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The Throughfall, Stemflow, and Canopy Interception Loss in Corn and Soybean Fields in Northeast China

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Abstract: Information about throughfall, stemflow, and canopy interception loss is essential for the water use efficiency of crops and the dynamic processes of water erosion. A two-year field experiment was conducted under natural rainfall conditions to observe the characteristics and factors that affect throughfall, stemflow, and canopy interception loss in corn (*Zea mays* L.) and soybean (*Glycine max* L.) fields in northeast China from 2019 to 2020. Nine measurement sites (A, B, C, D, E, F, G, H, and I) were distributed horizontally between two planting rows under the crop canopy. The mean value of the throughfall volume (*TF*) in measurement locations B, C, and G under the corn canopy and measurement locations B and C could represent the mean level of *TF* of corn and soybean fields, respectively. The volume of *TF*, stemflow (*SF*), and canopy interception loss (*CI*) of two growing seasons from 2019 to 2020 accounted for approximately 58.5%, 30.1%, and 11.4% of the gross rainfall (*GR*) of two growing seasons in corn fields, and 78.0%, 7.5%, and 14.5% of the *GR* in the soybean field, respectively. The *TF* and *TFR* of each rainfall event in the corn and soybean fields could be predicted by linear regression models with a normalized root mean square error (NRMSE) lower than 25.0%. These results and prediction models will be used in water management and soil erosion control in northeast China.

Keywords: rainfall redistribution; throughfall; stemflow; canopy interception loss; water use efficiency

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1. Introduction

Rainfall redistribution by the crop canopy is an important part of hydrological processes in agro-ecosystems, and is crucial in the research on the water use efficiency of crops, the soil water cycle, and the water erosion of farmland [1,2]. Rainfall is partitioned into three components, the throughfall (*TF*), stemflow (*SF*), and canopy interception loss (*CI*), when the rainfall passes through the crop canopy [3,4]. The black soil region in northeast China is one of the main grain production areas in China [5,6]. Simultaneously, soil and water losses are widespread in the farmland in northeast China [7,8]. An adjustment of the cropping pattern has been conducted in local areas to promote sustainable development in northeast China. Cropping patterns could affect the water use efficiency of crops [9] and the water erosion on sloped farmland [10–12]. The characteristics of *TF*, *SF*, and *CI* in farmland may vary with the type of crops and rainfall conditions. A thorough understanding of the information about the *TF*, *SF* and *CI* could help us to master the hydrological processes of farmland, provide references for field water management, and understand the relationship between the crop canopy and soil erosion of farmland [2,13].

Crop canopies are discontinuous [14], and could affect the horizontal redistribution of rainfall at the row scale. Soil water movement characteristics observation and simulation are important pars of field water cycle research [15,16]. Rainfall partition by the crop canopy may influence soil water movement. Zheng et al. (2019) found that the horizontal variety of *TF* at the row scale under the corn canopy had a significant influence on the state of soil

water [17]. Other studies primarily focused on the characteristics of canopy interception loss, throughfall, and stemflow in farmland over recent decades. Haynes found that the *TF*, *SF,* and *CI* in corn fields comprised 68–71%, 17–25%, and 4–15% of the total rainfall amount, respectively [18]. Martello et al. (2015) pointed out that a corn canopy intercepted 78% of the rainfall on average and had a significant influence on soil water distribution by investigating the effect of corn canopies on rainfall and sprinkler irrigation [19]. Zheng et al. (2020) reported that the *TF*, *SF*, and *CI* in corn fields accounted for 32.5–87.0%, 0–33.5%, and 1.7–63.4% of the gross rainfall, respectively [20]. Sun and Li (2020) determined the horizontal variability of *TF* at the row scale in corn fields in northeast China [21]. Wang and Wang (2020) found that the interception loss from a corn canopy was higher than that from an apple canopy [22]. Kang et al. (2005) measured the interception of spray water by the wheat canopy [23]. Liu et al. (2022) determined the *TF*, *SF*, and *CI* of sprinkler irrigation water in a wheat field and found that approximately 60%, 30%, and 10% of the gross sprinkler irrigation water were redistributed into *TF*, *SF*, and *CI*, respectively [24]. Research on the *TF*, *SF*, and *CI* in farmland has focused more intensively on corn and wheat fields, and the major studies have measured the *TF*, *SF*, and *CI* of a single crop species. The characteristics of *TF*, *SF*, and *CI* in farmland vary with the types of crop and the study area. There is still a need for the additional study of *TF*, *SF*, and *CI* under different crop types and the horizontal distribution of *TF* at the row scale to clarify the effects of crop type on *TF*, *SF*, and *CI*. Corn and soybeans are the main crops cultivated in northeast China. Investigation of the interception loss that occurs in corn and soybean canopies is necessary to accurately evaluate the water use efficiency of corn and soybeans. Research about the *TF*, *SF*, and *CI* in corn and soybean farmland are important to evaluate the effect of corn and soybean cultivation on field water cycles and soil erosion in slope farmlands. However, the characteristics of the rainfall redistribution by corn and soybean canopies in northeast China remain unclear.

Therefore, the objectives of this study were (1) to determine the horizontal variability of the TF of each rainfall event at the row scale under corn and soybean canopies, (2) compare the characteristics of *TF*, *SF*, and *CI* of corn and soybean during each rainfall event, and, finally, (3) to establish models of the *TF*, *SF*, and *CI* of each rainfall event and their influencing factors of rainfall amount, rainfall intensity, and the leaf area index.

2. Materials and Methods

2.1. Description of Experimental Sites and Agronomic Management

Field research was conducted from 2019 to 2020 at the Lishu Experiment Station (124°26′ E, 43°17′ N) of the China Agricultural University in Lishu Country, Jilin Province, with a northern temperate and semi-humid continental monsoon climate. The average annual rainfall in the study area is 572.8 mm, and approximately 65% of this precipitation occurs from June to August. The annual temperature of this study area is 5.9 °C, and the annual frost-free period is approximately 150 days. During the rainfall redistribution experiment from 2019 to 2020, a total of 23 rainfall redistribution events were measured with a cumulative rainfall of 678 mm, which accounts for approximately 62% of the total rainfall during the crop growing season. The individual depth of rainfall ranged from 5.6 to 90.4 mm, with an average of 29.5 mm. The rainfall intensity ranged from 0.40 to 20.35 mm h^{-1}, with an average of 4.56 mm h^{-1} (Figure 1).

The corn variety used was ‘Liangyu 66’. The corn seeds were hand-planted at a depth of 5 cm using a hole-driller, with a planting spacing of 28 cm × 60 cm, on 6 May 2019, and 6 May 2020, respectively, with a density of approximately 60,000 plants ha^{-1}. The variety of soybean was ‘Jiyu 47’. Soybean seeds were manually planted at a depth of 5 cm using a hole-driller, with a planting spacing of 8.5 cm × 60 cm, on 16 May 2019 and 15 May 2020, with a density of approximately 200,000 plants ha^{-1}. Each experimental plot was 24 m long and 3 m wide with three replicates, and the testing apparatuses for rainfall redistribution by the crop canopy were arranged in the middle of each test plot.

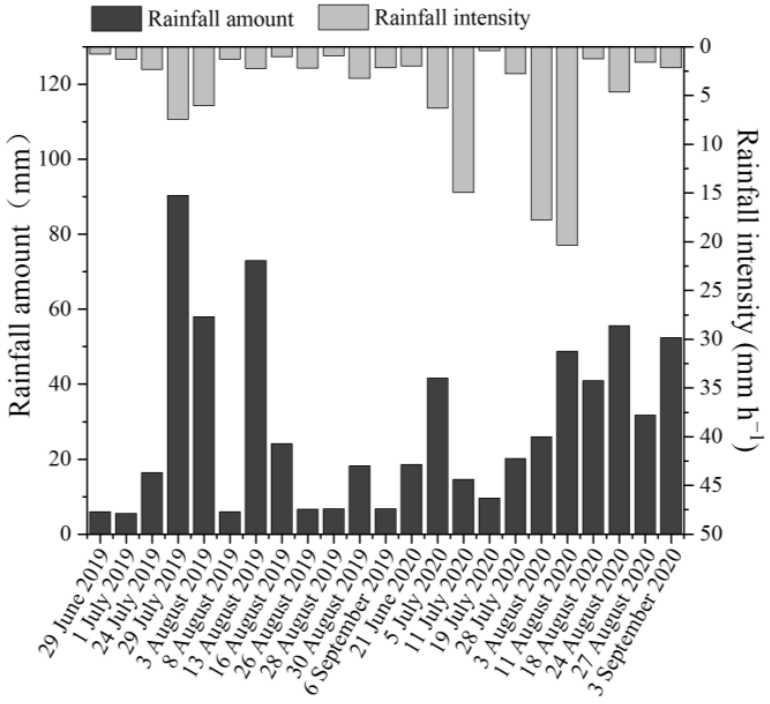


Figure 1. Rainfall depth and rainfall intensity from 2019 to 2020.

