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Throughfall and its spatial heterogeneity in a black locust (*Robinia pseudoacacia*) plantation in the semi-arid loess region, China

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ABSTRACT

Throughfall in a forest ecosystem has potential hydrological impacts in the semi-arid loess region of China due to continuous human intervention. However, in black locust forests in this region, throughfall and its spatial heterogeneity and controlling factors remain unclear. We examined throughfall, its spatial variability and the effects of rainfall characteristics and vegetation structure on throughfall in a black locust stand experiment. Of the 489.72 mm cumulative gross rainfall during 20 sampled events, the average of throughfall for all trees, interception loss (IL) and stemflow (SF) were 380.93 mm (77.71%), 98.48 mm (20.19%) and 10.30 mm (2.10%), respectively. For a single tree, measured throughfall percentage decreased from upper to bottom in the canopy vertical layer, and the horizontal distribution increased with distance from the trunk. A correlation analysis between throughfall and rainfall characteristics, indicated that rainfall amount had a greater effect on throughfall than rainfall intensity and duration. Throughfall generally occurred following rainfall events of more than 0.76 mm for black locust. Throughfall percentage initially increased weakly, and then decreased with increasing rainfall intensity, while it initially increased, and then remained constant with increasing rainfall duration. Throughfall percentage decreased with increasing leaf area index (LAI) during differently-sized rainfall events, whereas throughfall variations were different in differently-sized rainfall events. Throughfall is affected by tree height, diameter at breast height (DBH), canopy width and canopy openness to some degree, while the effects were higher in larger storms than in smaller storms. Our study highlights the need to consider the effects of throughfall on hydrological processes, particularly for forest management in semiarid regions.

1. Introduction

Globally, forests cover approximately 3.9 billion hectares, which is about 30% of the world's land surface (Wibberley, 2016). According to FAO (2016), more than a quarter of the world forests are located in drylands, and trees are present in almost a third of the world's dryland regions. Forests play an important role in the hydrological cycle by affecting the amount of rainwater that reaches the ground surface and are valued globally for the services they provide to society (Brauman et al., 2010; Pan et al., 2011).

As the main moisture input to forests, rainfall can be partitioned into vegetation canopy interception loss (IL), throughfall, and stemflow (SF) (Zhang et al., 2015). IL is the part of incident rainfall that is intercepted, stored and subsequently evaporated from forest leaves, branches and stems during and after rainfall events (Shi et al., 2010). The remaining net rainfall reaches the soil surface by throughfall and SF. Throughfall is the rainfall fraction that reaches the ground directly through canopy gaps (free throughfall) or indirectly through leaf and branch drip (canopy throughfall) (Magliano et al., 2019a). SF is the rainfall fraction that reaches the base of trees via their trunks or stems (Levia and Germer, 2015). Therefore, the vertical and horizontal spatial distribution of rainfall is transformed via IL, throughfall and SF, which obviously affect the ecology and hydrology of arid/semi-arid areas (Jian et al., 2019).

Throughfall is a primary component of the hydrological and

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ecological processes in forest ecosystems, and its spatial patterns have an important influence on soil processes, watershed hydrology and biogeochemistry (Keim et al., 2005; Staelens et al., 2006). Related studies shown that throughfall spatial variability has important effects on spatially distributed processes in forest soils such as trace gas fluxes, ion loading, and solute leaching (Hansen, 1996), as well as implications for sampling strategies and interpretation of throughfall data in terms of water and ionic inputs (Whelan and Anderson, 1996). Specifically, spatial variations in throughfall volume influence soil moisture patterns and fine root distribution in forest soil (Ford and Deans, 1978; Schume et al., 2003), forest floor vegetation composition such as lichens and mosses (Carleton and Kavanagh, 1990), soil moisture infiltration and surface runoff generation (Nanko et al., 2011), and water and nutrient cycling (Chang and Egbert, 2000).

Throughfall in forest ecosystems is a complex process affected by morphological attributes such as plant density, leaf area index, canopy cover and canopy storage capacity, and meteorological conditions including rainfall characteristics, wind and evaporation rate (Ma et al., 2019; Magliano et al., 2019a; Staelens et al., 2008). For example, leaf size and canopy vertical layering clearly influence throughfall drop size and terminal velocity (Calder, 2001; Nanko et al., 2006). Tree density, branch angle, crown height uniformity or lack of it, the nature and thickness of the bark layer, leaf shape and inclination, and leaf area index also influence throughfall (Crockford and Richardson, 2000). Vegetation canopy throughfall has been investigated in different vegetation types, including coniferous forests (Shi et al., 2010), deciduous forest (Mużyło et al., 2012), semiarid afforestation areas (Sadeghi et al., 2016), shrublands (Jian et al., 2019) and crops (Nazari et al., 2020). A review of rainfall partitioning in drylands (delimited by a rainfall-potential evapotranspiration ratio < 0.65) shows that throughfall can account for 61.4–81.2% of gross rainfall (Magliano et al., 2019a). Additionally, trees have a higher relative throughfall and a lower relative SF than shrubs (Llorens and Domingo, 2007).

The Loess Plateau of China has become a region with severe soil erosion due to steep slopes, frequent heavy rainfall in rainy seasons (June-September) and anthropogenic activities (Gao et al., 2016; Yu et al., 2014; Zhao et al., 2013). To control severe soil erosion and improve ecosystem services on the Loess Plateau, afforestation measures were implemented in the 1950s (Jia et al., 2017), and vegetation cover has increased by 25% over the last decade (Feng et al., 2016). However, a series of negative ecohydrological impacts have been reported due to afforestation, such as dry soil layer formation and runoff reduction (Wang et al., 2010b; Zhang et al., 2016). On the Loess Plateau, where limited rainfall is almost the sole water source (Tan et al., 2016), gross rainfall plays an important role in regulating climate change, the ecological environment, surface runoff and soil moisture dynamics (Wang et al., 2015; Xu et al., 2018a; Zhao et al., 2015).

Black locust (*Robinia pseudoacacia*) is a major reforestation species in the Loess Plateau due to its high drought, infertility and low/high temperature tolerance, as well as faster growth than some native tree species (Vitkova et al., 2017; Wang et al., 2010a). Black locust plantations provide a wide range of ecological and socio-economic functions in this region (Zhou et al., 2014), such as soil water retention (Wang et al., 2010a), soil respiration regulation (Xue et al., 2007), and soil chemical and microbiological improvements (Wang et al., 2011). At a macro-scale, black locust plantations can significantly impact hydrology processes, however, their throughfall characteristics and spatial heterogeneity are less clear on the Loess Plateau, which hinders an understanding of hydrological processes. In this region, large plantations have increased soil water consumption, and therefore, to alleviate soil drought, a greater understanding of hydrological characteristics in black locust plantings is necessary. This is the first study to characterize throughfall in different canopy locations for a single tree, and to further analyze the effects of rainfall characteristics and tree attributes on throughfall in this region.

Our overall aims, therefore, are to: (1) quantify throughfall, IL and SF rainfall partitioning for black locust forest in the semi-arid Loess region of China, (2) compare throughfall spatial characteristics in different single tree locations, and, (3) examine the effect of rainfall characteristics and tree attributes on throughfall. Our results should provide a reference for black locust forest management from the perspective of water management in semi-arid loess regions.

2. Materials and methods

2.1. Site description

Our study in the semi-arid loess region of China was conducted in black locust (*Robinia pseudoacacia*) plantations in Zhifanggou watershed (109°13′03″–109°16′46″ E, 36°46′28″–36°46′42″ N) from August 2018 to October 2019. Zhifanggou watershed is a typical catchment located in a hilly gullied loess landscape, with a drainage area of 8.7 km^2, slope ranging from 0 to 65°, and altitude ranging from 1010 to 1431 m (Qiu et al., 2012; Zhao et al., 2016). The watershed is located in the warm temperate semi-arid climate zone, where the total annual sunshine is 2415.6 h, and annual average temperature is 8.8 °C. Average annual precipitation is 543 mm, 70% of which occurs between June and September due to the monsoon climate (Luo et al., 2019), and annual evaporation ranges from 1010 to 1400 mm (Zhao et al., 2017). The study area soil type is Huangmian soil, which is comprised of sand (21 ± 6%), silt (63 ± 3 %) and clay (16 ± 4 %), respectively (Ye et al., 2018). The Chinese government implemented the Grain for Green program on the Loess Plateau in 1999, and the watershed ecosystems gradually began to recover. By 2005, the watershed ecosystems reached a relatively stable state, with forest and grassland cover of more than 80% (Xu et al., 2018b). The vegetation types in this watershed are typical for the western Loess Plateau, where forests are dominated by black locust (*Robinia pseudoacacia*) (Zhao et al., 2016).

