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Soil splash detachment and its spatial distribution under corn and soybean cover

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ABSTRACT

To evaluate the effects of splash erosion on crops, throughfall and splash detachment were measured in different crop-growth stages and rainfall intensities under corn and soybean cover. The relation between splash detachment under the crop canopy and leaf area index and throughfall intensity was analyzed. The characteristics of the spatial distribution of splash detachment under the crop canopy were discussed as well. The results indicated that, compared with bare soil, the average splash detachment rate under the canopy during corn growth was reduced from 77% to 43%, with an average of 68% approximately, while a soybean canopy can reduce the splash detachment rate from 77% to 48% with an average of 61% approximately during the growth stage. The splash erosion detachment rate increased significantly with increasing leaf area index and rainfall intensity. The throughfall was concentrated in the centers of rows as crop grows, and a sharp increase in the splash detachment rate was caused by concentrations of throughfall under the canopy, which resulted in uneven distribution of splash detachment. The spatial distributions of splash detachment depended on the spatial distributions of throughfall under the crop canopy. The change in throughfall intensity under the canopy was the main reason for the variation in splash detachment. The reduction of kinetic energy because of interception by the crop canopy contributed to a decrease in splash erosion. However, large raindrops formed at the tips and edges of leaves can generate substantial erosion, and this part of the splash may become the main portion of splash erosion under the canopy. These results indicated that continuous and concentrated raindrops impacted splash detachment and caused its uneven distribution under crop cover.

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1. Introduction

Splash erosion is a process of detachment and transportation of soil which is caused by the impact of raindrops reaching the soil surface. It happens mainly before runoff starts or at the beginning of runoff (Zheng et al., 2008). The impact of raindrops detaches the soil, destroys soil structure, increases runoff turbulence, and enhances the detaching and transporting capacity of surface flow. It makes a great contribution to the development of sheet erosion (Zhu, 1981). Splash erosion is also an important component of the soil-erosion process. Law and Sreenivas started the study of splash erosion as early as the 1940s, after which many researchers developed similar discussions (Law and Parsons, 1943; Sreenivas et al., 1947). Some of their results linked splash intensity with factors such as cover, slope, soil erosion propensity, and physical parameters of rainfall (Liu et al., 2011; Ma et al., 2010; Miao et al., 2011; Zheng et al., 2009; Zhou et al., 2008, 2009). Typically, the higher the speed at which raindrops hit the soil, the more soil is splashed; the larger the diameter of raindrops, the bigger will be the impact area, and higher rainfall intensity means more erosion (Guo, 1997; Han et al., 2010; Morgan, 1982; Moss and Green, 1987; Zheng et al., 2008). The relationship between splash erosion and rainfall physical parameters can be described using rainfall kinetic energy and momentum (Gao and Bao, 2001; Jiang et al., 1983; Law and Parsons, 1943; Mou, 1983; Xu, 1983; Zhang et al., 2002).

The effect of crops on splash erosion was different from that of forest and grassland because of the special environment and of human management in the crop growth stage. Sreenivas et al. (1947) was one of the earliest researchers studying splash erosion under crop cover. He found that splash intensity decreased with increasing canopy density and decreasing canopy height. However, Morgan (1982) presented different opinions after further research. He suggested that there was a complex relation between rainfall energy and splash erosion. He supported the conclusion that the reduction in the value of rainfall energy was not proportionate to the amount of interception by the crop

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canopy. The effect of crops on splash was mainly dominated by changes in throughfall intensity, the diameter distribution of water drops under the canopy, and throughfall energy. He also noted that the effect of crops on splash was changed not only by rain characteristics, but also by crop coverage, surface soil crust, rainfall intensity, and various other factors must be considered while evaluating the effects of crops on splash erosion. With further research, Noble and Morgan (1983) discovered that the proportion of large raindrops forming at the edges of kale leaves (*Brassica oleracea* Linnaeus) to total rainfall did not correspond to their effects on splash detachment and that the effects were not proportionate. Finney (1984) believed that as crops like kale, beets (*Beta vulgaris* Linn.), and potatoes (*Solanum tuberosum* L.) grew, the increase in canopy interception would make throughfall decrease, but that dripping water from leaf edges would still increase. He concluded that this would result in more drastic splash erosion because of the larger raindrops and the higher energy of dripping water forming at leaf edges in some regions under the crop canopy, although total splash erosion was decreased. After examination of corn and soybeans, Morgan (1985) found that the effects of these two crops on splash erosion were exactly opposite. Splash erosion increased with corn coverage and was about 1.5–2 times the erosion on bare soil when the canopy coverage was greater than 90%. For soybeans, splash decreased as canopy coverage increased, and erosion was only 20%–60% of that on bare land when the canopy coverage became greater than 90%. The growth of the corn canopy enhanced raindrop splash erosion because of the interaction among size of throughfall raindrops, falling distance, and splash erosion; on the other hand, when the falling distance of throughfall raindrops is greater, they may accumulate more energy and strengthen splash (Morgan, 1985). Inside or underneath canopies, there was no splash when the distance was less than 0.3 m. However, as distance increased, erosion ability would increase gradually, and the erosion propensity of raindrops would increase rapidly, especially for raindrops falling from more than two meters high (Moss and Green, 1987). From Morgan's results, splash intensities in different areas under canopies exhibited substantial differences, an observation which also explains the uneven distribution of splash in the space under crop canopies (Ma, 2009; Morgan, 1982, 1985; Noble and Morgan, 1983). Armstrong and Mitchell (1987, 1988) hypothesized that the spatial distribution of throughfall under the canopy was a critical factor for splash erosion. It was assumed that it would strength splash at some locations under crop canopies because of the concentrated distribution of rainfall. They found that the potential splash intensity for a soybean canopy varied from 5% to 304% of that on bare land. The effects of crop canopy on splash erosion are complex, and significant differences exist among crops because of the diversity of their morphological and structural characteristics.

Corn and soybeans are important food and commercial crops on the Loess Plateau. The growth periods of the two crops coincide with the timing of rainstorms. The purpose of this research is to evaluate throughfall, splash erosion, and LAI under crop canopies during different growth stages and to discover the relationships between splash erosion and LAI, throughfall intensity, and rainfall intensity to determine the spatial distribution characteristics of splash erosion with respect to the throughfall distribution. This study will provide the practical basis for water and fertilizer management of cropland as well as for the study of soil erosion, thus making a contribution to further understanding of fundamental erosion process and mechanics.

2. Materials and methods

2.1. General information

The research area is located in Yang Ling, Shanxi Province, which is on the southern edge of the Loess Plateau. Experiments were conducted in the Simulated Rainfall Hall at Northwest A&F University. The simulated rainfall laboratory has been in operation since it was finished in 2005. It has an area of 200 m^2 and a height of 4.5 m. A rainfall simulation system was installed on the ceiling of the lab. The rainfall simulator was designed and constructed by the Institute of Soil and Water Conservation, Yangling, China. The downward-facing sprinkling rainfall simulation system was similar to that used by Jin et al. (2008). Four nozzles were positioned at a drop fall height of 4 m. The rainfall simulator consisted of two 3 m-long sprinkler booms, each positioned 30 cm apart on each sprinkler boom, and two nozzles fixed 1.5 m apart. Different rainfall intensities could be achieved by changing the hydrostatic pressure by moving the valve system horizontally. The mean drop size of the rainfall simulator was 1.8 mm, and the kinetic energy of the rainfall simulator was approximately 75% of that of natural rainfall (Ma, 2009). The effective rainfall area of the simulator was 3 m × 3 m, and rainfall uniformity was >80% as calculated by the following formula using rain gauge.

$$RN = 1 - \frac{\sum_{i=1}^{n} |P_i - \overline{P}|}{n\overline{P}} \quad (1)$$

where RN is the rainfall uniformity (%), P_i is the rain capacity in the ith rain gauge (mm), $\overline{P}$ is the average rain capacity (mm), and n is the number of rain gauges.