2.2. Measurements and Calculations

The rainfall was recorded using a data logging rain gauge (HOBO RG3-M; Onset Computer Corporation, Bourne, MA, USA) near the experimental plots with a one-minute interval and an accuracy of measurement of 0.2 mm. Four collection containers that had an internal diameter of 6 cm and a height of 13 cm were also set up around the experimental plots to measure the volume of rainfall.

The *TF* of each rainfall event was measured by setting throughfall collectors with an internal diameter of 6 cm and height of 13 cm under the crop canopy in each experimental plot (Figure 2). The volume of *TF* was determined manually as the individual rainfall events stopped [20]. The measurement locations of I, II, III, and IV represented different positions parallel to the direction of the planting rows. The measurement locations of A, B, C, D, E, F, G, H, and I represented different positions between the planting rows, the arrangement direction of which was perpendicular to the planting rows. The amount of *TF* was calculated using Equation (1):

$$TF = \frac{\sum_{i=1}^{n} \frac{V_i}{A_g} \times 10}{n} \quad (1)$$

where *TF* is the throughfall depth (mm); n is the number of throughfall collectors under the crop canopy; V_i is the volume of the throughfall in the rainfall measuring containers under the crop canopy (mL); and A_g is the area of the caliber of a throughfall collector (cm^2). The throughfall ratio (*TFR*, %) is defined as the proportion of the *TF* that accounts for the total rainfall amount (*RA*) above the crop canopy.

The *SF* of the crop plants during each rainfall event was obtained by the *SF* collection device shown in Figure 2 [25,26]. The distance was kept to less than 1 cm from the crop stem to the upper edge of the funnel that wrapped around the crop stem and gathered the stem flow. The amount of *SF* was calculated using Equation (2):

$$SF = \frac{V_{SF}}{A_C} \times 10 \quad (2)$$

where SF is the stemflow amount (mm); V_{SF} is the volume of the stemflow (mL); and A_C is the ground area occupied by the crop plant, 8.5 cm × 60 cm for a soybean plant and 28 cm × 60 cm for a corn plant (cm^2). The stemflow ratio (SFR, %) is defined as the proportion of the SF that accounts for the RA above crop canopy.

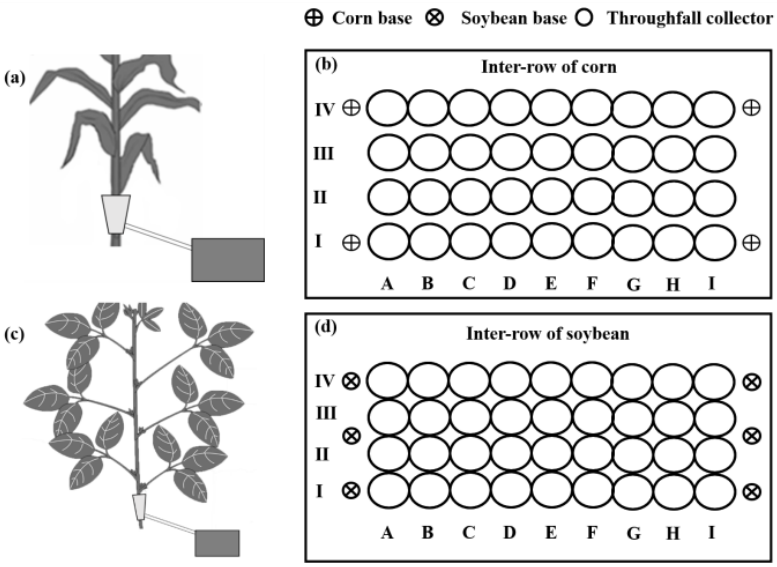


Figure 2. Schematic layouts of (**a**) the corn stemflow, (**b**) throughfall under the corn canopy, (**c**) the soybean stemflow, and (**d**) throughfall under the soybean canopy. A–I were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. I, II, III, and IV represented different positions parallel to the direction of the planting rows.

The CI of crop plants during each rainfall event was obtained using the water balance method [20]. The CI was calculated using Equation (3):

$$CI = RA - TF - SF \quad (3)$$

where CI is the amount of canopy interception loss (mm). The canopy interception ratio (CIR, %) is defined as the proportion of the CI accounted for in the RA above the crop canopy.

Three crop plants in each test plot were randomly selected to determine the leaf area after each rainfall event. The leaf area of corn and soybean plants was measured using a leaf area meter (LI-3000C; LI-COR, Lincoln, NE, USA) and was then used to calculate the leaf area index (LAI, $cm^2\ cm^{-2}$) using Equation (4).

$$LAI = \frac{LA}{A_C} \quad (4)$$

where LAI is the leaf area index ($cm^2\ cm^{-2}$); LA is the total leaf area of an individual crop plant (cm^2); and A_C is the ground area occupied by the crop plant, 8.5 cm × 60 cm for a soybean plant and 28 cm × 60 cm for a corn plant (cm^2).

2.3. Statistical Analyses

The horizontal variability of TF at the row scale under the crop canopy and the differences of TF, SF, and CI between corn and soybean in each rainfall event were analyzed statistically using a one-way analysis of variance (ANOVA). The multiple comparisons of TF among different measurement locations were evaluated using the Bonferroni method. The relationships between TF, SF, or CI and their affecting factors, including rainfall characteristics and LAI, were analyzed using a Pearson correlation [13]. All the descriptive statistics and correlations were performed using SPSS 23.0 (IBM, Inc., Armonk, NY, USA).

Multiple linear regressions were conducted to establish regression models between the rainfall redistribution components and the affecting factors, based on the experimental data from both the corn and soybean treatments in 2019 using SPSS 23.0 (IBM, Inc., Armonk, NY, USA). The regression models were validated using the data from both corn and soybean treatments in 2020. The quality of the multiple regression models was tested using the coefficient of determination (R^2), root mean square error (RMSE), and normalized root mean square error (NRMSE) [20].

3. Results

3.1. Horizontal Variability of Throughfall for Each Rainfall Event in Corn and Soybean Rows

The horizontal variability of the *TF* was identified at the row scale under corn and soybean canopies from 2019 to 2020 (Figures 3 and 4). The *TF* in the middle position between the planting rows was higher than that in the location closest to the planting row. For the individual *TF* events, the difference between the highest and the lowest values of the *TF* among the nine measurement locations (A, B, C, D, E, F, G, H, and I) ranged from 1.5 to 39.4 mm for corn and from 2.4 to 19.2 mm for soybean, from 2019 to 2020. The cumulative *TF* in different locations under the corn canopy ranged from 109 to 245 mm in 2019, and from 150 to 318 mm in 2020, respectively (Figure 5). The cumulative *TF* of different measurement locations under the soybean canopy ranged from 203 to 297 mm in 2019, and from 212 to 349 mm in 2020. The *TF* in measurement location E was the highest for both corn and soybean fields. The cumulative *TF* of the soybean canopy was significantly higher than that of corn in the same measurement location. The mean value of the cumulative *TF* in the nine measurement locations was close to the *TF* of location G in 2019 and the *TF* of locations C and D in 2020, under the soybean canopy. The average of cumulative *TF* in the nine measurement locations for corn was between the *TF* of location B and C in both 2019 and 2020. The *TFR* of individual rainfall events differed in its highest and the lowest values across the nine measurement locations, which ranged from 25.1% to 64.4% for corn and from 15.2% to 91.0% for soybean during the crop growth season from 2019 to 2020 (Figures 6 and 7). The mean *TFR* of several measurement locations from individual rainfall events ranged from 34.3% to 77.1% for corn and from 63.7% to 93.3% for soybean in 2019. During the crop growth season of 2020, the mean *TFR* of several measurement locations from individual rainfall events ranged from 41.5% to 88.2% for corn and from 58.8% to 96.9% for soybean.

In addition, the frequencies of *TF* in each measurement location closest to the mean value of *TF* under the crop canopy were investigated to explore more representative measurement locations (Figure 8). The measurement locations of B, C, and G were the most representative compared to the others, and their rainfall frequency was 29.0%, 24.6%, and 30.4% of the total *TF* events under the corn treatment, respectively. In addition, in 79.7% of the total *TF* events, the mean value of *TF* in the measurement locations of B, C, and G had less than 10% differences relative to the mean *TF* under the corn canopy, from 2019 to 2020. The measurement locations of C and G for soybean were more representative than the others, and their rainfall frequencies were both 33.3% of the total TF events from 2019 to 2020. The mean value of the *TF* in the measurement locations B and C had less than a 10% difference relative to the mean *TF* under the soybean canopy from 2019 to 2020 for 73.9% of the total *TF* events. Therefore, the measurement locations of B, C, and G could be used to collect the *TF* for the corn field, and the measurement locations of B and C could be used for the *TF* collection for the soybean field.