2.2. Field experimental arrangement

In Zhifanggou watershed, an area 20 m × 30 m (600 m^2) of typical black locust forest was selected for this study. The stand was located on a 30° slope with a northwest exposure and an elevation of 1251 m. According to the field survey, average tree height was 9.60 m and ranged from 5.00 m to 15.00 m; the range of canopy height, canopy diameter and diameter at the breast (DBH) was 2.5 ~ 9.0 m, 2.0 ~ 5.0 m and 6.00 ~ 23.00 cm, respectively. According to black locust distribution, canopy structure, and tree architecture in the sample area, nine robust and healthy trees were selected as experimental trees. Tree height, canopy height, canopy diameter, and DBH of the nine experimental trees were in the range of those found at the field site, and therefore typical and representative. The morphological and structural features of the 9 individual trees were characterized (Table 1).

In this study, tree height was measured with a tree height meter that could freely extend and contract to a maximum of 20 m. Canopy diameter was measured according to canopy shape, whereby a point on the canopy edge was determined by vertical projection to the ground

Table 1
Morphological and structural features of the black locust experimental trees.

Tree code	Tree height (m)	Canopy diameter (m)	Diameter at breast height (cm)
T-1	12.10	4.35	19.00
T-2	11.45	4.13	10.50
T-3	10.70	3.23	13.50
T-4	9.75	3.67	10.10
T-5	11.19	3.81	10.04
T-6	9.08	2.72	8.20
T-7	10.25	3.14	8.90
T-8	9.53	3.03	10.00
T-9	7.86	2.86	9.70

and a similar point opposite to it, and directly through the center of the trunk also determined. The distance between the two points was measured, the process repeated three times, and the average of the 3 measurements taken as canopy diameter. Trunk DBH was measured 1.3 m above the ground. A canopy photograph was taken with an unmanned aerial vehicle directly above each throughfall collector; the image was loaded into the Gap Light Analyzer software and then the results were exported by Sidelook software where the threshold value was determined; and finally, LAI was calculated in the Gap Light Analyzer software according to the determined threshold value. To measure throughfall vertical distribution, the canopy was divided into three layers according to tree canopy height, (upper-, middle- and below-canopy; Fig. 1a), and rainfall collectors were placed in each layer. To measure throughfall horizontal distribution 7 throughfall collectors were located in each layer, one at the center of the tree trunk, and the remaining six in three directions (0°, 120° and 240°), and equidistant from the tree trunk to crown periphery (Fig. 1b). The three directions were mutually staggered in each layer to avoid the influence of the upper layer on the lower layer in the process of throughfall collection. In this study, we assumed that meteorological factors were consistent at different observation locations. The collectors were 20 cm in diameter and 20 cm high, and collected throughfall passed through a plastic pipe connected to a measuring device above the ground. Stemflow (SF) was sampled using white halved rubber hose (5 mm thick), which was spirally wrapped around the tree trunk and Vaseline used to create a water-tight environment between the stem and the hose (Dong et al., 2020). The lower side of the hose was connected to a 25 L plastic bucket, and after each rainfall event water volume in the bucket was measured.

2.3. Field measurements

Gross rainfall (GR), throughfall and SF were measured from 22 August 2018 to 5 October 2019. GR was measured by an automated meteorological station (a resolution of 0.2 mm), installed on an open hillside 50 m from the plot. Rainfall indicators were measured using a HOBO U30-NRC monitor (U.S.A.), with a rainfall measurement interval of 30 min. An intermittence longer than 2 h between rainfall events was used to define individual rainfall events (Chen et al., 2009; Li et al., 2016; Yu et al., 2007). Throughfall and SF was measured after each rainfall event and rain gauges then emptied.

Throughfall depth of each rainfall collector (TF_i) was calculated as

$$TF_i = \frac{TF_v}{CA} \tag{1}$$

where TF_i is throughfall depth of each rainfall collector (mm), TF_v is throughfall volume of each rainfall collector (mm^3), and CA is the area of each rainfall collector (mm^2). Throughfall of each canopy layer is the average throughfall of each rainfall collector in this canopy layer. Throughfall for all trees is the average of throughfall of each rainfall collector in the below-canopy layer.

SF depth was calculated as

$$SF = \frac{1}{n}\sum_{i=1}^{n} SF_i/FA_i \tag{2}$$

where SF is average SF of per unit area (mm), n is the number of observed trees (n = 9), SF_i is the ith tree SF (mm^3), and FA_i is the canopy project area of ith tree (mm^2).

Interception loss (IL, mm) was calculated as

$$IL = P - TF - SF \tag{3}$$

where IL is canopy interception loss (mm), P is gross rainfall amount (mm), TF is throughfall of each tree (mm), and SF is stemflow (mm).

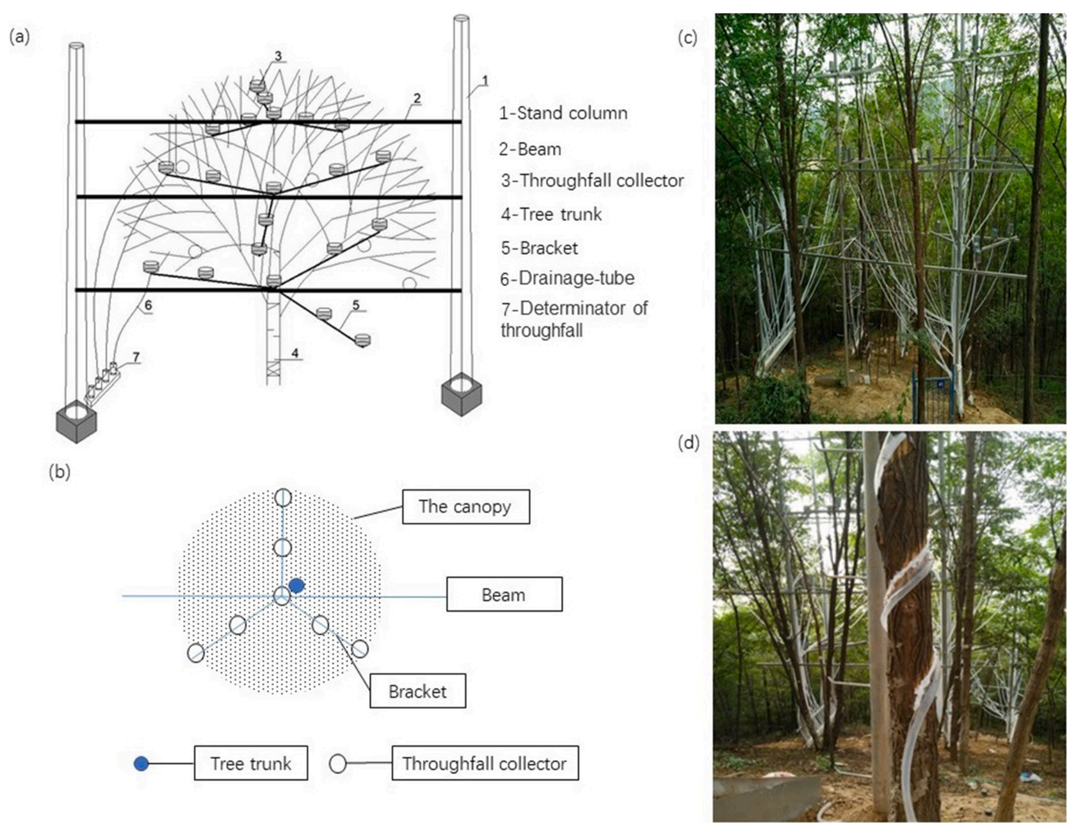

Fig. 1. Rainfall partitioning determination diagrams. Throughfall collector (a) vertical distribution, and (b) horizontal distribution, (c) and (d) field layout photographs.