2.2. Research design

The corn used in this study was Zhengdan 958 and was started from seed on June 20, 2009. According to the local conditions, the row and plant spacings in cornfields were 60 cm and 25 cm. On each, crop plants were cut at ground level. The crops were grown nearby, so that plants could be taken quickly into the laboratory. The leaf area and the effects on splash erosion under throughfall during the growing season were tested. The soybeans used in the research were Zhonghuang 13 and were started from seed on June 30, 2007 with a planting density of 20 cm × 40 cm. Planting management was conducted according to local custom, and the whole growing period of corn was divided into a seedling stage (V4), an early jointing stage (V6), a middle jointing stage (V9), a late jointing stage (V12), and a tasseling stage (VT) according to the growth and leaf conditions of corn plants. The whole growing period of soybean was divided into an initial blossoming stage (R1), a full flowering stage (R2), an initial pod-filling stage (R4), and a pod-bearing stage (R6). Simulated rainfall was provided during the corn and soybean growing period in each growth stage. The soil used in this study was Eum-Orthic Anthrosol, which is a kind of Cumulic soil in WRB. To avoid wilt during long-duration experiments, the rainfall intensities in each growth stage were 40 mm h^{-1} and 80 mm h^{-1}, with 30 min of rainfall according to the local storm characteristics that are concentrated in summer and autumn. The crop growth, vegetative growth stages and average leaf area for each sample date are shown in Table 1.

2.3. Measurement of throughfall

To test throughfall and splash intensities for the cropland at different places and growing times, eight corn or soybean plants were cut randomly and taken to the laboratory during the observation period. They were fixed on iron stands and placed in the same position as on the cropland to simulate the real spacing conditions outside. The row spacing of corn was 60 cm—the same as actual conditions—and the row length was 100 cm; the row spacing of soybeans was 40 cm, and the row length was 70 cm. Rain gauges 5.5 cm in diameter and 7 cm in height were placed under the crop canopy in a matrix pattern (Fig. 1). With a design rainfall intensity of 30 min, these gauges collected and measured water amounts inside and calculated rainfall intensity at different spots under the canopy.

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Table 1
Corn and soybean growth and vegetative stage at each sampling date.

Crops	Observing date	Growth stage	Symbol	Average plant height, cm	Leaf area, cm^2 $plant^{-1}$	LAI
Corn	2009/7/10	Seedling stage	V4	35	470	0.31
	2009/7/25	Early jointing stage	V6	92	2220	1.48
	2009/8/3	Middle jointing stage	V9	128	4250	2.83
	2009/8/10	Late jointing stage	V12	161	4830	3.22
	2009/8/17	Tasseling stage	VT	215	6470	4.31
Soybean	2007/7/30	Initial blossoming stage	R1	38	1730	2.16
	2007/8/10	Full flowering stage	R2	46	3020	3.77
	2007/8/20	Initial pod-filling stage	R4	76	4170	5.21
	2007/8/28	Pod-bearing stage	R6	79	5210	6.51

2.4. Measurement of splash erosion

Splash cups were used to test splash erosion intensity under the canopy in the same places after every throughfall test. Each splash cup was 5 cm tall with a diameter of 7 cm. Small holes for infiltration were evenly distributed at the bottom of the splash cup. Splash detachment tests using splash cups were performed as proposed by Finney (1984). The height of cup (5 cm) probably had little influence on the results because the plant was high enough (average 35 cm in corn V4 stage, average 38 cm in soybean R1 stage). The soil used in the study was dug from cropland topsoil (Eum-Orthic Anthrosol) and was sifted using 5-mm sieves and then oven-dried at 105 °C until the weight became constant. A piece of filter paper was placed on the bottom of the cup, and the soil in the splash cup was fixed and weighed. Splash cups were placed under the canopy at equal spacings in a matrix pattern (Fig. 1) and exposed to rain for 30 min under the specified rainfall intensity. After the rain, the splash cups were oven-dried and weighed. The difference in the weight of soil in each splash cup before and after artificial rainfall was defined as the splash amount per cup. The splash erosion amount per unit area and per unit time (splash detachment rate, SDR) was calculated according to the splash-cup diameter and the rainfall duration. The splash detachment rate on bare soil was also tested using the same method. Movement of soil into and out to a certain location under crop canopy was a dynamic process during the rainfall. The splash erosion determined in the tests was the final results of this process after rainfall. From this point of view, it appears that neighboring cups had little influence on each other. The rainfall amount and intensity were also determined using a gauge located as shown in Fig. 1. All the steps described above were followed to calculate the intensities of throughfall, rainfall, and splash under design rainfall of 40 mm h^{-1} and 80 mm h^{-1}.

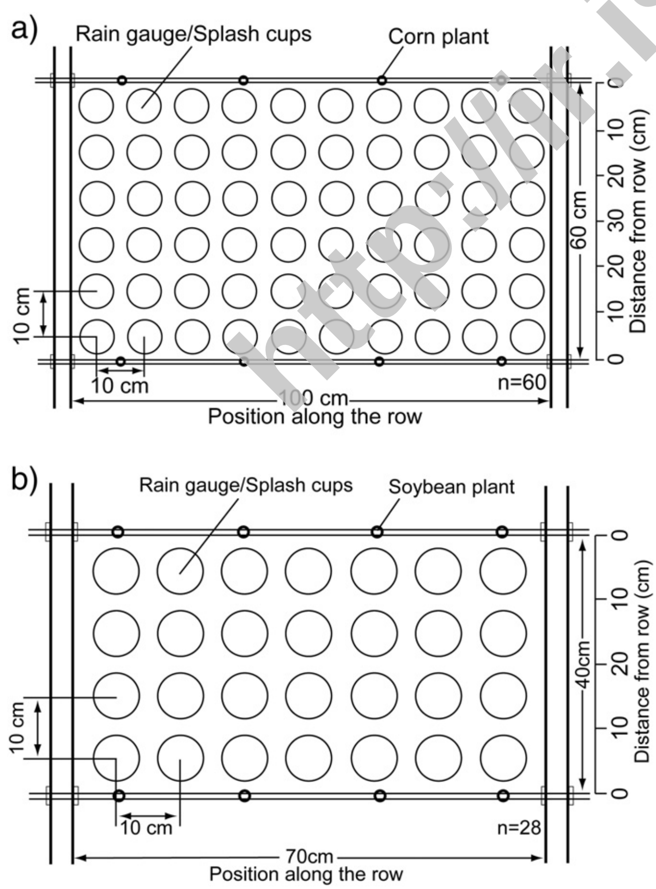

Fig. 1. Schematic diagram of splash detachment under corn (a) and soybean (b) canopies.