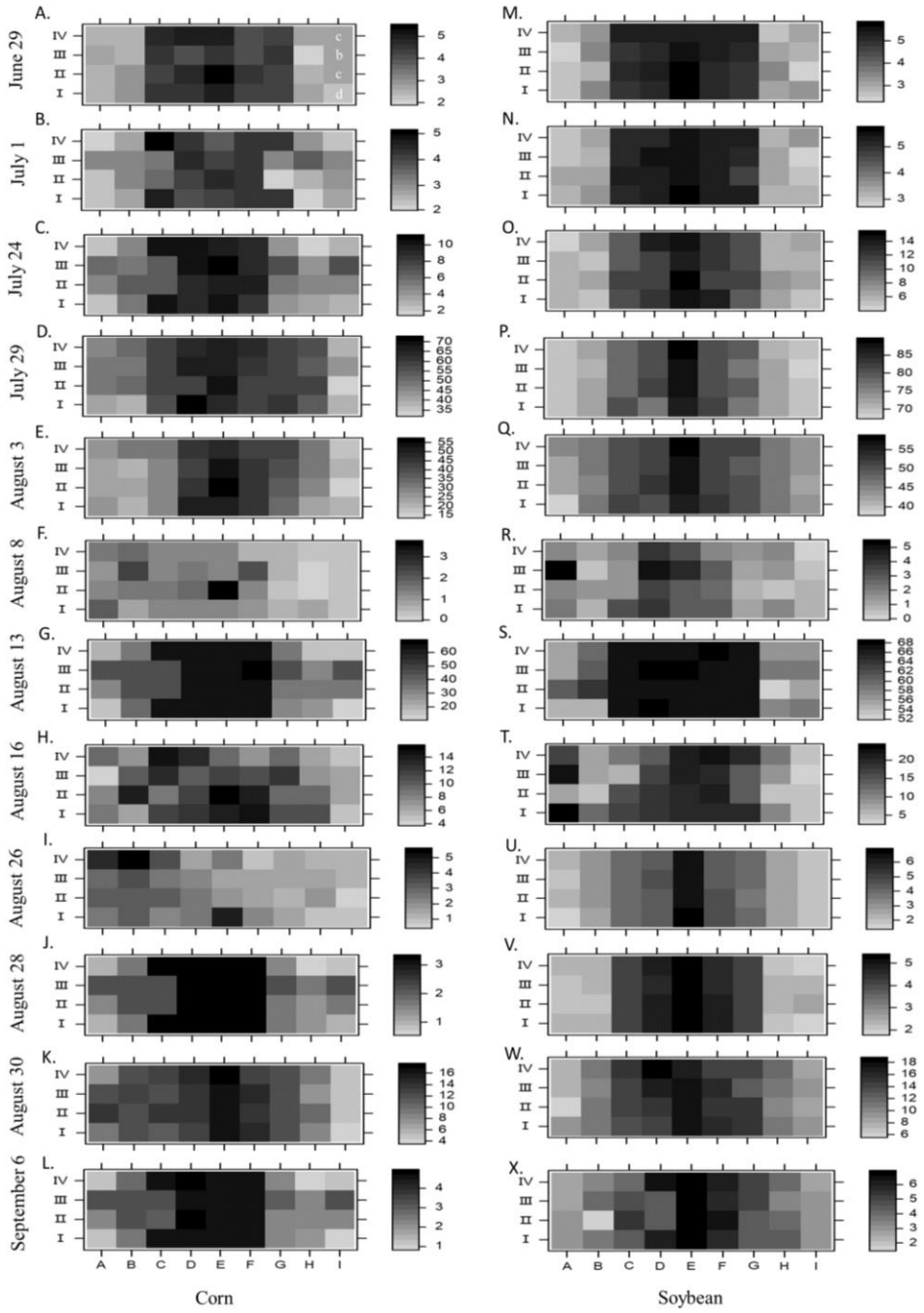


Figure 3. Horizontal variability of the throughfall depth (mm) across the nine measurement locations under the canopies of (**left**) corn and (**right**) soybean in 2019. (A–I) were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. (**A.–X.**) were horizontal variability observations on different dates. I, II, III, and IV represented different positions parallel to the direction of the planting rows.

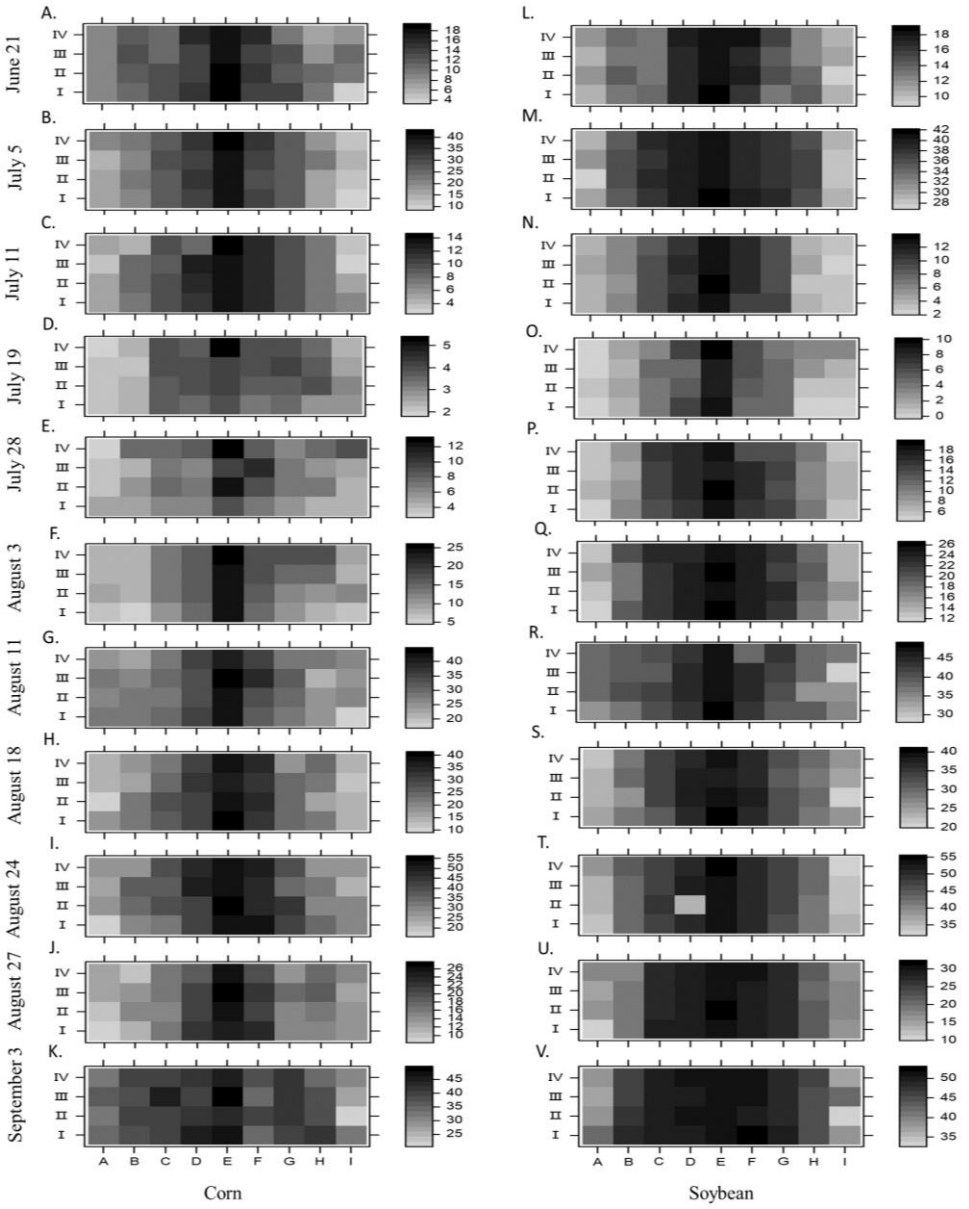


Figure 4. Horizontal variability of throughfall depth (mm) across the nine measurement locations under the canopy of (**left**) corn and (**right**) soybean in 2020. (A–I) were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. (**A.–V.**) were horizontal variability observations on different dates. I, II, III, and IV represented different positions parallel to the direction of the planting rows.