2.4. Statistical analysis

Descriptive statistics were used to analyze rainfall characteristics (rainfall amount, duration and intensity) and trees morphological characteristics. Statistical analysis was carried out using SPSS v. 17.0 (IBM Company) and Microsoft Excel 2016 (Microsoft, Redmond, USA) software. Duncan's multiple range tests with a $p < 0.05$ significance level were conducted to identify significant differences in spatial location for each tree.

3. Results

3.1. Rainfall characteristics

A total of 604.4 mm of rainfall occurred during this period, which was unevenly distributed through time (Fig. 2). Rainfall was concentrated mainly in August to October of 2018, and June to October of 2019, equivalent to 189.2 mm (31.3%) and 386.4 mm (63.9%) of rainfall, respectively. During this experimental period (grey rectangles in Fig. 2a) from 22 August to 18 October 2018, and from 7 May to 5 October 2019, 58 rainfall events occurred, totaling 503.8 mm of rainfall.

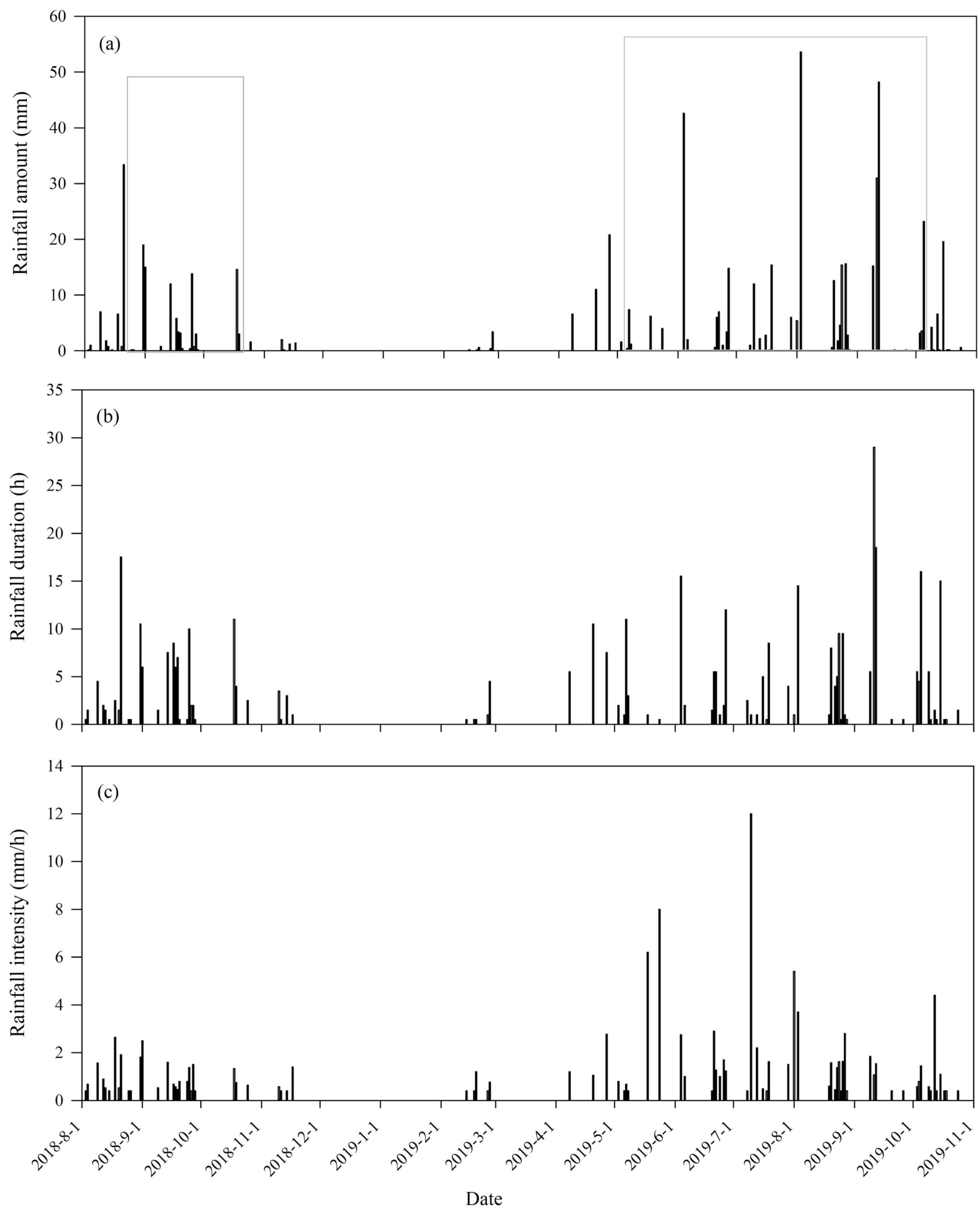

Fig. 2. Rainfall (a) amount, (b) duration, and (c) intensity of each rainfall event, from August 2018 to October 2019. Note: the grey rectangles represent the observed experimental period.

The average rainfall for individual rainfall events was 6.5 mm with a range of 0.2–53.6 mm. Average rainfall duration was 4.57 h with a range of 0.5–29 h. Average rainfall intensity was 1.39 mm/h with a range of 0.4–12 mm/h.

Generally, low intensity rainfall events were the most frequent, and contributed a lower percentage of total rainfall than larger rainfall events (Fig. 3a). For example, individual rainfall events ≤ 2 mm occurred 41 times with total rainfall of 28.2 mm, accounting for 47.13% of total rainfall events but only 4.67% of total rainfall amount. Individual rainfall events >20 mm was much less frequent (8.05% of total rainfall events), but provided 41.83% of total rainfall. Short-duration (≤6 h) rainfall events mainly occurred in this period (accounting for

