfall is a huge disadvantage to the soil layer of banana plantations. Therefore, further studies are warranted to optimise the management of banana plantations to protect them from severe splash erosion.

4.2. Effects of two-canopy scales

By comparison, different TF distributions by the distance from the trunk were detected under the two-canopy scales. Under the IBP canopy, the areas close to the banana pseudostem had a smaller TF than the middle and margin areas of the canopy (Fig. 3). This result is similar to those reported by studies on hybrid shrub stands (Li et al., 2013; Zhang et al., 2016) and a Norway spruce [*Picea abies* (L.) Karst.] plantation (Whelan et al., 1998) but contrary to those reported by studies on a hybrid pine stand (Fan et al., 2015) and beech (*Fagus sylvatica*) forest (Robson et al., 1994). Nanko et al. (2011) explained that the spatial distribution of TF volume is dominated by branch position and canopy shape. Moreover, Cattan et al. (2007) demonstrated that the funnel-shaped canopy of banana plants could drive more raindrops draining in the form of stemflow in the area close to the pseudostem. Thus, the spatial distribution of TF was expected to be correlated with the distance from the trunk under the IBP canopy. However, under the WBP canopy, some drip points with relatively large TF were occasionally noted close to the banana pseudostem (Fig. 5). The reason for this might be the fact that because the long leaves of banana plants can expand to nearby banana plants, the large TF close to the pseudostem possibly comprised partly of water from the nearby plant leaf surfaces (Herwitz and Slye, 1992). Thus, the neighbouring canopy played a key role in the redistribution of rainfall, substantially modifying the spatial distribution of TF by the distance from the banana pseudostem.

Although the spatial distributions of TF are different under the two canopy scales, the similarity is that there is a remarkable variability in TF under both canopy scales. The banana canopy could converge the intercepted raindrops, leading to greater TF volumes at some drip points than in the open field (Lloyd and Marques, 1988). Results of the present study showed that the recorded maximum TF was 1.7–8.6times higher than the incident gross rainfall (Table 2), which is in agreement with the results reported by Cattan et al. (2007), who found that TF was up to five-fold higher than the incident rainfall at some drip points under the banana canopy. Evidently, the banana canopy has a considerable funnelling effect on water, so it can converge more raindrops at some drip points (Cattan et al., 2009). Simultaneously, it should be also mentioned that smaller TF volumes than open rainfall were noted at several collectors under the leaf shade, suggesting that the banana canopy synchronously had a shading effect on water. Peterson and Rolfe (1979) and Germer et al. (2006) indicated that the funnelling and shading effects amplify the spatial variability of TF, which could also explain our observations under the banana canopy. The high variability of TF distribution under the banana canopy possibly resulted from the large banana leaves providing more sheltered areas (shading effect) and the contrarily converged areas (funnelling effect). Consequently, very few raindrops are drained away in sheltered areas, whereas a larger number of raindrops are drained away in converged areas. In addition, the canopy funnelling effect is likely to be very detrimental to soil protection and heavy raindrops at drip points have a large negative splash effect on soil particles.

Under both the canopy scales, comparisons in KEs among the three treatments—canopy drip points, non-drip points, and open field—sufficiently reflected the canopy effect against soil splash erosion in the banana plantation. Firstly, the fact that the accumulative mean KE_{ND} was lower than KE_{CK} suggests that the canopy non-drip points had a protective effect against splash soil erosion. Secondly, KE_D exhibited higher values than KE_{ND} or KE_{CK} under both the canopy scales. In detail, KE_D was 3.3–123.5 and 3.8–60.5 times greater than KE_{ND} and KE_{CK}, respectively, under the IBP canopy and 3.3–140.3 and 1.2–50.2 times greater than KE_{ND} and KE_{CK}, respectively, under the WBP canopy. Accordingly, the negative effect of the canopy due to the provision of drip points on the soil was far beyond its protective effect of simultaneously providing non-drip points. The canopy drip points can generate substantial splash erosive power, and this part of the splash may become the primary contributor to splash erosion in the banana plantation. In the same region as this study, Liu et al. (2018) showed that the TKE of rubber monoculture was approximately 1.2- and 2.3- times higher than that of rubber-based agroforestry systems and open field, respectively, and Zhu et al. (2018) revealed that the runoff from rubber monoculture systems was approximately 2.6 times greater than that from rubber-based agroforestry systems. Based on their results, we speculate that the splash erosion potential in the banana plantation was greater than that under the rubber monoculture and rubber-based agroforestry systems. Even more, banana canopy drip points could exacerbate soil particle detachment and runoff. Thus, further erosion events could provide further insight into this matter in the banana plantation.