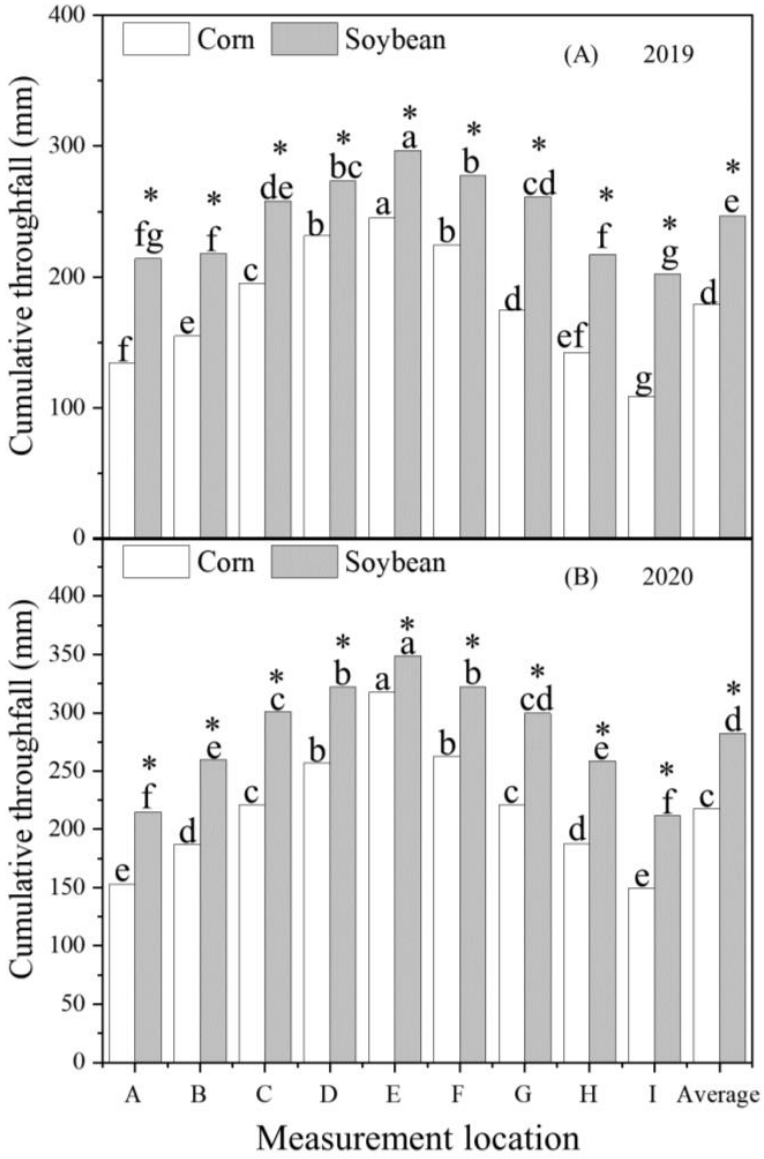


Figure 5. The cumulative throughfall at different measurement locations under corn and soybean canopies from 2019 to 2020. A, B, C, D, E, F, G, H, and I were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. Different lowercase letters indicate significant differences among measurement locations at $p < 0.05$. "*" indicates that the difference reached $p < 0.05$ between the cumulative throughfall under the corn and soybean canopies.

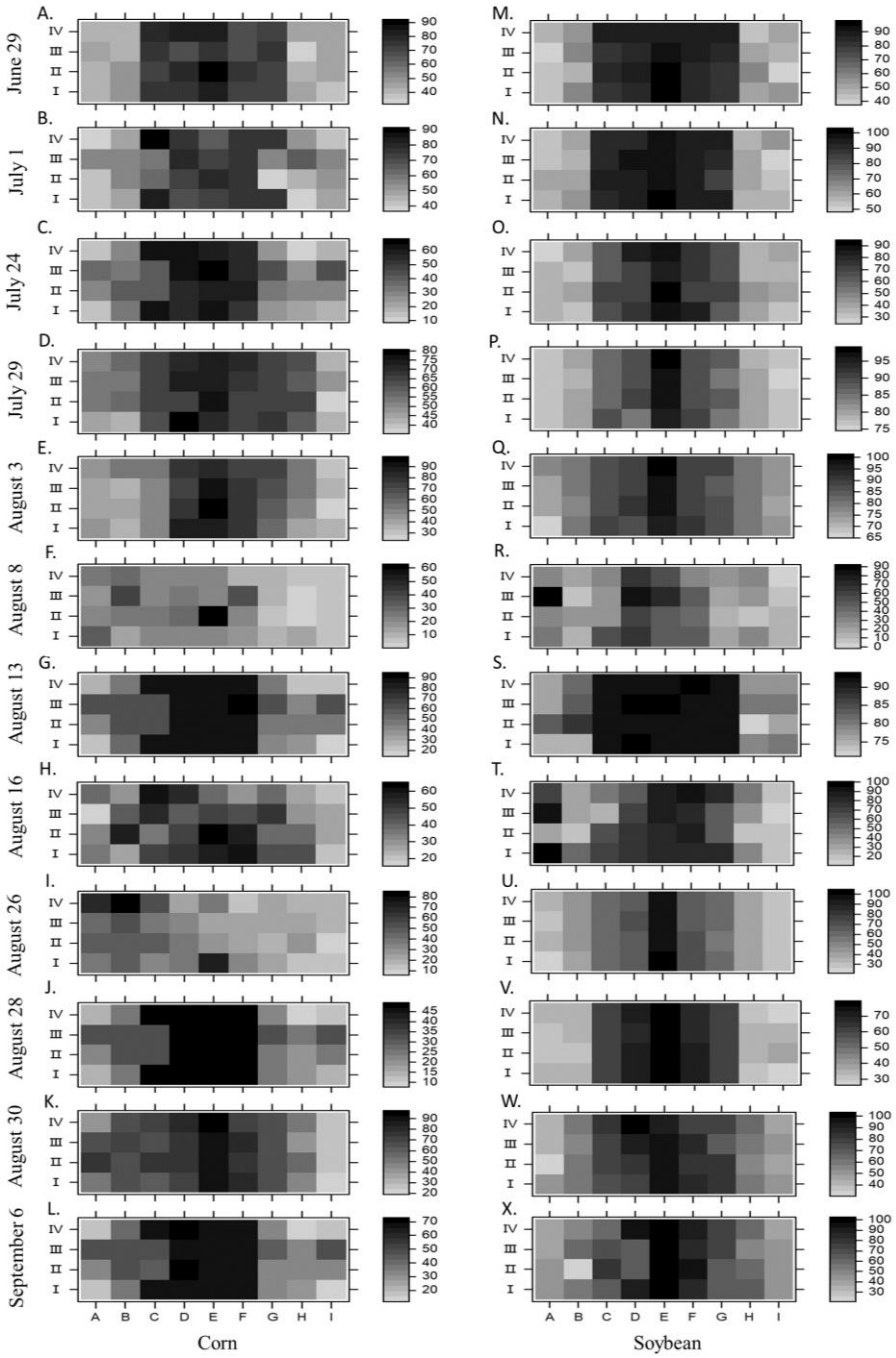


Figure 6. Horizontal variability of the throughfall ratio (%) across the nine measurement locations under the canopy of (**left**) corn and (**right**) soybean in 2019. (A–I) were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. (**A.–X.**) were horizontal variability observations on different dates. I, II, III, and IV represented different positions parallel to the direction of the planting rows.