2.5. Measurement of leaf area index

After artificial rainfall experiments with crops in different stages, the length–width proportion method was used to measure the leaf area of the corn. Then the total leaf area of single plant was calculated according to Eq. (2):

$$A_L = \sum_{i=1}^{n} (K \times L_i \times W_i) \tag{2}$$

where A_L is the total leaf area of single plant, K is a correction coefficient (0.75), L_i is the length of the ith leaf, W_i is the width of the widest part of the ith leaf, and n is the number of leaves on a single plant.

Soybean leaves were scanned by a scanner at 600 dpi, and then leaf area was measured using Image J.

Ten corn and soybean plants were used to measure the total leaf area of a single plant in each growth stage and to calculate the average value. With the measured leaf area, the average total leaf area on the land could be divided by the total land area to obtain the leaf area index (LAI).

2.6. Statistical analysis and parameter calculation

The IBM SPSS statistics 20.0 (IBM Inc.) software was used to perform statistical analysis of the data. The significance of the effect of LAI, rainfall intensity and throughfall on splash detachment rate was determined using a general linear model ($\alpha = 0.05$). The significance of splash detachment rate at different locations between the rows was determined using a paired t-test ($\alpha = 0.05$).

The reduction coefficient for splash detachment under the crop canopy in Table 2 was calculated according to Eq. (3):

$$\text{Reduction coefficient} = \frac{SDR_{BL} - SDR_{crop}}{SDR_{BS}} \times 100\% \tag{3}$$

where SDR_{BL} is the splash detachment rate on bare land (g m^{-2} h^{-1}), and SDR_{crop} is the splash detachment rate under crop canopy (g m^{-2} h^{-1}).

The contour maps in this paper were drawn using Golden Software Surfer 9 (Golden Software Inc.) to express the distribution of throughfall

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Table 2
Throughfall and splash detachment rate as affected by corn and soybean canopies in different crop growth stages.

Crop	Rainfall intensity, mm h^{-1}	Observation date	Growth stage	Leaf area index	Rainfall intensity above the crop canopy, mm h^{-1}	Average throughfall intensity under the canopy, mm h^{-1}	Splash detachment rate on bare land, mm h^{-1}	Splash detachment rate under crop canopy		Reduction coefficient (%)
								Average splash detachment rate under crop canopy, mm h^{-1}	Coefficient of variation (Cv)	
Corn	40	2009-7-10	V4	0.31	39.85 ± 1.59	37.15 ± 9.56	435.66 ± 20.11	247.77 ± 110.27	0.45	43.13
		2009-7-25	V6	1.48	41.05 ± 1.45	33.73 ± 20.20	410.04 ± 20.81	183.41 ± 226.09	1.24	55.27
		2009-8-3	V9	2.83	40.05 ± 1.75	30.56 ± 29.97	375.87 ± 18.02	125.29 ± 229.47	1.85	66.67
		2009-8-10	V12	3.22	39.77 ± 1.42	24.25 ± 19.25	474.1 ± 21.72	211.87 ± 293.07	1.39	55.31
		2009-8-17	VT	4.31	41.12 ± 1.82	20.29 ± 20.32	444.2 ± 22.32	244.05 ± 527.15	2.18	45.06
	80	2009-7-10	V4	0.31	80.26 ± 2.13	71.58 ± 14.65	1973.57 ± 59.89	748.33 ± 273.04	0.37	62.08
		2009-7-25	V6	1.48	79.85 ± 2.29	64.90 ± 52.09	1914.95 ± 53.09	452.05 ± 683.51	1.52	76.39
		2009-8-3	V9	2.83	80.66 ± 2.53	63.60 ± 74.22	2188.51 ± 84.31	592.06 ± 1122.20	1.91	72.95
		2009-8-10	V12	3.22	81.46 ± 2.29	49.64 ± 51.66	2090.81 ± 53.83	478.74 ± 943.36	1.99	77.10
		2009-8-17	VT	4.31	78.97 ± 2.30	38.56 ± 60.52	1700.01 ± 52.80	520.76 ± 1367.21	2.65	69.37
	Average			2.43	60.3 ± 19.95	43.43 ± 17.10	1200.77 ± 782.04	380.43 ± 195.74	1.56	68.32
Soybeans	40	2007-7-30	R1	2.16	41.25 ± 1.59	33.81 ± 17.42	512.54 ± 17.58	264.56 ± 270.71	1.04	48.38
		2007-8-10	R2	3.77	40.60 ± 1.48	31.82 ± 21.57	469.83 ± 15.30	187.38 ± 252.45	1.37	60.12
		2007-8-20	R4	5.21	39.86 ± 1.42	32.35 ± 21.17	392.95 ± 10.89	132.65 ± 232.05	1.78	66.24
		2007-8-28	R6	6.51	40.24 ± 1.53	30.09 ± 19.85	457.02 ± 12.61	106.68 ± 127.08	1.21	76.66
	80	2007-7-30	R1	2.16	79.86 ± 2.18	65.39 ± 28.92	2344.84 ± 84.49	976.99 ± 1143.30	1.19	58.33
		2007-8-10	R2	3.77	81.56 ± 2.63	70.33 ± 28.84	2149.43 ± 75.19	919.29 ± 1139.24	1.26	57.23
		2007-8-20	R4	5.21	80.24 ± 2.46	67.38 ± 37.09	1856.33 ± 61.55	744.53 ± 893.85	1.22	59.89
		2007-8-28	R6	6.51	80.66 ± 2.30	61.40 ± 44.02	1797.71 ± 75.10	584.42 ± 794.24	1.38	67.49
	Average			4.41	60.53 ± 20.05	49.07 ± 17.23	1247.58 ± 805.53	489.56 ± 337.67	1.31	60.76

intensity and splash detachment rate at various locations under the crop canopy.

3. Results and analysis

3.1. Throughfall and splash detachment rate under the crop canopy

The observed values of throughfall intensity and splash detachment rate under the crop canopy for different growth periods and rainfall intensities are shown in Table 2.

The average splash detachment rate under the crop canopy during the whole growth stage was lower than that on bare land. The analysis of variance showed a significant difference in splash detachment rate between crop field and bare land at the 0.01 level; there was an extremely significant difference between splash detachment rate and rainfall intensity ($p < 0.01$), but no significant difference between splash detachment rate and LAI ($p > 0.05$). The average splash detachment rates for corn under rainfall of 40 mm h^{-1} and 80 mm h^{-1} were 202.48 g m^{-2} h^{-1} and 558.39 g m^{-2} h^{-1} respectively, a reduction of 53.09% and 71.58% compared with bare land. The average splash detachment rates for soybeans under rainfall of 40 mm h^{-1} and 80 mm h^{-1} were 172.82 g m^{-2} h^{-1} and 806.31 g m^{-2} h^{-1} respectively, a reduction of 62.85% and 60.74% compared with bare land. The measured results indicated that the crop canopy has a strong inhibiting effect on splash erosion of surface soil.