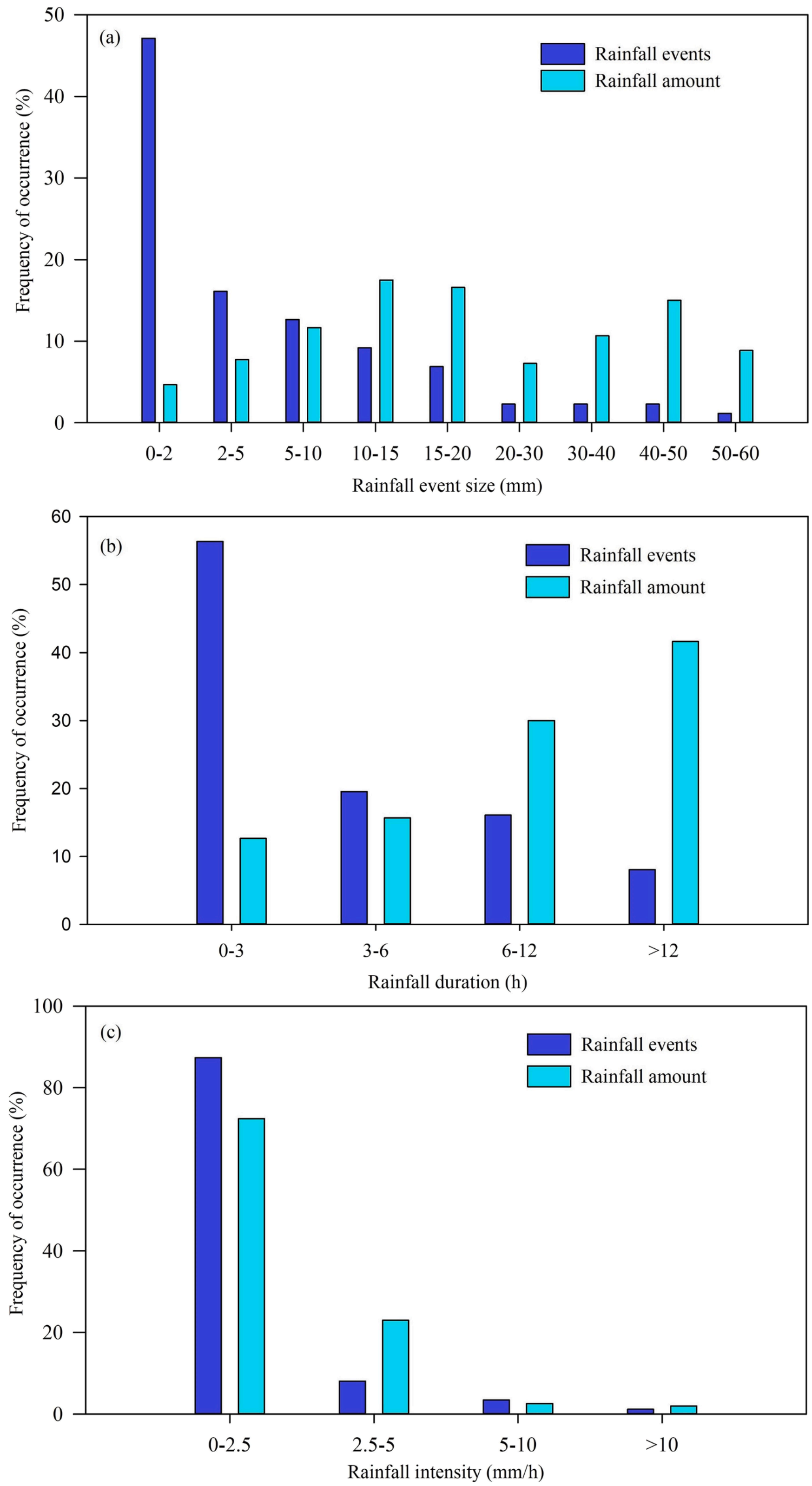

Fig. 3. Frequency distribution of rainfall and rainfall events in different ranges of (a) amount, (b) duration and (c) intensity from August 2018 to October 2019.

75.86% of total rainfall events), while long-duration (>6 h) rainfall events contributed a greater portion to total rainfall (71.64%; Fig. 3b). Lower intensity rainfall events were much more frequent than higher intensity rainfall events, while the sum of rainfall events with ≤ 5 mm/h accounted for 95.40% of total rainfall events and 95.43% of total rainfall amount (Fig. 3c).

3.2. Rainfall partitioning

Rainfall partitioning was calculated using the averages of below-canopy throughfall data. During the study period, 20 effective rainfall events (effective rainfall events are those that can produce throughfall and stemflow, which were effectively collected) were recorded (490.2 mm). For 20 rainfall events, event size was mainly concentrated from 10 to 15 mm, accounting for 31.43% of total rainfall events (Fig. 4a). Rainfall duration and intensity were mainly focused on 6–12 h and 0–2.5 mm/h, accounting for 42.86% and 80.00% of total rainfall events, respectively (Fig. 4b and c). Mean rainfall amount for recorded rainfall events was 24.51 mm with a range of 4.30–55.94 mm. Rainfall intensity ranged from 0.34 to 7.43 mm/h with a mean of 2.11 mm/h. Only 2 of 20 recorded rainfall events had rainfall intensity greater than 6 mm/h (high-intensity rainfall events). It shows that the rainfall characteristics of 20 rainfall events were broadly typical of this region.

Throughfall ranged between 3.23 mm and 42.30 mm (coefficient of variation, CV = 62.07%), accounting for 62.25–81.98% (CV = 7.68%) of corresponding incident rainfall. IL minimum and maximum were 1.06 mm and 12.24 mm (CV = 59.96%), accounting for 11.34–36.46% (CV = 25.91%) of corresponding incident rainfall. SF was 0.003–1.41 mm (CV = 76.72%), accounting for 0.06–3.70% of corresponding individual incident rainfall (Fig. 5a). Total throughfall depth was 380.93 mm during observation periods, accounting for 77.71% of corresponding gross rainfall. IL and SF depths were 98.48 mm and 10.30 mm during observation periods, accounting for 20.19% and 2.10% of corresponding gross rainfall, respectively (Fig. 5b).

3.3. Throughfall canopy spatial heterogeneity

Throughfall depth did not significantly differ with canopy height ($p > 0.05$) (Fig. 6b). Throughfall depth was greatest in the upper-canopy, followed by the middle-canopy, and least in the below-canopy, with an average of 20.59 mm (CV = 64.02%), 19.64 mm (CV = 63.32%) and 19.02 mm (CV = 62.17%), respectively. The vertical distribution of throughfall percentage with canopy height was consistent with throughfall depth, however, the differences were significant ($p < 0.05$). Averages of throughfall percentage were 81.80% (CV = 7.29%), 78.24% (CV = 8.15%) and 76.39% (7.95%) at upper-canopy, middle-canopy and below-canopy, respectively. The horizontal distribution of throughfall depth and throughfall percentage increased with increasing distance from the trunk, but there were no significant differences at different horizontal locations ($p > 0.05$) (Fig. 6c and 6d). Throughfall depths were 19.89 mm (CV = 62.73%), 19.75 mm (CV = 63.31%) and 19.46 mm (CV = 64.24%) at crown radius, 1/2 crown radius and trunk locations, respectively. Throughfall percentages were 79.61% (CV = 7.18%), 78.65% (CV = 7.78%) and 77.28% (CV = 8.02%) at crown radius, 1/2 crown radius and trunk locations, respectively.

3.4. Throughfall in relation to rainfall characteristics

Throughfall depth was significantly linearly correlated with amount of rainfall ($r^2 = 0.98$, $P < 0.0001$; Fig. 7a). According to the fitted equations, rainfall depth for throughfall generation were 0.76 mm for black locust. Throughfall percentage showed a Quadratic function relationship with rainfall amount, whereby it initially increased and then stabilized with increasing rainfall (Fig. 7b). The throughfall depth/rainfall intensity relationship followed a quadratic polynomial function, and the throughfall percentage/rainfall intensity relationship was similar (Fig. 7c and d). Throughfall depth initially increased, and then decreased with increasing rainfall intensity, from a critical value of 3.35 mm/h. Throughfall percentage weakly increased, and then decreased rapidly with increasing rainfall intensity. Throughfall depth followed a power function, typically increasing with increasing rainfall duration, followed by a gradual slowing with increasing rainfall duration (Fig. 7e). The corresponding throughfall percentage also followed a power function with increasing rainfall duration, where throughfall percentage initially increased, and then slowed to a constant (Fig. 7f).

3.5. Throughfall in relation to trees attributes

In the analysis of tree attributes on throughfall, data from each rainfall collector produced by a single rainfall event was used, not the

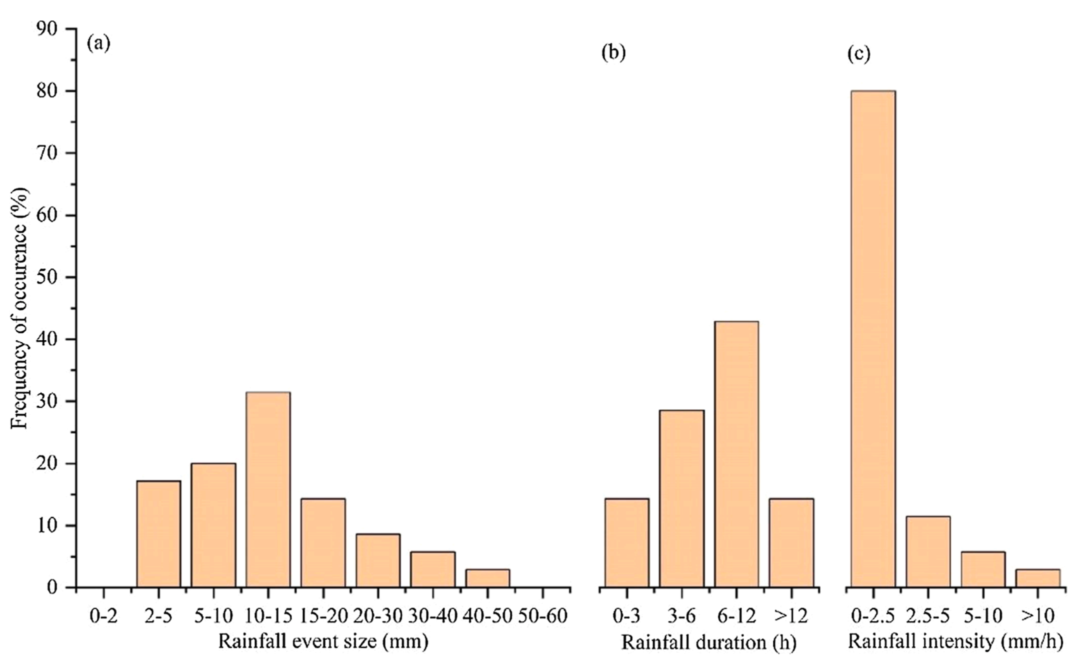

Fig. 4. The frequency of occurrence of (a) rainfall event size, (b) rainfall duration, and (c) rainfall intensity for 20 rainfall events.