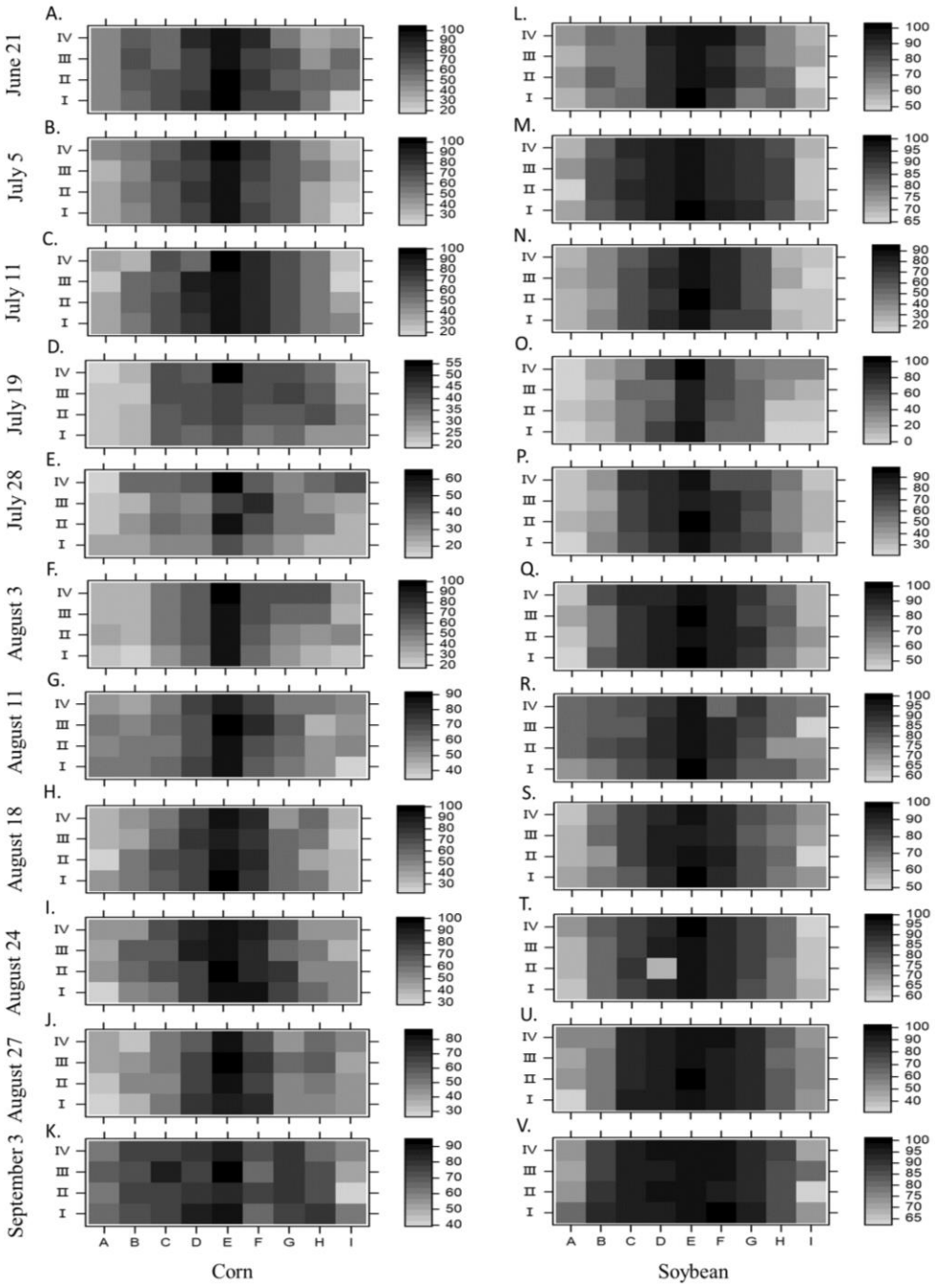


Figure 7. Horizontal variability of the throughfall ratio (%) across the nine measurement locations under the canopy of (**left**) corn and (**right**) soybean in 2020. (A–I) were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. (**A.–V.**) were horizontal variability observations on different dates. I, II, III, and IV represented different positions parallel to the direction of the planting rows.

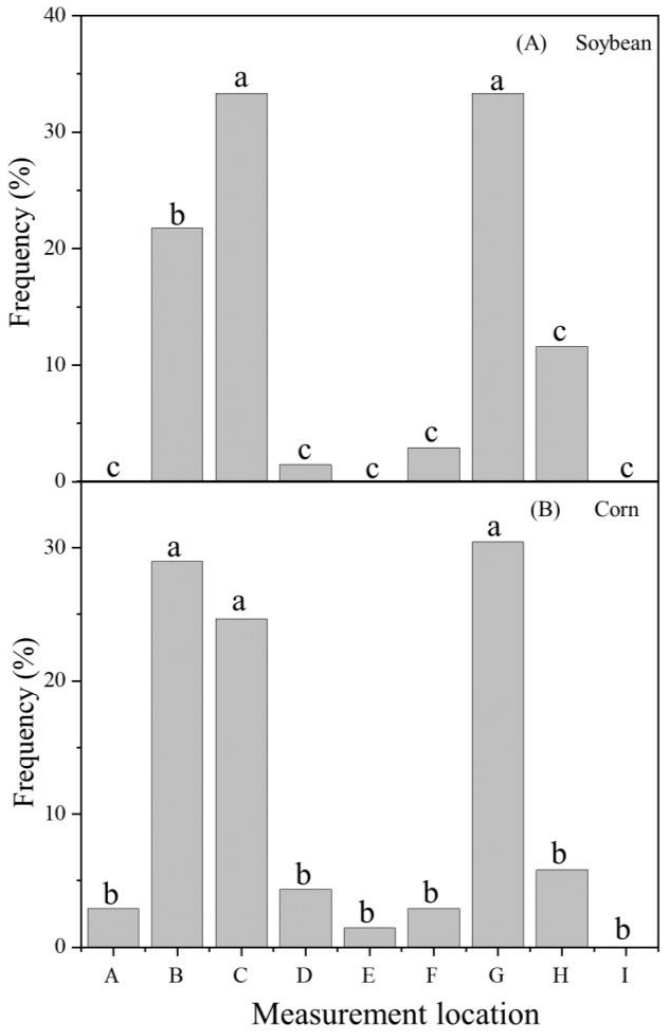


Figure 8. The proportion of individual measurement locations (A, B, C, D, E, F, G, H, and I) that best represented the mean throughfall from all the measurement locations from 2019 to 2020 under (**A**) soybean and (**B**) corn treatments, respectively. A, B, C, D, E, F, G, H, and I were the nine measurement sites distributed horizontally between two planting rows under the crop canopy. Different lowercase letters indicate significant differences between measurement locations at $p < 0.05$.

3.2. Pearson Correlation Coefficients between the TF or TFR of Each Rainfall Event in Corn or Soybean Fields and Its Influencing Factors at Each Measurement Location

The Pearson correlation coefficients between the *TF* in the different measurement locations and the *RA* ranged from 0.95 to 0.98 and from 0.98 to 1.00 for corn and soybeans, respectively (Table 1). The *TF* in several locations under the soybean canopy had a significantly positive correlation with the *RI*. The TF in the measurement locations A, E, G, H, and I under the corn canopy had a significantly positive correlation with the *RI*. The Pearson correlation coefficients between the *TF* and *LAI* in different measurement locations did not reach the level of significance. The *TFR* in the different measurement locations under the corn canopy had a positive relationship with the *RA* at the 0.01 level. The *TFR* under the soybean canopy had a positive relationship with the *RA* at the 0.05 level in the measurement location E and at the 0.01 level in other measurement locations. The *TFR* in the measurement locations E, F, G, H, and I under the corn canopy and that of B under the soybean canopy positively correlated with the *RI* at the 0.05 level. The Pearson correlation coefficients between the *TF* in different measurement locations and *LAI* reached a significant level with the exceptions of the measurement location H under the corn canopy and A under the soybean canopy.

Table 1. Pearson correlation coefficients between the throughfall or throughfall ratio in different locations under the corn or soybean canopy and the rainfall amount, rainfall intensity, or leaf area index (n = 69).

Location	Rainfall Amount		Rainfall Intensity		Leaf Area Index	
	Corn	Soybean	Corn	Soybean	Corn	Soybean
			Throughfall			
A	0.95 **	0.99 **	0.27 *	0.25 *	0.14	0.13
B	0.96 **	0.99 **	0.21	0.27 *	0.09	0.07
C	0.98 **	0.99 **	0.21	0.25 *	0.15	0.10
D	0.98 **	0.99 **	0.22	0.26 *	0.17	0.10
E	0.98 **	1.00 *	0.29 *	0.27 *	0.18	0.13
F	0.98 **	1.00 **	0.23	0.25 *	0.18	0.10
G	0.97 **	0.99 **	0.27 *	0.25 *	0.14	0.10
H	0.95 **	0.99 **	0.26 *	0.25 *	0.16	0.07
I	0.96 **	0.98 **	0.28 *	0.24 *	0.14	0.12
			Throughfall ratio			
A	0.40 **	0.71 **	0.16	0.19	−0.35 **	−0.15
B	0.37 **	0.73 **	0.04	0.32 **	−0.52 **	−0.33 **
C	0.39 **	0.56 **	0.09	0.22	−0.49 **	−0.33 **
D	0.52 **	0.41 **	0.19	0.18	−0.41 **	−0.33 **
E	0.47 **	0.30 *	0.39 **	0.19	−0.31 *	−0.32 **
F	0.48 **	0.46 **	0.24 *	0.18	−0.33 **	−0.43 **
G	0.46 **	0.53 **	0.27 *	0.21	−0.36 **	−0.33 **
H	0.54 **	0.71 **	0.30 *	0.24	−0.19	−0.33 **
I	0.44 **	0.75 **	0.22	0.23	−0.36 **	−0.24 *

Notes: "*" indicates that the correlation reaches the $p < 0.05$ level. "**" indicates that the correlation reaches $p < 0.01$. A, B, C, D, E, F, G, H, and I were the nine measurement sites distributed horizontally between two planting rows under the crop canopy.

3.3. Comparisons of the Average TF, SF, or CI of Each Rainfall Event between Corn and Soybean Fields

The 9-location average *TF* of each rainfall event under the crop canopy ranged from 1.2 to 55.4 mm for corn and from 2.1 to 76.3 mm for soybean, with an average value of 14.9 mm for corn and 20.5 mm for soybean in 2019 (Figure 9). The *TFR* of individual rainfall events under the crop canopy ranged from 20.2% to 64.3% for corn and from 34.9% to 85.8% for soybean, with an average of 56.3% for corn and 77.4% for soybean during 2019. In 2020, the *TF* of individual rainfall events under the crop canopy ranged from 3.3 to 38.5 mm for corn and from 3.8 to 46.8 mm for soybean, with an average value of 19.8 mm for corn and 25.7 mm for soybean in 2020. The *TFR* of individual rainfall events under the crop canopy ranged from 33.7% to 73.4% for corn and from 39.6% to 89.3% for soybean, with an average of 60.4% for corn and 78.3% for soybean during 2020. For individual throughfall events, the proportion of *TF* that accounted for the gross rainfall for soybean was always greater than the proportion of *TF* relative to the gross rainfall under the corn treatment, except for an event on August 30, 2019. The total amount of *TF* under the soybean canopy was 246 mm in 2019 and 282 mm in 2020, which was 137.4% in 2019 and 129.8% in 2020 of the *TF* under the corn canopy.