4.3. Effects of specific leaf shapes

In the present study, TKE differed significantly with the different leaf shapes under the banana canopy, which could be related to drop size distribution, given that leaf traits can change the drop size of leaf drips (Mosley, 1982; Zhou et al., 2002; Goebes et al., 2015a). For instance, leaf drips at the sharpened-toothed leaf margins were found to have considerably smaller drop diameters than leaf drips at the region between the toothed margins, thus resulting in lower TKE (Nanko et al., 2013). For the banana leaves, five leaf shapes that we categorised had different leaf geometries. Both the Va and Ov shapes had an obtuse leaf margin, whereas the spires of Ti and Br were relatively sharpened, similar to a triangular geometrical morphology. Such differences in leaf shapes could generate different drop diameters of TF. Therefore, we speculate that the difference in TKE among leaf shapes is a consequence of the variation in the drop size distribution of leaf drips. In addition, the significant difference in TKEs among leaf shapes was found under the IBP canopy, while not found under the WBP canopy (Table 3). For the large canopy scale, the interactions among neighbourhood canopies can divert and/or block raindrops falling from leaves (Goebes et al., 2015b). In the present study, the extremely long and wide banana leaves were spread out and inevitably had extensive neighbourhood interactions. Such an arrangement of banana canopies across the WBP could interfere with the raindrops falling from multiple leaves of different shapes, which differs from the raindrops that fall directly from leaves under the IBP canopy. Taken together, the unique shapes of banana leaves under individual canopies had a greater effect on TKE at drip points than multiple canopies.

The data obtained for the five types of leaf shapes showed that the TKE of Ti was significantly lower than that of the other leaf shapes (i.e. Va, Ov, Br and Cs) (Fig. 8). The lower TKE_{Ti} was most likely attributable to the lateral flow because a large amount of water had already been beforehand drained away via other leaf shapes and only a small amount of water afterwards reached Ti. Lateral water flow commonly occurs in forest systems, and it may result in the accumulation of raindrops at one point and a deficiency at another (André et al., 2011; Frischbier and Wagner, 2015). Accordingly, extremely large banana leaves are likely to fuel lateral water flow and water accumulation and then increase the TKE of certain leaf shapes, for instance, the larger TKE values of Va, Ov and Br than that of Ti. Nevertheless, banana leaf Ti still potentially aggravates splash erosion because of the occurrence of larger TKE in Ti than that in open field. In addition, banana leaf Cs resulted from random interactions among leaves of the other four shapes. Consequently, such a pattern could generate ambiguous TKE_{Cs} despite its mean value being larger than those of the other four leaf shapes. Thus, the insightful knowledge for the splash erosion in multiple shapes of banana leaf needs to be further studied.

Besides, TKE values at drip points might be underestimated due to the frequent translocation of leaf shapes during rainfall events. Banana leaves are easily wiggly in the rain owing to wind and raindrop strikes, which is most likely a reason for translocation of the canopy drip points. Accordingly, the splash cups beneath the banana canopy may not receive raindrops continuously from the same canopy drip points. It follows that some values of TKE under the canopy drip points were abnormally low and similar to those of non-drip points or the open field. This suggests that the TKE values measured under the canopy drip points might be underestimated. Nevertheless, there is no doubt that the TKE under the banana canopy was greater than that in the open field. Meanwhile, as can be observed, leaf shape is an important biotic driver affecting the spatial distribution of TKE. Further study should be conducted to understand the effect of leaf shapes on drip size distribution and soil particle detachment in banana plantations.

5. Conclusions

The present study demonstrated the characteristics of throughfall (TF) and throughfall kinetic energy (TKE) and the effect of leaf shape on TKE at canopy drip points under the individual banana plant (IBP) and the whole banana plantation (WBP) canopies. The TF volume accounted for 80.2% and 84.7% of the incident rainfall under the IBP and WBP canopies, respectively. Banana canopy potentially induced high variability in the TF distribution at the both canopy scales.

The KE of raindrops significantly varied among canopy drip points (D), canopy non-drip points (ND) and the open field (CK). The cumulative mean KE_D was up to 36.2 and 10.3 times higher than the KE_{ND} and KE_{CK}, respectively, under the IBP canopy as well as 23.7 and 2.7 times, respectively, under the WBP canopy. These results suggest that raindrops at the canopy drip points greatly aggravated splash soil erosion. Moreover, the TKE exhibited different patterns among the five leaf shapes, valley (Va), overlap (Ov), tip (Ti), breakage (Br) and complex shapes (Cs). In particular, the highest TKE appeared under Cs, the lowest under Ti, and TKE did not significantly differ among Va, Ov and Br. These results suggest that the influence of the distinctive banana leaf shapes on TKE was notable. These findings will provide an essential reference for future studies concerning the mechanism of soil erosion under banana plantations and other agroecosystems.

We recommend that further ecohydrological studies be conducted to improve the current environment of banana plantations and to create sustainable banana plantations with lower levels of soil erosion.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Declaration of Competing Interest

The authors declare no competing financial interests.

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