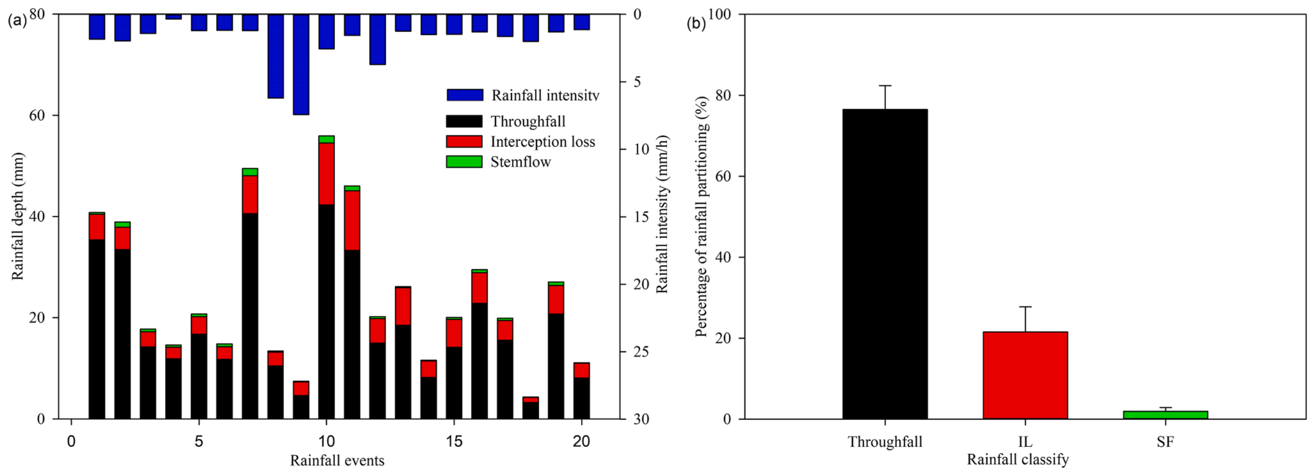

Fig. 5. (a) Throughfall, IL and SF and associated rainfall intensity during study periods; (b) Mean and standard deviation of rainfall partitioning into throughfall, IL and SF.

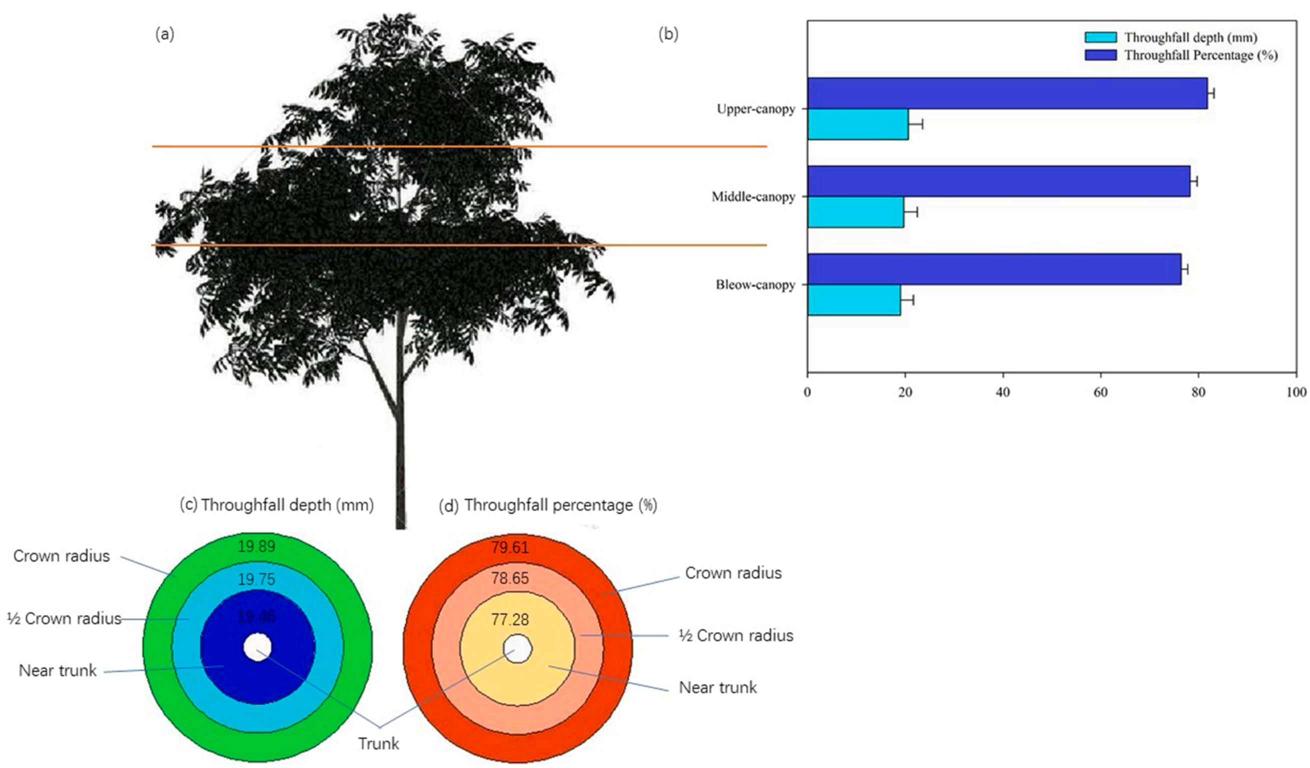

Fig. 6. The spatial distribution of throughfall under the canopy. (a) Black locust canopy layering; (b) vertical distribution of throughfall depth and percentage; (c) and (d) horizontal distribution of throughfall depth and percentage.

average of all 20 rainfall events (Figs. 8 and 9). Corresponding LAI (LAI gradually change in the growing season) was measured during the period of approaching single rainfall. In Fig. 8, throughfall data of each collector is the average of below-canopy in each tree.

In four rainfall conditions (light (4.30 mm), moderate (11.57 mm), heavy (20.22 mm) and rainstorm (45.97 mm)), the relationship between throughfall percentage and LAI was a second-degree polynomial, where the coefficient of determination was higher in light and moderate rainfall than in heavy rainfall and rainstorm. In light rainfall conditions, throughfall percentage initially declines and then weakly increases with increasing LAI (Fig. 8a). In moderate rainfall conditions, throughfall percentage weakly declines with increasing LAI (Fig. 8b). In heavy rainfall conditions, throughfall percentage followed the opposite trend to light rainfall (Fig. 8c). However, in rainstorm conditions, throughfall percentage trends were similar to those for moderate rainfall (Fig. 8d). Generally, LAI/throughfall percentage coefficients were negative, and the effect of LAI on throughfall was more obvious when precipitation was low, and conversely, the effect was weak when precipitation was high.

The relationship between throughfall percentage and tree height, DBH, canopy width, and canopy openness was a second-degree polynomial in different size rainfall events (Fig. 9). However, the coefficient of determination was different for different tree attributes in the same rainfall conditions. In light rainfall, the best relationship was between throughfall percentage and tree height ($R^2 = 0.17$). In moderate and heavy rainfall, the best relationship was between throughfall percentage and canopy width ($R^2 = 0.75$ and $R^2 = 0.33$), and in a rainstorm, it was between throughfall percentage and DBH ($R^2 = 0.39$).