The *SF* of each rainfall event ranged from 0.4 to 31.2 mm for corn and from 0.3 to 7.3 mm for soybean, with an average value of 8.1 mm for corn and 2.0 mm for soybean in 2019 (Figure 10). The *SFR* of individual rainfall events ranged from 6.5% to 39.1% for corn and from 4.3% to 15.0% for soybean, with an average value of 30.6% for corn and 7.6% for soybean during 2019. In 2020, the *SF* of individual rainfall events ranged from 4.0 to 15.2 mm for corn and from 1.1 to 4.6 mm for soybean, with an average value of 9.7 mm for corn and 2.5 mm for soybean (Figure 10). The *SFR* of individual rainfall events ranged from 20.2% to 45.0% for corn and from 5.0% to 23.4% for soybean, with an average value of 29.7% for corn and 7.5% for soybean during 2020. For individual *SF* events, the proportion of *SF* that accounted for the gross rainfall under the corn canopy was always higher than the proportion under the soybean canopy, with the exception of the event on 6 September, 2019. The total amount of *SF*

under the soybean canopy was 24.0 mm in 2019 and 26.9 mm in 2020, which was 24.7% in 2019 and 25.2% in 2020 of the *SF* under the corn canopy.

The *CI* of each rainfall event ranged from 1.6 to 5.7 mm for corn and from 0.8 to 7.6 mm for soybean, with an average of 3.5 mm for corn and 4.0 mm for soybean in 2019 (Figure 11). The *CIR* of individual rainfall events by crop canopy ranged from 4.2% to 55.9% for corn and from 7.5% to 57.2% for soybean, with an average of 13.1% for corn and 15.0% for soybean during 2019. In 2020, the *CI* of individual rainfall events by crop canopy ranged from 1.6 to 5.6 mm for corn and from 3.0 to 7.3 mm for soybean, with an average of 3.3 mm for corn and 4.7 mm for soybean. The *CIR* of individual rainfall events by crop canopy ranged from 5.9% to 27.7% for corn and from 5.7% to 45.4% for soybean, with an average of 10.0% for corn and 14.2% for soybean. Rainfall events for corn and soybean that had no significant difference in their *CI* occurred five times. Four rainfall events that affected the *CI* of the corn canopy were significantly higher than those of the soybean canopy. The total amount of *CI* in the soybean canopy was 47.8 mm in 2019 and 51.1 mm in 2020, which was 115.1% in 2019 and 142.7% in 2020 of the *CI* under the corn canopy.

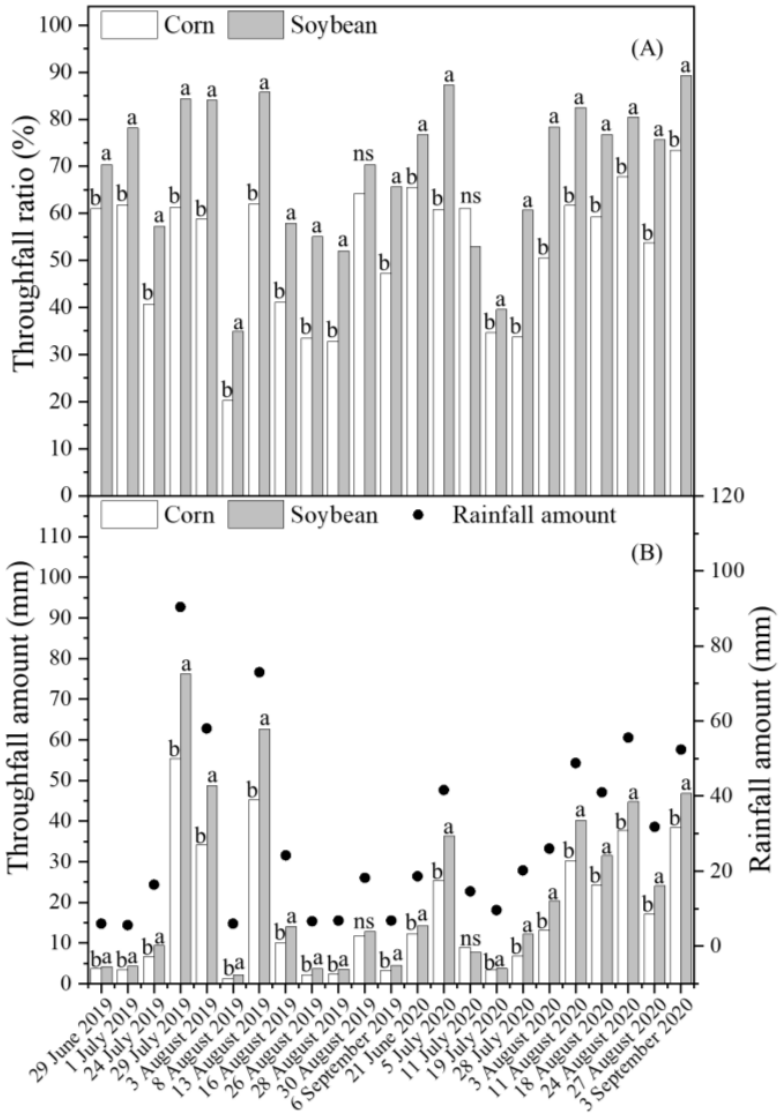


Figure 9. Characteristics of the throughfall ratio (**A**) and throughfall amount (**B**) under corn and soybean canopies from 2019 to 2020. Different lowercase letters indicate significant differences between the corn and soybean treatments at $p < 0.05$. "ns" indicates no significant differences between the corn and soybean treatments at $p < 0.05$.

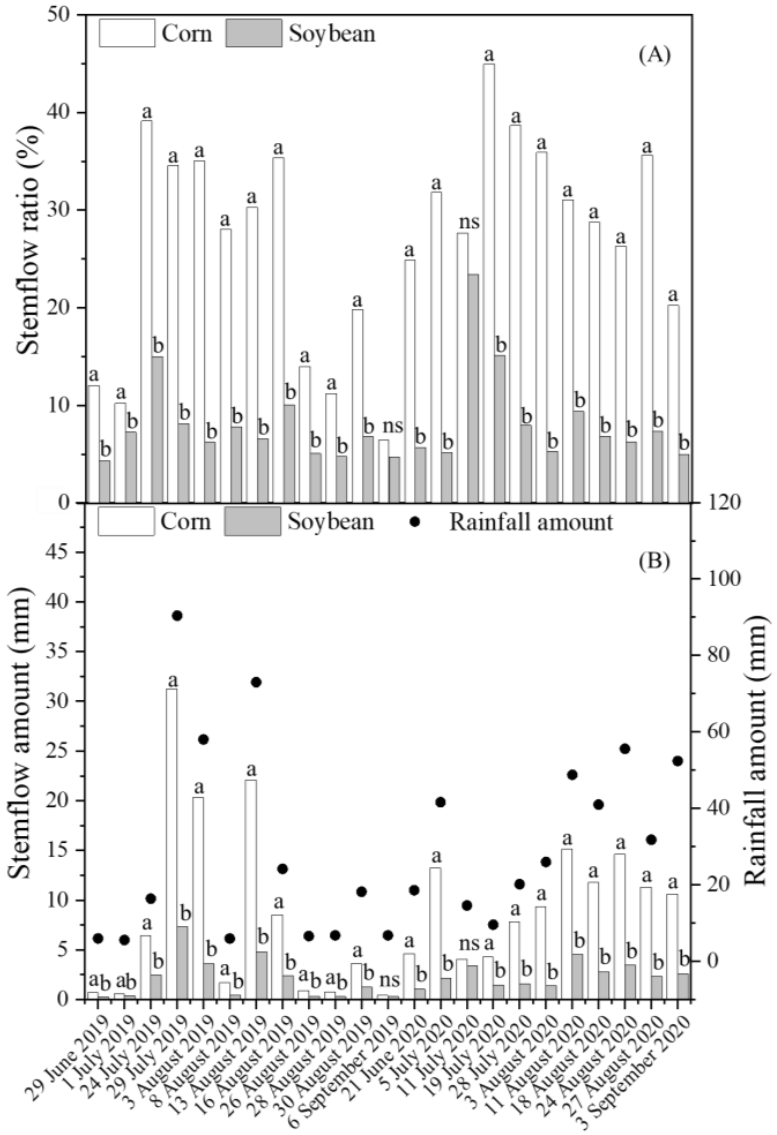


Figure 10. Characteristics of the stemflow ratio (**A**) and stemflow amount (**B**) of corn and soybean from 2019 to 2020. Different lowercase letters indicate significant differences between the corn and soybean treatments at $p < 0.05$. "ns" indicates no significant differences between the corn and soybean treatments at $p < 0.05$.