The inhibiting effect was stronger under the corn canopy under 80 mm h^{-1} of rainfall intensity. The differences among the splash values at various corn growth stages were not significant ($p > 0.05$) and strongly random. Under rainfall of 40 mm h^{-1}, the average splash detachment rate under a corn canopy fluctuated strongly over the whole growth stage. It decreased in the V6 and V9 stages and then increased in the V12 stage. Especially from V9 to V12 stage, the average splash detachment rate increased faster, and the value was similar to that in the V4 stage in case of 40 mm h^{-1} rainfall. When corn was in the V12 stage, although the LAI kept increasing, the leaves at the bottom of the plants were beginning to decline, but had not yet come off the plant, which could have left considerable areas of exposed ground in the intervening space, leading to increased splash erosion. The average splash detachment rate under 80 mm h^{-1} rainfall also showed obvious fluctuations with no regular pattern of variation, but the average splash detachment rate in the VT stage was reduced by approximately 30% compared with the V4 stage. This means that the corn canopy could reduce splash erosion effectively, but that the pattern of resistance was irregular.

Under a soybean canopy, the average splash detachment rate tended to decrease as the soybeans grew. From the R1 stage to the R6 stage, average splash detachment rates decreased by 59.68% under rainfall of 40 mm h^{-1} and 40.18% under rainfall of 80 mm h^{-1}. This meant that as the soybeans grew, the resistant effects of the canopy on splash erosion were becoming stronger and more regular. In the R1 stage, the average splash detachment rate under rainfall of 80 mm h^{-1} was 3.69 times that under 40 mm h^{-1}. This ratio increased to 5.48 in the R6 stage, which means that the average splash detachment rate under high rainfall intensity was much higher than under low rainfall intensity and that this difference increased as the soybeans grew. This occurred because rainfall kinetic energy under heavy rain could bend down the soybean petiole, increasing the amount of bare land between rows and weakening the dissipating effect of the canopy on energy. The resistant effect on splash erosion under 40 mm h^{-1} rainfall was stronger than that under 80 mm h^{-1} for soybean plants.

Compared with corn, under rainfall of 40 mm h^{-1}, the average splash detachment rate under a soybean canopy was lower than under a corn canopy. Soybeans are a kind of leguminous plant with wide soft leaves, and these leaves are prone to bend down under rainfall. Under rainfall of 80 mm h^{-1}, the larger rainfall kinetic energy produced more throughfall while passing through the soybean canopy and exposed more bare soil between rows than for corn, therefore producing more splash under high rainfall intensity than for the corn canopy. During rainfall at 40 mm h^{-1}, it was observed that under less intense rain with lower kinetic rainfall energy, the bending down of soybean leaves was less. Therefore, splash erosion was lower than for corn under low rainfall intensity.

The functional relationships between splash erosion under the corn canopy and LAI were not significant (Fig. 2a). The R^2 for rainfall of 40 mm h^{-1} and 80 mm h^{-1} was 0.501 and 0.096 respectively. This occurred because the corn plants were higher (≤2.2 m) than the soybean. Since lower falling height of throughfall collected from corn leaves grown in the lower part of canopy, the rainfall kinetic energy in this case was correspondingly lower. However, throughfall collected from corn leaves growing in the middle and upper part of canopy had higher rainfall kinetic energy, which could have led to more soil splash

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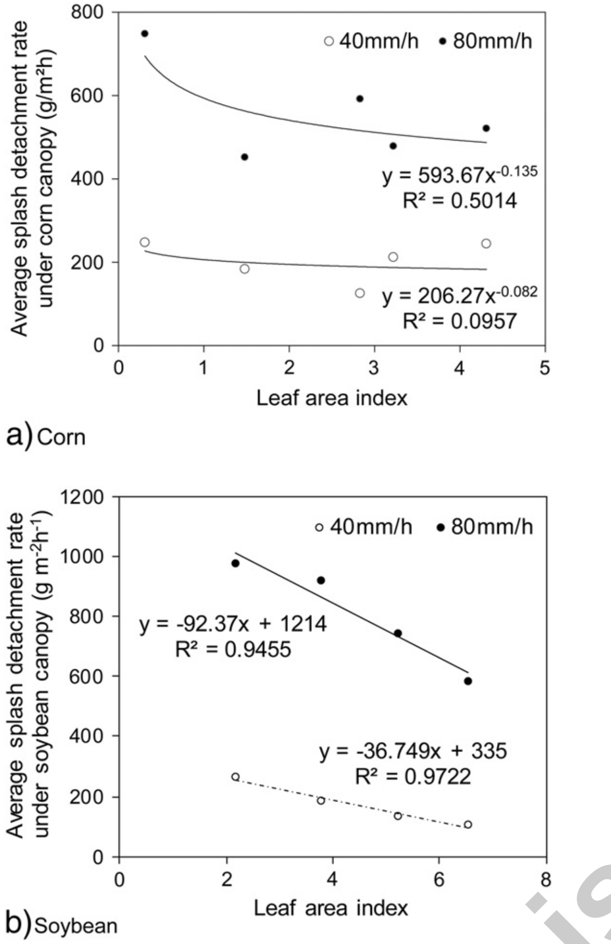

Fig. 2. Relationship between LAI and average splash detachment rate under corn (a) and soybean (b) canopies under different rainfall intensities.

detachment. Therefore, as corn grew, canopy coverage was increased, and the rainfall kinetic energy was correspondingly reduced, but the kinetic energy of throughfall produced by the upper canopy increased as the corn plants became higher, thus increasing soil splash detachment. Therefore, the regression relationship between splash detachment rate and LAI of corn was not significant. However, functional relationships between average splash detachment rate and LAI yielded much better results, with all R^2 values over 0.9 under the soybean canopy (Fig. 2b).

As rainfall intensity increased, the average splash detachment rate under the crop canopy increased significantly. However, because of the existence of the crop canopy, throughfall intensity among all locations under the canopy was uneven when rainfall passed through. The extent of this non-uniformity increased as the crops grew. At a rainfall intensity of 40 mm h^{-1}, the throughfall intensities at each position under the corn canopy ranged from 20.29 mm h^{-1} to 37.15 mm h^{-1} over the whole growth stage. For rainfall of 80 mm h^{-1}, the intensities ranged from 38.56 mm h^{-1} to 71.58 mm h^{-1}. The same ranges of variation under soybean canopies were 30.09–33.81 mm h^{-1} and 61.40–70.33 mm h^{-1} respectively.

When rain passes through the canopy, rain water is intercepted by leaves, and bigger drops form at the leaf margins and apex, producing more throughfall at some positions under the canopy and increasing the potential threat of splash erosion. This means that, although splash erosion under a crop canopy may be lower than on bare land, for some regions under the canopy, splash erosion may be higher than the values observed on bare land. A regression between splash detachment rate and throughfall intensity under a crop canopy at different observation times was therefore performed, with the results shown in Table 3.