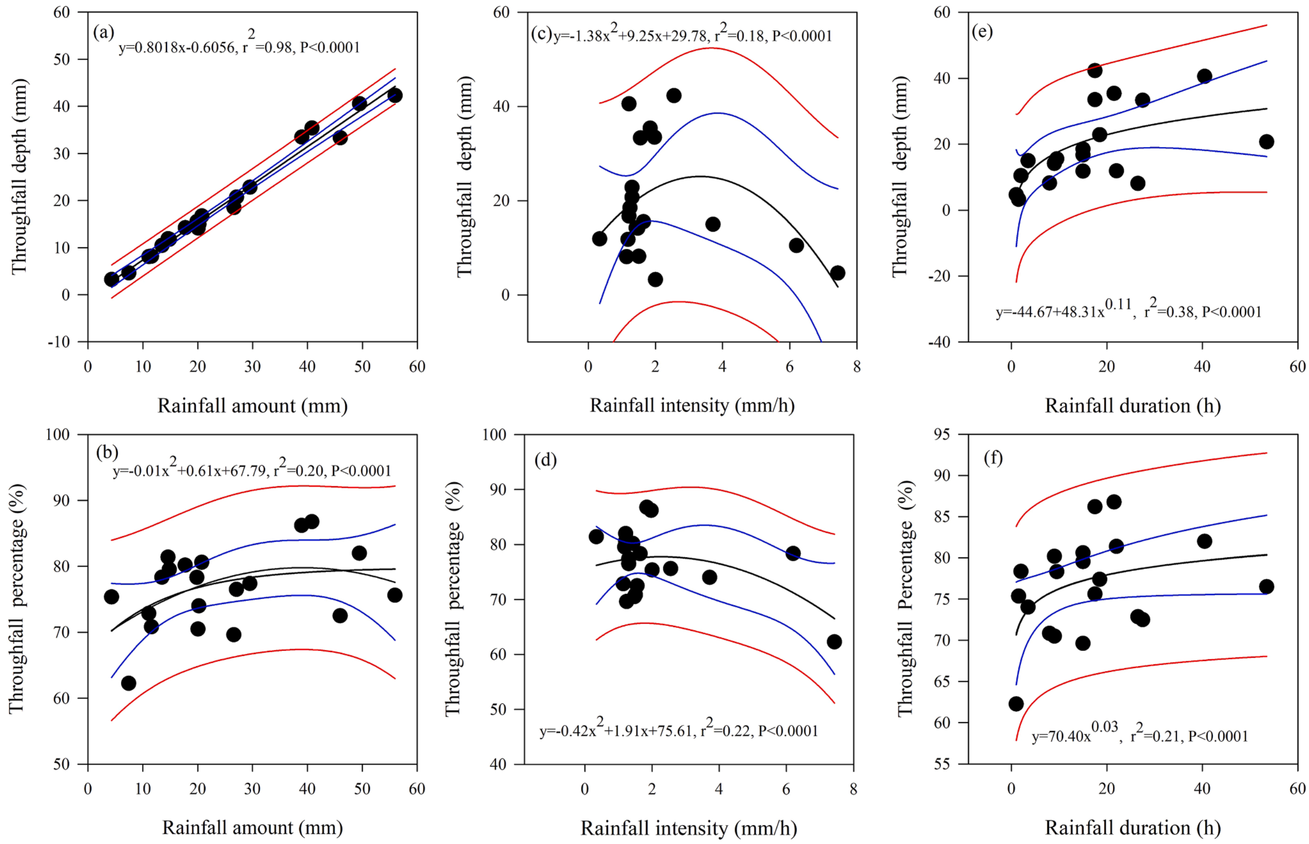

Fig. 7. Throughfall depth and throughfall percentage as a function of rainfall: (a, b) amount, (c, d) intensity and (e, f) duration.

Throughfall percentage declined with increasing tree height under light rainfall (Fig. 9a), while it increased under moderate rainfall (Fig. 9e). Throughfall percentage increased weakly at first and then decreased with increasing tree height in heavy rainfall (Fig. 9i), but in contrast, throughfall percentage changes during rainstorms was similar to moderate rainfall (Fig. 9m). Throughfall percentage declined initially, and then increased with increasing DBH in light rainfall, while it increased and then decreased in moderate rainfall (Fig. 9b and 9f). Under heavy rainfall, throughfall percentage increased with increasing DBH, but it decreased during rainstorms (Fig. 9j and n). In contrast, changes in throughfall percentage with canopy width were similar during moderate and heavy rainfall, where they initially increased, and then declined (Fig. 9g and k). With light rainfall throughfall percentage decreased with increasing canopy width, while it increased during rainstorms (Fig. 9c and o). Throughfall percentage declined with increasing canopy openness in light and moderate rainfall (Fig. 9d and h), while it initially decreased, and then increased in heavy rainfall (Fig. 9l). In contrast, throughfall percentage increased with increasing canopy openness during rainstorms (Fig. 9p).

4. Discussion

4.1. Throughfall characteristics in different studies

Rainfall characteristics directly affect throughfall when they make contact with the tree canopy. Over the study period, rainfall events between 0 and 10 mm (75.86%), rainfall duration between 0 and 3 h (56.32%), and rainfall intensity is 0–2.5 mm/h (87.35%) were the most frequent rainfall characteristics. Li (2011) showed that $<$ 5 mm rainfall events account for 75% of total rainfall events in the semi-arid areas of China, and where the contribution of rainfall events is relatively stable, they account for 14%-25% of total precipitation. However, the frequency of $\geq$ 10 mm rainfall events account for 16% of total rainfall events, and has larger inter-annual variation, accounting for 52.1%-65.4% of total precipitation. Our results show that $<$ 10 mm events occur more frequently in semiarid areas, but $\geq$ 10 mm rainfall events contribute the most to total precipitation.

Numerous studies on throughfall for different plant species exist in different global regions, and differences in vegetation type and regional climate lead to great variation in throughfall. For example, throughfall percentage for various forest types ranged from 55% to 90% depending on canopy structure and climatic conditions (Siles et al., 2010). Throughfall percentage varied from 70% to 90% in temperate coniferous broad-leaved forest, while it varied more widely in tropical forest, from 60% to 95% (Bruijnzeel, 2004; Levia and Frost, 2006; Llorens and Domingo, 2007; Torsten et al., 2008). Throughfall percentages were 65.2% $\pm$ 15.5% in arid areas, where the throughfall of herbaceous plants was lower than for trees and shrubs (Li, 2011; Magliano et al., 2019a). Furthermore, related studies show that the throughfall percentage was higher for trees (72.3%) than shrubs (72.3%), deciduous (69.8%) than evergreen trees (65.3%), pinnate-leaved (72.9%) than needle- (65.5%) and broadleaved trees (66.6%), and rough (70.5%) than smooth bark (61.8%) (Magliano et al., 2019a). In our study, the throughfall percentage contribution to gross rainfall was 77.71%, comfortably falling within this range, indicating that our experimental results are dependable. However, during our study period, values for throughfall rather than gross rainfall were obtained partially from the canopy region, mainly because preferential drip points in the canopy occurred during continuous rainfall events (Queiroz et al., 2020; Siegert et al., 2016; Vernimmen et al., 2007).

Moreover, we analyzed black locust throughfall, IL and SF percentages in previous studies, and our results were comparable, although some studies had obvious differences (Table 2). Black locust forms a wide broadleaved deciduous forest, therefore throughfall percentage is lower than evergreen forest and higher than needle-leaved forest. Previous studies show that these forests range from 62.00% to 89.00%,