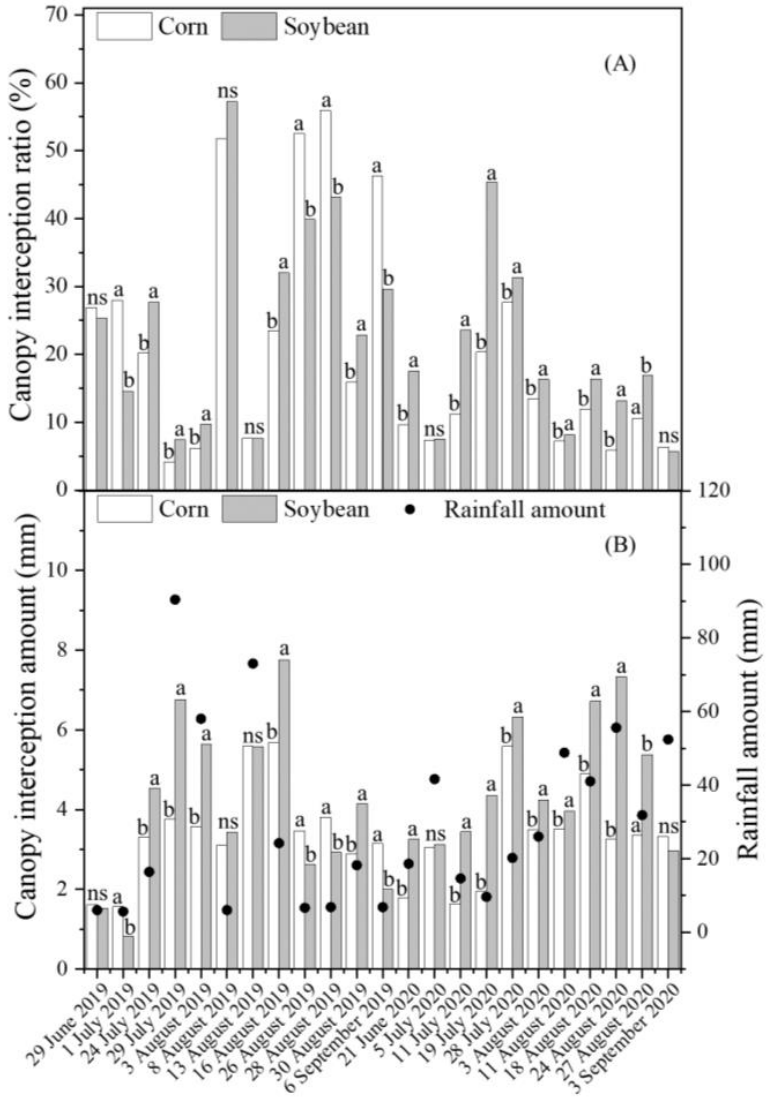


Figure 11. Characteristics of the canopy interception ratio (**A**) and canopy interception amount (**B**) of corn and soybean from 2019 to 2020. Different lowercase letters indicate significant differences between the corn and soybean treatments at $p < 0.05$. "ns" indicates no significant differences between the corn and soybean treatments at $p < 0.05$.

3.4. The Relationship and Models between the Average TF, Average TFR, SF, SFR, CI or CIR and Their Influencing Factors in Corn or Soybean Fields

The 9-location average *TF* had a positive relationship with the *RA*, and the Pearson correlation coefficient between the 9-location average *TF* and *RA* reached 0.99 for corn and 1.0 for soybean (Table 2). The 9-location average *TFR* had a positive relationship with the *RA* at the 0.01 level, and the Pearson correlation coefficient between the 9-location average *TFR* and *RA* was 0.54 for corn and 0.70 for soybean. The 9-location average *TFR* of corn had a negative correlation with the *LAI* at the 0.01 level, and the Pearson correlation coefficient between the 9-location average *TFR* and *LAI* was −0.43 for corn and −0.37 for soybean. There was a positive correlation between the *SF* and *RA*, and the Pearson correlation coefficients were larger than 0.90 for both corn and soybean. The *SF* of corn had a positive relationship with the *LAI* at the 0.01 level, but the correlation between the *SF* and *LAI* did not reach the 0.05 level when the soybeans were cultivated. A significantly positive correlation was identified between the *SFR* and *LAI* in both the corn and soybean treatments. A significant correlation was found between *CI* and RA with a Pearson correlation coefficient of 0.40 for corn and 0.55 for soybean. The *CI* in the canopy

had a positive correlation with *LAI* at the 0.01 level, and the Pearson correlation coefficient was 0.47 for corn and 0.35 for soybean. The *CIR* had a negative correlation with the *RA* at the 0.01 level, and the Pearson correlation coefficient between the *CIR* and *RA* reached −0.70 for corn and −0.72 for soybean. There was a negative relationship between the *CIR* and *RI* with a Pearson correlation coefficient of −0.38 for corn and −0.37 for soybean.

Table 2. Pearson correlation coefficients between rainfall redistribution and the rainfall amount, rainfall intensity, or leaf area index (n = 69).

Item	Crop Type	*TF*	*SF*	*CI*	*TFR*	*SFR*	*CIR*
RA	Corn	0.99 **	0.97 **	0.40 **	0.54 **	0.37 **	−0.70 **
	Soybean	1.00 **	0.90 **	0.55 **	0.70 **	−0.14	−0.72 **
RI	Corn	0.25 *	0.29 *	−0.08	0.26 *	0.24 *	−0.38 **
	Soybean	0.26 *	0.40 **	0.03	0.26 *	0.28 *	−0.37 **
LAI	Corn	0.16	0.39 **	0.47 **	−0.43 **	0.65 **	−0.05
	Soybean	−0.05	0.17	0.35 **	−0.37 **	0.36 **	0.30 *

Notes: "*RA*" is the gross rainfall amount, mm. "*RI*" is the rainfall intensity, mm h^{-1}. "*LAI*" is the leaf area index, cm^2 cm^{-2}. "*TF*" is the throughfall amount, mm. "*SF*" is the stemflow amount, mm. "*CI*" is the amount of canopy interception loss, mm. "*TFR*" is the throughfall ratio, %. "*SFR*" is the stemflow ratio, %. "*CIR*" is the canopy interception ratio, %. "*" indicates that the correlation reaches $p < 0.05$. "**" indicates that the correlation reaches $p < 0.01$.

The multiple linear regression method was used to establish models between the rainfall components of each rainfall event and their influencing factors in corn and soybean fields (Table 3). The R^2 values of the fitted equations were higher than 0.85 for the 9-location average *TF* and *SF*. The *p*-values of the fitted equations were all below 0.05, with the exception of the soybean *SFR*, with a determinant coefficient of 0.448 and a *p*-value of 0.171.

Table 3. Multiple linear regression analysis of rainfall redistribution with regard to the rainfall amount, rainfall intensity, and leaf area index for corn and soybean using the measured results from 2019.

	Regression Equation	R^2	*p*
Corn	$CI = 0.033RA - 0.524\ RI + 1.278\ LAI - 1.169$	0.687	0.020
	$TF = 0.649RA + 0.262RI - 2.580LAI + 7.341$	0.997	<0.001
	$SF = 0.318\ RA + 0.263RI + 1.301LAI - 6.173$	0.992	<0.001
	$CIR = -0.533RA - 0.963\ RI + 7.248\ LAI + 15.783$	0.629	0.039
	$TFR = 0.435RA + 2.125\ RI - 23.205\ LAI + 124.355$	0.771	0.006
	$SFR = 0.098RA - 1.162\ RI + 15.921LAI - 40.138$	0.765	0.007
Soybean	$CI = 0.033RA + 0.146RI + 0.796LAI - 0.053$	0.677	0.023
	$TF = 0.901RA + 0.124RI - 1.016LAI + 1.480$	0.997	<0.001
	$SF = 0.065RA + 0.022RI + 0.219LAI - 0.897$	0.955	<0.001
	$CIR = -0.475RA - 1.806\ RI + 5.514\ LAI + 13.914$	0.692	0.019
	$TFR = 0.505\ RA + 1.265\ RI - 7.188\ LAI + 86.041$	0.769	0.006
	$SFR = -0.031RA - 0.179\ RI + 1.673\ LAI + 0.045$	0.448	0.171

Notes: "*RA*" is the gross rainfall amount, mm. "*RI*" is the rainfall intensity, mm h^{-1}. "*LAI*" is the leaf area index, cm^2 cm^{-2}. "*TF*" is the throughfall amount, mm. "*SF*" is the stemflow amount, mm. "*CI*" is the amount of canopy interception loss, mm. "*TFR*" is the throughfall ratio, %. "*SFR*" is the stemflow ratio, %. "*CIR*" is the canopy interception ratio, %.