The relationships between splash detachment rate, LAI, and throughfall intensity for each single position were all linear. This indicated that for each position under the crop canopy, splash erosion increased as throughfall increased at the same position. Higher throughfall intensities would often lead to a higher splash detachment rate. At the V4 stage, the corn plants were short. Raindrops were intercepted and converged to bigger drops or dispersed to smaller drops as rainfall passed through the canopy. Because of the limited falling height, the renewed drops did not have strong erosion potential. Even if rainfall intensities at some places were strong, the splash erosion was relatively less because of loss of energy. For this reason, the corresponding relationship between splash detachment rate and throughfall intensity was not significant in the V4 stage. As the corn plants grew, the stalks became higher, reaching 2.2 m at the VT stage, which meant that the renewed large drops had more erosion energy to produce more splash detachment. For soybeans, the linear relationships between splash detachment rate and throughfall intensity at particular locations were not significant, which meant that positions of high throughfall intensity did not necessarily generate higher splash detachment rates. The soybean canopy is low, meaning that the renewed raindrops do not have enough energy to cause much splash detachment. The rainfall kinetic energy increased with rainfall intensity, and the impact of the rainfall was intensified at the same crop growth stage. For corn, the increase in rainfall kinetic energy had a relatively small impact on the change of leaf inclination (the angle between leaves and stem). However, it could produce more vibration in the corn leaves, which was detrimental to the flow orientation of water from the leaves to the stem. Meanwhile, more and more raindrops were produced on the leaf apex and edge with increasing rainfall, and throughfall was increased accordingly. Combined with the greater height of the canopy, soil splash erosion

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Table 3
Regression equations and coefficient values between splash detachment rate and throughfall intensity under a crop canopy at each observation point.

Crops	Growth stage	40 mm h^{-1} of rainfall intensity			80 mm h^{-1} of rainfall intensity		
		Regression equation	R^2	F value	Regression equation	R^2	F value
Corn	V4	$SDR_P = 7.18\ TI_P - 19.02$	0.381	35.71**	$SDR_P = 12.27\ TI_P - 130.09$	0.426	43.09**
	V6	$SDR_P = 8.85\ TI_P - 114.88$	0.614	92.37**	$SDR_P = 10.94\ TI_P - 257.75$	0.683	125.07**
	V9	$SDR_P = 6.48\ TI_P - 72.84$	0.705	138.64**	$SDR_P = 14.38\ TI_P - 322.33$	0.889	464.62**
	V12	$SDR_P = 12.94\ TI_P - 101.88$	0.710	142.05**	$SDR_P = 14.17\ TI_P - 224.52$	0.592	84.11**
	VT	$SDR_P = 21.38\ TI_P - 189.67$	0.668	116.66**	$SDR_P = 21.02\ TI_P - 289.68$	0.851	331.90**
Soybean	R1	$SDR_P = 4.512\ TI_P + 112.02$	0.081	2.30	$SDR_P = 28.159\ TI_P - 864.24$	0.489	24.92**
	R2	$SDR_P = 8.157\ TI_P - 72.124$	0.468	22.90**	$SDR_P = 26.078\ TI_P - 914.73$	0.420	18.84**
	R4	$SDR_P = 7.717\ TI_P - 117.00$	0.478	23.81**	$SDR_P = 19.433\ TI_P - 564.87$	0.627	43.68**
	R6	$SDR_P = 2.728\ TI_P + 24.607$	0.175	5.52*	$SDR_P = 15.957\ TI_P - 395.35$	0.754	79.78**

SDR_P is the splash detachment rate at each monitoring point (each single splash cup) under a crop canopy (g m^{-2} h^{-1}), TI_P is throughfall intensity at each monitoring point (each single rain gauge which corresponds to each single splash cup) under a crop canopy (mm h^{-1}).

* At 0.05 significant level.

** At 0.01 significant level.

Table 4
Regression equations and coefficient values between average splash detachment rate and average throughfall intensity under crop canopy.

Crop	Equation	R^2	F value	Significance level
Corn	$SDR_A = 47.62\ LAI + 11.66\ TI_A - 241.59$	0.812	15.131	<0.0001
Soybeans	$SDR_A = -49.05\ LAI + 18.50\ TI_A - 201.66$	0.982	133.73	<0.0001

SDR_A is the average splash detachment rate under the crop canopy (g m^{-2} h^{-1}), LAI is the leaf area index, and TI_A is the average throughfall intensity under the crop canopy (mm h^{-1}).

was accelerated. For soybeans, more rainfall was collected by the wider leaves, but the vast majority of this water fell as throughfall because of the velvety texture of soybean leaves, which easily bend down under stronger rainfall intensity. Water on the leaf surface tends to fall from the sagging leaf apex as large-diameter water drops. Because the canopy height was low, soil splash erosion was not affected by these large drops. Since the lower height of canopy, the soil splash erosion was not affected by these large water drops. Meanwhile, during rainfall, soybean leaves bent down under raindrop impact, reducing coverage and increasing bare soil between rows, thereby increasing soil splash erosion. As the soybeans grew, the increasing number of thicker leaves substantially increased coverage and overlap in the canopy. This enhanced the capability of leaves to resist bending and thus increased the effective rain-receiving area, enhancing stemflow and correspondingly reducing throughfall, thus helping to reduce soil splash erosion. In this study, certain parameters related to canopy structure were not