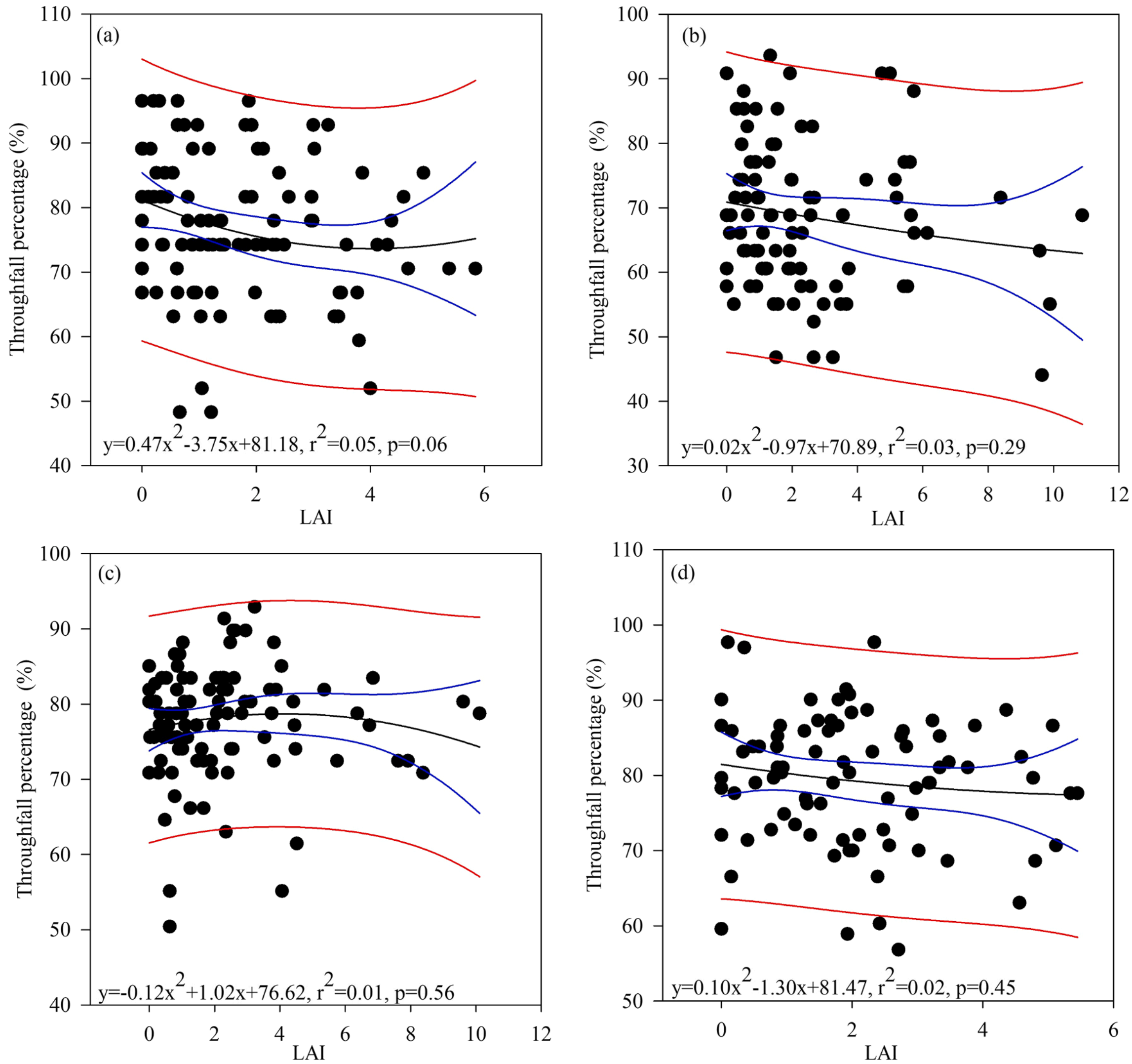

Fig. 8. Throughfall percentage as a function of LAI during different size rainfall events: (a) light rainfall (4.30 mm), (b) moderate rainfall (11.57 mm), (c) heavy rainfall (20.22 mm), and (d) rainstorms (45.97 mm). Note: blue line represents the 95% Confidence Band, red line represents the 95% Prediction Band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

6.00%–37.50% and 1.30%–5.00%, respectively. Our throughfall was much higher than that found by Sadeghi et al. (2016) and Gao et al. (2020), but much lower than in Ma et al. (2019), Wei et al. (2008), Wang et al. (2012) and Zhang et al. (2016). The main reasons for these differences are likely related to rainfall characteristics, topographic variables and canopy structure in different study regions (Aboala et al., 2000). For example, thicker crown depth and denser leaves results in greater rainfall interception and a reduced throughfall percentage because of increased length of interaction between raindrops and the crown surface (Ma et al., 2019). Meanwhile, throughfall percentage is affected by collector amount, size, spatial location, and measurement method. Compared with previous studies, our arrangement of throughfall collectors was denser and individual tree-centered.

4.2. Throughfall spatial heterogeneity

Throughfall horizontal spatial variation (the horizontal distribution from the trunk center to the periphery of the canopy) has been widely studied in forests (Mululo Sato et al., 2011; Staelens et al., 2006; Zuecco et al., 2014). Related studies also show a significant relationship between throughfall generation and the distance from the center to canopy periphery (Magliano et al., 2019b). To examine throughfall spatial variation, throughfall depths were measured in different horizontal locations and at canopy vertical heights for each single tree in our study. We found that the horizontal distribution of throughfall depth and throughfall percentage increased with distance from the trunk (Fig. 6b). However, the horizontal distribution of throughfall is not consistent, for example, Mululo Sato et al. (2011) and Magliano et al. (2019b) found that throughfall was higher close to the trunk than further away, while Staelens et al. (2008) found that throughfall was lower close to the trunk. Moreover, a related study showed higher throughfall near the trunk in young coniferous forest, lower in old coniferous forest, and in other situations, no relationship between throughfall and distance from the trunk (Keim et al., 2005). Studies of throughfall vertical spatial variation exist but are relatively rare. In our study, the order of throughfall depth and percentage was upper-canopy > middle-canopy > below-canopy in different vertical canopy height (Fig. 6a). Hansen (1996) showed that for a Norway spruce canopy divided into six depths, throughfall depth was highest at the top of tree and decreased down through the canopy. However, Fritsche et al. (1989) found that throughfall increased from top to bottom. Moreover, spatial throughfall variability has time stability (Mululo Sato et al., 2011).

Related studies show that throughfall exhibits "gathering effects" in the canopy (Queiroz et al., 2020), which are caused by the lateral flow of

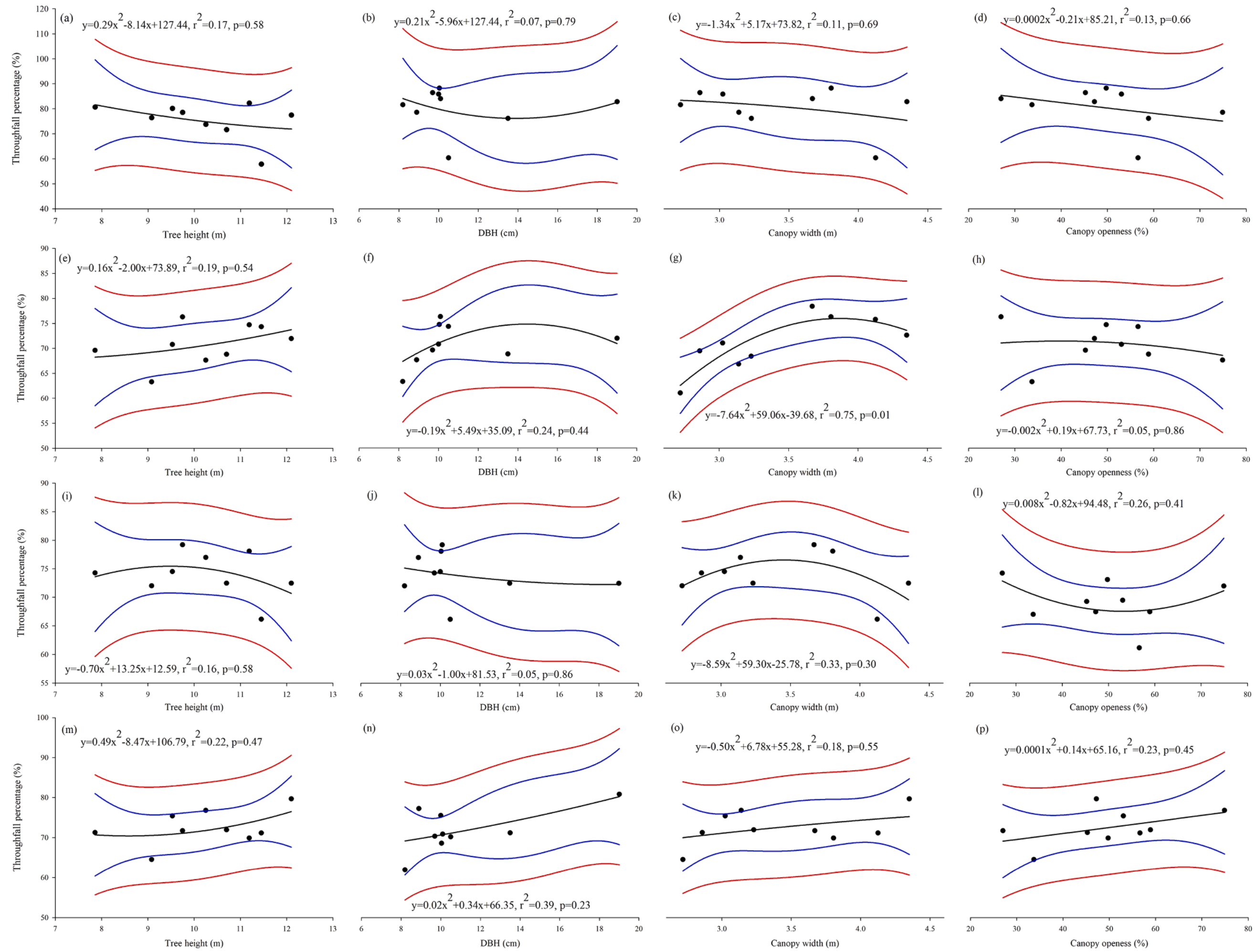

Fig. 9. Throughfall percentage as a function of tree attributes in different precipitation classes. (a)–(d): Light rainfall (4.30 mm); (e)–(h): moderate rainfall (11.57 mm); (i)–(l): heavy rainfall (20.22 mm); (m)–(p): rainstorms (45.97 mm). Note: DBH-diameter at breast height. The blue line represents the 95% Confidence Band, and the red line represents the 95% Prediction Band. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Review of measured values of rainfall partitioning for black locust from different study sites.