The NRMSEs of *TF* for corn and soybean between the predicted and observed values were all below 15.0% (Table 4). The NRMSEs of the *TF* and *TFR* for corn and soybean between the predicted and observed values were all below 25.0%. The results indicated that the quality of the simulation of *TF* and the *TFR* for corn and soybean was excellent. The NRMSEs of the *SF* for corn and soybean between the predicted and observed values were 30.8% and 32.8%, respectively. The NRMSEs of the *CIR* for corn and the *CI*, *SF*, *CIR*, and *SFR* for soybean were all higher than 30.0%, and the results indicated the high quality

of the simulation for the *SF* for corn and soybean, whereas those for the *CI*, *CIR*, and *SFR* of corn and soybean were poor.

Table 4. The root mean square error (RMSE) and normalized root mean square error (NRMSE) for rainfall redistribution under the corn and soybean canopies, as predicted by multiple liner regression.

Crop	*TF*	*SF*	*CI*	*TFR*	*SFR*	*CIR*
	RMSE					
	mm			%		
Corn	2.4	3.0	3.6	13.3	15.6	11.3
Soybean	2.5	0.8	2.4	12.9	6.9	12.8
	NRMSE					
	%			%		
Corn	12.0	30.8	111.8	23.4	49.5	94.5
Soybean	9.8	32.8	51.1	17.7	75.3	69.7

Notes: "*TF*" is the throughfall amount, mm. "*SF*" is the stemflow amount, mm. "*CI*" is the amount of canopy interception loss, mm. "*TFR*" is the throughfall ratio, %. "*SFR*" is the stemflow ratio, %. "*CIR*" is the canopy interception ratio, %.

4. Discussion

4.1. Horizontal Variability of TF at the Row Scale under Corn and Soybean Canopies

To observe the horizontal distribution of *TF* at the row scale under corn and soybean canopies, four lines (I, II, III, and IV) and nine rows (A, B, C, D, E, F, G, H, and I) of *TF* collectors, for a total of 36, were arranged between the two planting rows of crops (Figure 2). The results identified the horizontal variability of *TF* at the row scale under the crop canopy. The proportion of rainfall events that revealed differences among the average *TF*s of the measurement locations of I, II, III, and IV were 21.7% for corn and 8.7% for soybean, accounting for the total rainfall redistribution events from 2019 to 2020. Differences existed among the measurement locations through to I, under the planting conditions of both corn and soybean, during each rainfall redistribution event. Therefore, the horizontal variability of the *TF* among different locations between the planting rows could not be ignored. The average value of the *TF* in location E was higher than that in other locations for both corn and soybean. The *TF* in locations B, C, and G of the corn was the closest to the average level of field. The *TF* in locations C and G of the soybean was the closest to the average level of the field. In addition, the horizontal variability of the *TF* at the row scale could lead to an inconsistent distribution of rainfall energy under the crop canopy, and this could affect soil erosion under the crop canopy. Alternatively, the rainfall redistribution by crop canopy and the horizontal variability of *TF* at the row scale could also cause the nonconformity of the soil water content [21]. Therefore, the horizontal variability of *TF* at the row scale is highly important. The horizontal distribution of rainfall energy at the row scale under the crop canopy, and the relationship between rainfall redistribution and the soil water content, should be studied more closely in the future.

4.2. The Effect of the Crop Canopy on TF, SF, and CI

Rainfall redistribution by the crop canopy is a crucial eco-hydrological process of farmland that cannot be neglected [27,28]. The characteristics of throughfall, stemflow, and canopy interception loss in corn fields were the focus of past research on the rainfall redistribution in farmland, and the research results varied with the experimental settings, including the crop types, observing periods, and rainfall conditions [20,22,29]. To contrast the characteristics of corn and soybean under the conditions of natural rainfall in northeast China, a two-year field experiment about the rainfall redistribution of corn and soybean canopies was conducted from 2019 to 2020. The average *CI*, *TF*, and *SF* of the 23 rainfall redistribution events under the corn canopy were 3.4 mm, 17.2 mm, and 8.9 mm, with the average of *CIR*, *TFR*, and *SFR* at 11.4%, 58.5%, and 30.1%, respectively, from 2019 to 2020. There were some differences between the results in this study and those of Zheng et al. (2018), who observed averages of 12.5% of the *CIR*, 65.2% of the *TFR*, and 22.3% of the *SFR* [20]. The main factors that cause these differences could be the unequal volume of

natural rainfall conditions and corn varieties. The average *CI*, *TF*, and *SF* of the 23 rainfall redistribution events for soybeans were 4.3 mm, 23.0 mm, and 2.2 mm, respectively, with an average *CIR*, *TFR*, and *SFR* of 14.5%, 78.0%, and 7.5%, respectively. Therefore, soybean may cause more invalid losses of rainfall than corn. The variation in the canopy structure across crop types may be the main factor that causes the diversity seen in the rainfall redistribution of different crop canopies. The significant differences between the rainfall redistribution by the corn and soybean canopies were caused by the various plant morphologies and structures of corn and soybean. Corn plants are tall with a strong and straight stem, narrow and large leaves that alternate on both sides of the stem. The unique morphological structure of corn forms a particular trait of rainfall redistribution with a high *SFR*. From the perspective of soil erosion in slope farmland, stemflow is a concentrated flow that is positive at promoting the development of soil erosion on slope farmland [13]. Therefore, rainfall redistribution must be taken into account when studying the water use efficiency, field water management, and dynamic processes of water erosion on farmland. The results in this study could provide a reference for research about the mechanisms of soil erosion on slope farmland. Future studies that investigate the effects of different crop canopies on raindrop kinetic energy, water infiltration characteristics, and soil water content are merited to improve our knowledge about the redistribution of rainfall by the crop canopy.

4.3. The Regression Models for the TF, SF, CI, TFR, SFR and CIR in Corn and Soybean Fields

A model simulation has several advantages in research and production. The development and application of a canopy interception model, such as the Gash model, is used extensively across rainfall distribution simulations [30]. The canopy interception model is widely used in rainfall forestry systems, and its applicability on crop canopy interception simulation is still in the research stage [31]. Models on the throughfall, stemflow, and canopy interception loss in farmland are predominantly statistical models. In this study, the throughfall, stemflow, and canopy interception loss were significantly influenced by the *RA*, *RI*, and *LAI*, which is consistent with the results of Liu et al. (2015) and Zheng et al. (2018) [20,27]. Several models were established to describe the relationship between the throughfall, stemflow, or canopy interception loss and rainfall characteristics in this study. However, only the regression models of the *TF*, *SF*, *TFR*, and *SFR* of corn and those of the *TF*, *SF*, and *TFR* of soybean had a higher determination coefficient (R^2) with a value of more than 0.70. The R^2 of regression models concerning the *SFR* was only 0.448, with a *p*-value of 0.171, for soybean. The NRMSEs of the *TF* and *TFR* of corn and soybean were all lower than 25.0%. The results indicated that these models could provide a reference for the prediction of the *TF*, *SF*, and *CI* in corn and soybean fields. The process of the crop canopy when in contact with rainfall is complex. To obtain more accurate prediction data about the throughfall, stemflow, and canopy interception loss, more parameters for both the plants and rainfall need to be measured and then used to develop mechanistic models for the rainfall redistribution by crop canopy that consider the movement process of raindrops. Therefore, mechanistic models based on the movement and adsorption of rainfall drops on the surface of a crop canopy merit more research in future studies. The results of this study could provide references for the adjustment of cropping patterns, the improvement of efficient irrigation water use, and the prediction of the partitioning of rainfall and irrigation water by a crop canopy in the field.

5. Conclusions

The horizontal variability of throughfall was found at the row scale under corn and soybean canopies. The *TF* in the center between planting rows was higher than that in other measurement locations for both corn and soybean, and the mean *TF* of the measurement locations B, C, and G under the corn canopy and that of measurement locations B and C under the soybean canopy could represent the mean level of the *TF* in the corn and soybean fields, separately. The *TF*, *SF*, and *CI* in soybean field accounted for approximately 77.4%, 7.6%, and 15.0% of the total gross rainfall in 2019, whereas they were 137.4%, 24.7%, and

115.1% of the *TF*, *SF*, and *CI* in the corn field, respectively. The *TFR*, *SFR*, and *CIR* in the soybean field were 78.3%, 7.5%, and 14.2% of the total gross rainfall in 2020, respectively, whereas they were 129.8%, 24.2%, and 142.7% of *TF*, *SF*, and *CI* in the corn field, respectively. The *CI* and *TF* in the soybean field increased by 27.4% and 33.3% compared with those in the corn field, and the *SF* of soybean decreased by 75.0% compared with that of corn, from 2019 to 2020. The *CIR* decreased with an increase in the *RA* and *RI*. The *TFR* increased with an increase in the *RA* and *RI* and was negatively correlated with the *LAI*. The *SFR* was positively correlated with the *LAI*. Linear regression models could predict the *TF*, *SF*, and *CI* in corn and soybean fields, and the quality of the simulation of *TF* and *TFR* for corn and soybean was excellent.

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