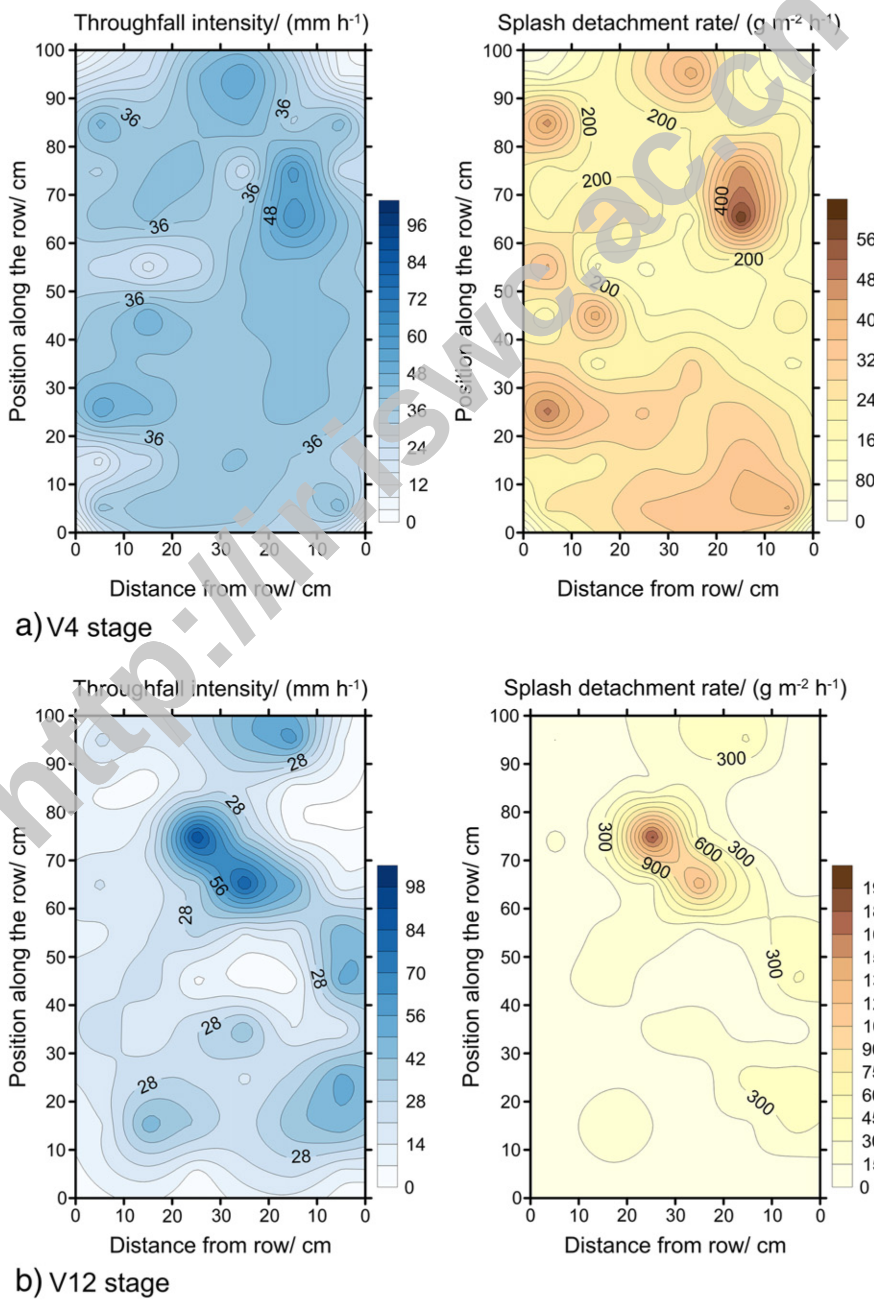

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Fig. 3. Spatial distribution of throughfall intensity and splash detachment rate under a corn canopy in different growth stages, take the V4 (a) and V12 (b) stages as examples. Rainfall intensity was 40 mm h^{-1}. Plants were positioned to simulate 60 cm between rows and 25 cm between plants within a row.

observed, such as leaf inclination and crown breadth. These parameters would better explain the relationship between throughfall and splash with crop growth and should be observed in future study. Average throughfall intensity and LAI can be used to describe average splash detachment rate, as shown in Table 4. From the regression equations, significant linear relationships can be determined between leaf area index, average throughfall intensity, and average splash detachment rate. Therefore, the two equations in Table 4 can be used to evaluate average splash rate under corn or soybean canopies at different growth stages.

3.2. Spatial distribution of splash detachment rate under crop canopy

From Table 2, it is apparent that the coefficient of variation (Cv) of the average splash detachment rate under a corn canopy increased from 0.41 at the V4 stage to 2.42 at the VT stage, while the Cv of soybeans increased from approximately 1.0 at the R1 stage to 1.7 at the R6 stage. That meant that the spatial distributions of splash detachment rates under the canopy became unequal as the crops grew. Areas in a 0–20 cm band nearest to a corn plant were defined as the region directly under the canopy (Fig. 3 shows the areas 0–20 cm and 20–0 cm on the X-axis), and areas in a 20–30 cm band in the intervening space were defined as the region in the central row position (the areas at 20–30–20 cm on the X-axis in Fig. 3). The area between two rows of soybean plants was divided into a 0–10 cm band nearest to the soybean plants (the region directly under the canopy; Fig. 4 shows areas 0–10 cm and 10–0 cm on the X-axis) and a 10–20 cm band (regions in the central row position, areas at 10–20–10 cm on the X-axis in Fig. 4). In these two regions, differences in splash detachment rates

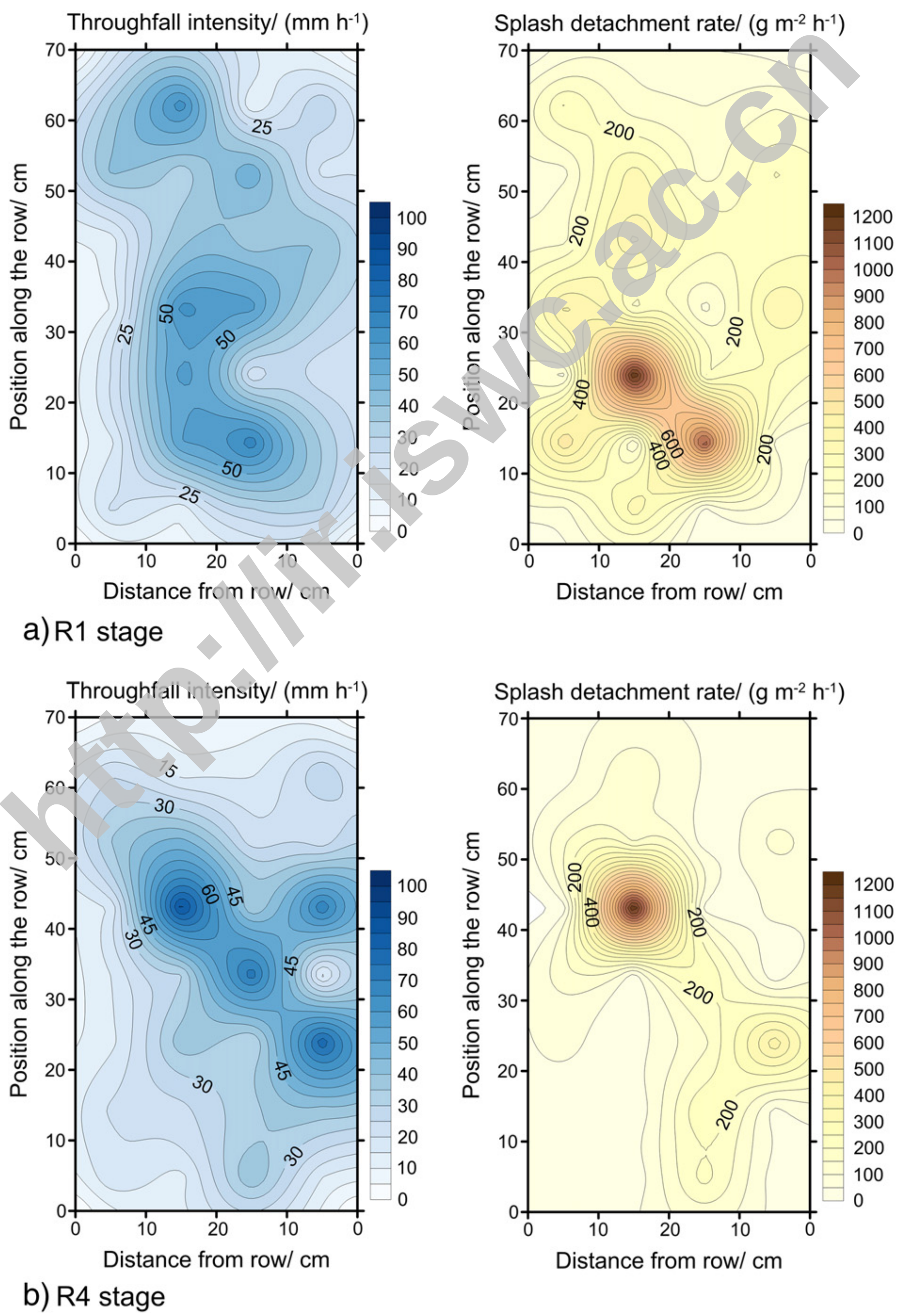

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Fig. 4. Spatial distribution of throughfall intensity and splash detachment rate under a soybean canopy in different growth stages, take the R1 (a) and R4 (b) stages as examples. Rainfall intensity was 40 mm h^{-1}. Plants were positioned to simulate 40 cm between rows and 20 cm between plants within a row.