No	Location	Age (year)	P_g (mm)	Through fall (%)	IL (%)	SF (%)	References
1	Yeheshan watershed (Fufeng County, Shaanxi Province, China)	17	510	81.10	17.60	1.30	(Ma et al., 2019)
2	Chitgar Forest Park (City of Tehran, Tehran Province, Iran)	–	730.5	62.00	37.50	2.00	(Sadeghi et al., 2016)
3	Yangou watershed (Yanan city, Shaanxi Province, China)	26	402.62	84.79	12.75	2.47	(Wei et al., 2008)
4	Wangjiagou watershed (Lvliang city, Shanxi Province, China)	30	366.9	86.54	10.68	2.78	(Wang et al., 2012)
5	Yanan city, Shaanxi Province, China	30	504.4	89.00	6.00	5.00	(Zhang et al., 2016a)
6	Miyun county, Beijing city, China	–	468.4	78.73	17.16	4.11	(Li et al., 2002)
7	Beijing city, China	–	262.5	71.79	25.63	2.58	(Gao et al., 2020)
8	Zhifanggou watershed (Ansai County, Shaanxi Province, China)	20	490.2	77.71	20.19	2.10	This study

rainwater within the tree crown (Frischbier and Wagner, 2015). Generally speaking, GoÂmez et al. (2002) found that gathering effects were more likely to occur at the edge of the canopy, or sometimes, within the canopy edge. However, the throughfall gathering area occurs more at the middle of the canopy radius, and sometimes, at the edge of the canopy. We found that higher throughfall occurs at the edge of the crown radius, and declines towards the trunk center, while previous studies show that throughfall depth and percentage were lower midway between the trunk and the canopy edge (Nanko et al., 2011). Interestingly, throughfall percentage minima were not closest to the trunk, but at a distance of 1–2 m from the trunk center in a *Pinus armandii* stand (Shi et al., 2009). We believe that the determinants of throughfall spatial variability are not the distance from the trunk, but rather canopy thickness, canopy cover and leaf area index at different distances from the trunk.

4.3. Factors influencing throughfall

Throughfall is affected by meteorological characteristics (rainfall amount, intensity and duration, and wind speed) and vegetation structure (canopy cover, thickness, tree height, DBH, and LAI). Related studies show that gross rainfall has a major impact on rainfall partitioning into throughfall, SF and IL (Kaushal et al., 2017). Previous studies found that throughfall increased as gross rainfall event size increased (Fleischbein et al., 2005; Magliano et al., 2019a; Marin et al., 2000; Xiao et al., 2000). In our study, we found a significantly linear relationship between throughfall and amount of rainfall, where throughfall increased with increasing rainfall (Fig. 8a). This is consistent with previous findings where higher throughfall was associated with higher gross rainfall (Mużyło et al., 2012; Zhang et al., 2015). However, the relationship was a quadratic function for throughfall percentage and rainfall amount, where it initially increased and then gradually stabilized (Fig. 7b), which agrees with Zhang et al. (2015). Zhang et al. (2015) also showed that higher intensity rainfall can generate stronger vegetation impacts than lower intensity rainfall, which helps throughfall generation. We found that throughfall depth increased initially and then decreased with rainfall intensity (Fig. 7c), and that throughfall percentage changes followed a similar trend (Fig. 7d). However, examining the relationship between throughfall and rainfall intensity is only meaningful when the analysis controls for rainfall duration (Keim, 2004). Throughfall depth increased gradually with increasing rainfall duration (Fig. 7e), whereas the corresponding throughfall percentage trend initially increased and then remained constant. In our study area, many rainfall events are of short duration that produce low amounts of rainfall (Fig. 2), but even in the longer rainfall events, the hourly time step reveals periods of low, and high intensity (Fig. 3). Previous studies have shown that low-intensity/short duration events generated the lowest throughfall (Staelens et al., 2008), which differs to our findings, where other climate factors and canopy structure differences may be important.

Vegetation structure can be extremely complex and includes tree height, LAI, bark thickness, and DBH (Sadeghi et al., 2016), and so understanding how it determines rainfall partitioning is no easy task. Previous studies show that leaf size and canopy vertical layering strongly affect throughfall drop size and terminal velocity (Calder, 2001; Nanko et al., 2006). In our study, the relationship between throughfall percentage and LAI followed a second-degree polynomial function (Fig. 8). The change shows that throughfall percentage initially increased and then decreased weakly with increasing LAI during light rainfall (Fig. 8a), while initially declined and then increased weakly during heavy rainfall (Fig. 8c). During moderate rainfall and rainstorms, throughfall percentage decreased with increasing LAI (Fig. 8b and 8d). An increase in LAI does not always lead to a reduction in throughfall because of the effects of time and nature of thinning on the ratio of basal area to LAI (Aboala et al., 2000). Other studies also show that higher throughfall did not correspond to lower LAI (Limin et al., 2015) because LAI alone did not correlate with throughfall (Park and Cameron, 2008).

Moreover, we analyzed the relationship between throughfall percentage and canopy structure characteristics (tree height, canopy width, DBH, and canopy openness) during differently-sized rainfall events, and found these relationships differed. In general, the relationship between throughfall percentage and tree attributes was described by a second-degree polynomial in differently-sized rainfall events, while the coefficient of determination was different for different tree attributes in the same rainfall conditions. For example, throughfall percentage in light, moderate and heavy rainfall, increased with increasing tree height, whereas during a rainstorm, throughfall percentage was higher, and increased with DBH. However, the best fitting relationships of canopy width and canopy openness with throughfall percentage were during moderate and heavy rainfall, respectively. These results suggest that tree attribute effects on throughfall are greater in larger storms that in lesser storms. This is consistent with previous findings that crown depth and canopy openness all affect throughfall during smaller storms, but live crown length was the only significant predictor of storms that were deeper than 20 mm (Park and Cameron, 2008). In our study, the weak correlations between tree attributes and throughfall could indicate that other parameters that could be inter-correlated, are influencing throughfall.

5. Conclusions

For black locust forest in the semi-arid loess region of China, throughfall was quantified and its spatial heterogeneity analyzed. Rainfall events are mainly of short-duration and low-intensity in this region, while the overall rainfall amount is mainly from long-duration and low-intensity rainfall. In rainfall partitioning, throughfall is the most important part, followed by the canopy interception loss, and finally by stemflow. For a single tree, throughfall varies in different canopy locations. In the vertical direction, throughfall depth and percentage decreased with decreasing canopy height. In the horizontal direction, throughfall depth and percentage increased with distance from the trunk. Rainfall characteristics exerted a dominant effect on throughfall, and the effects of rainfall amount were higher than rainfall intensity and duration. Throughfall is affected by tree attributes (LAI, height, DBH, canopy width and canopy openness) to some degree, and these effects are greater in large, rather than small storms.

CRediT authorship contribution statement

Wenbin Ding: Conceptualization, Methodology, Writing - original draft, Writing - review & editing. **Fei Wang:** Writing - original draft, Writing - review & editing. **Jianqiao Han:** Methodology. **Wenyan Ge:** Validation. **Chenyu Cong:** . **Liqiang Deng:** .

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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