exist in the same patterns as throughfall. Results are shown in Table 5. Compared with splash erosion in the 0–20 cm band, splash detachment rate increased by approximately 21%–26% in the 20–30 cm band. The SDR_{CR}/SDR_{DUC} ratio increased from 0.9 to more than 2.0. During the test period for soybeans, splash detachment rates increased by 190% in the 10–20 cm band over that in the 0–10 cm band at rainfall intensity of 40 mm h^{-1}. The SDR_{CR}/SDR_{DUC} ratios varied between 1.4 and 2.2. For rainfall of 80 mm h^{-1}, it varied mainly between 2.1 and 6.3. This indicated that splash erosion tends to concentrate in the central row position as corn and soybean plants grow. SDR_{CR} is smaller than SDR_{DUC} in V4 and V6 stages of corn; one possible reason is that most corn leaves were located in the 0–20 cm band and were young and small. Bigger drops form at the leaf margins and apex, producing more splash erosion in this region, though only by a narrow margin. According to a paired *t*-test, there was a significant difference between SDR_{CR} and SDR_{DUC} at the 0.01 level under corn and soybean canopies.

The spatial distribution of splash detachment rates under a corn canopy at rainfall of 40 mm h^{-1} is shown in Fig. 3. The differences in splash detachment rates at particular locations with different growth stages under the corn canopy were significant. At the V4 stage (Fig. 3a), splash erosion was focused in the 0–20 cm band, and the average splash detachment rate was 1.06 times that in the 20–30 cm band with less variation. This means that splash detachment rates were distributed evenly in the V4 stage. However, as the corn plants grew, their canopies changed, and splash erosion shifted from the 0–20 cm band to the 20–30 cm band. The concentration in the 20–30 cm band became most pronounced in the V12 stage, with an average splash detachment rate 2.05 times that in the 0–20 cm band (Fig. 3b). During this period, most of the splash erosion was concentrated in the 20–30 cm band, and the amount of splash erosion in the 20–30 cm band could be over half the total splash erosion amount under the corn canopy. Positions of high throughfall intensities usually have high splash detachment rates. Especially in the V9, V12, and VT stages (LAI ≥ 2.83), splash erosion under canopies tended to focus at certain spots, which corresponded with throughfall concentrations at the same spots. For example, in the VT stage, the two locations with the highest splash detachment rates both had 2933.54 g m^{-2} h^{-1}, which were 12 times average values, and the corresponding throughfall intensities were also maximum values—93.00 mm h^{-1} and 91.80 mm h^{-1} respectively.

Taking rainfall intensity of 40 mm h^{-1} as an example, the spatial distribution of splash detachment rates under a soybean canopy is shown in Fig. 4. The distribution of throughfall and the splash detachment rate changed significantly during the soybean growing season. In the R1 stage, high splash erosion was concentrated in regions of the 10–20 cm band, with an average splash detachment rate 1.54 times that in the 0–10 cm band (Fig. 4a). In and after the R4 stage, although positions of higher splash were still apparent in the 10–20 cm band, splash erosion under canopies tended to focus at certain spots and developed a dot-form distribution after the R4 stage (Fig. 4b). However, splash erosion in these high spots accounted for a large proportion of total splash erosion: 48.36% in the R4 stage and 37.96% in the R6 stage. It can be concluded that, as soybeans grow, splash erosion under their canopies decreases gradually, but most erosion becomes concentrated in several spots in the central row position which accounts for a large proportion of the total.

From the analysis described above, we found that there was no significant relationship between the distribution of throughfall intensity and the distribution of splash detachment rate under a soybean canopy. The same conclusion can be drawn from Fig. 4. With rainfall intensity of 40 mm h^{-1}, some positions with high throughfall intensities under the canopy did not show correspondingly high splash detachment rates. However, high splash rates existed at some positions with low throughfall intensity. Soybeans have short stalks and thick canopies, and throughfall was higher at some regions, but because the falling height of drops was limited, their energy was low and could not produce much erosion. Soybean leaves are soft, and during rainfall, the leaves bend down under raindrop impact, thus reducing coverage and increasing bare soil between rows, which leads to high splash erosion with less throughfall. The distribution of splash erosion under a soybean canopy was less affected by the spatial distribution of throughfall intensity and showed a random and uncertain pattern.

3.3. Relationship between rainfall intensity and spatial distribution of splash erosion

The spatial distribution of splash detachment rates under a crop canopy is related to throughfall intensity and rainfall intensity as well. The splash detachment rates varied under different rainfall intensities at the same corn growth stage (Figs. 3b and 5a). The positions where the splash erosion was concentrated did not correspond for the two different rainfall intensities. Under rainfall of 40 mm h^{-1}, high splash erosion appeared at two spots (>1000 g m^{-2} h^{-1}), while under rainfall of 80 mm h^{-1}, splash erosion was concentrated at four spots. In these locations, splash detachment rates were more than 2500 g m^{-2} h^{-1},

Table 5
Characteristics of splash detachment rates in different regions under the crop canopy during the growth period.

Crop	Rainfall intensity (mm h^{-1})	Growth stage	Leaf area index	Splash detachment rate in the region directly under the canopy (SDR_{DUC}, g m^{-2} h^{-1})	Splash detachment rate in the central row position (SDR_{CR}, g m^{-2} h^{-1})	SDR_{CR}/SDR_{DUC}	Average splash detachment rate under the crop canopy (g m^{-2} h^{-1})
Corn	40	V4	0.31	252.70 ± 122.42	237.92 ± 79.74	0.94	247.77
		V6	1.48	187.47 ± 250.55	171.33 ± 160.44	0.91	183.41
		V9	2. 83	114.97 ± 206.18	145.91 ± 268.90	1.27	125.29
		V12	3.22	156.99 ± 134.11	321.62 ± 451.24	2.05	211.87
		VT	4.31	219.06 ± 474.92	294.04 ± 615.49	1.34	244.05
	80	V4	0.31	768.75 ± 261.94	707.48 ± 289.69	0.92	748.33
		V6	1.48	425.13 ± 598.76	505.88 ± 824.72	1.19	452.05
		V9	2.83	543.93 ± 1082.40	688.31 ± 1192.01	1.27	592.06
		V12	3.22	391.52 ± 716.80	653.17 ± 1263.54	1.67	478.74
		VT	4.31	480.52 ± 1456.45	601.22 ± 1164.29	1.25	520.76
Soybeans	40	R1	2.16	208.5 ± 130.83	320.6 ± 350.96	1.54	264.6
		R2	3.77	69.39 ± 52.74	305.4 ± 311.18	4.40	187.4
		R4	5.21	84.23 ± 106.30	181.1 ± 302.83	2.15	132.7
		R6	6.51	93.14 ± 92.98	120.2 ± 152.59	1.43	106.7
	80	R1	2.16	623.8 ± 338.49	1330 ± 1500.04	2.13	977.0
		R2	3.77	392.2 ± 344.86	1446 ± 1386.06	3.69	919.3
		R4	5.21	475.0 ± 691.40	1014 ± 987.19	2.14	744.5
		R6	6.51	161.8 ± 222.90	1007 ± 924.50	6.22	584.4

SDR_{DUC} was splash detachment rate in the region directly under the canopy (g m^{-2} h^{-1}), SDR_{CR} was splash detachment rate in the central row position (g m^{-2} h^{-1}). Standard deviation was calculated based on splash detachment rate in different positions in the region directly under the canopy and the region in the central row respectively.

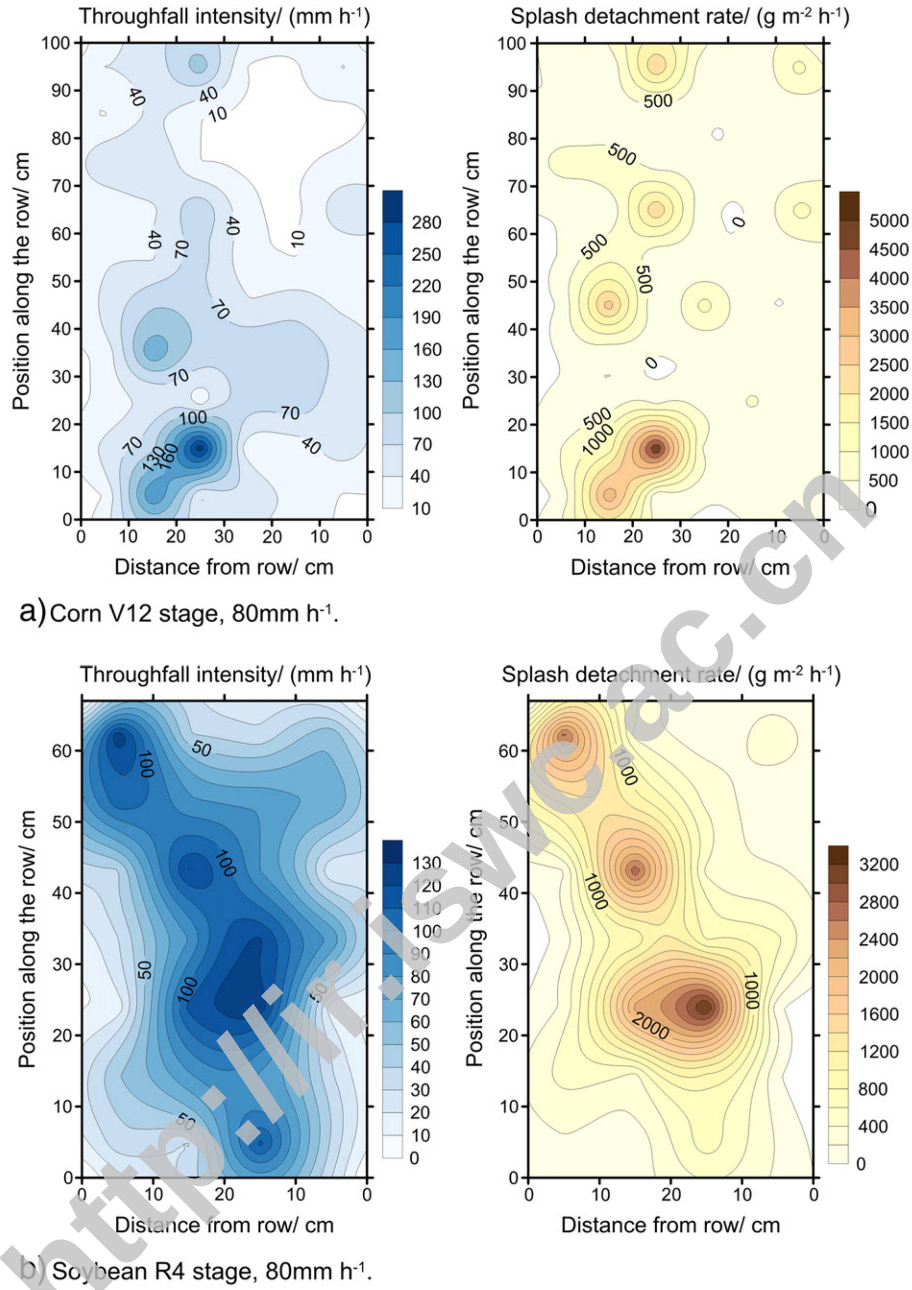

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Fig. 5. Spatial distribution of splash detachment rate under corn (a) and soybean (b) canopies under rainfall intensity of 80 mm h^{-1}. Spatial distribution of splash detachment rate under rainfall intensity of 40 mm h^{-1} was shown in Fig. 3b (corn) and Fig. 4b (soybean). The growth stage of corn examined was the V12 stage, and the LAI was 3.22. The growth stage of soybeans examined was the R4 stage, and the LAI was 5.21.

and splash erosion here accounted for approximately 56.91% of the total amount under the canopy. This suggests that rainfall intensity not only controls splash detachment rates, but also affects the choice and number of splash-erosion collection points as well. Combined with the distribution of throughfall under a corn canopy, when rainfall is heavy, more water and higher rainfall kinetic energy increase the numbers of renewed raindrops at the leaf edge and apex, and therefore the number of positions where extremely high throughfall values are concentrated becomes greater. Because these extreme throughfall concentrations usually appear at the leaf edge and apex, where the renewed drops are bigger and more numerous, these positions increase splash erosion accordingly. Therefore, the number of positions where extreme values of splash erosion occurred became greater when rainfall intensity increased. It can be concluded that rainfall intensity exerted a kind of indirect influence on the distribution of splash rates. Rainfall influenced the spatial distribution of splash detachment rates by affecting the spatial distribution of throughfall intensity. Therefore, the distribution of splash erosion under stronger rainfall intensities was similar to the throughfall distribution, which showed more uncertainty and volatility than that under rainfall of 40 mm h^{-1}. However, regardless of the design rainfall intensities, extreme concentrations of throughfall in certain areas with a high height of corn canopy generated extremely high splash erosion and made the average splash detachment rate increase. This explains the phenomenon that average splash detachment rates did not fall, but rather rose during the period of exuberant corn growth. Briefly, for high-stalk crops like corn, the high canopy height and the special form of the plant have important impacts on the amount and distribution of splash erosion under the canopy.

The spatial distribution of splash was also affected by rainfall intensities under a soybean canopy. The positions where concentrated splash erosion appeared under different rainfall intensities did not correspond with each other during the same growth stage (Figs. 4b and 5b). Splash erosion was concentrated at two points (>400 g m^{-2} h^{-1}) under rainfall of 40 mm h^{-1}, while under 80 mm h^{-1} rainfall, splash erosion was concentrated at 4 spots (>2000 g m^{-2} h^{-1}) and tended to be distributed in a sheet or zonal pattern. Stronger rainfall intensity influenced the soybean canopy greatly by increasing leaf bending extents and ranges, thus enlarging the area and scope of bare soil between rows, which augmented between-row splash erosion markedly. At the same time, strong rainfall enhanced the corresponding relationship between throughfall concentration and splash-erosion concentration. The correlation between splash distribution and throughfall intensities was higher than that at rainfall of 40 mm h^{-1}. The indirect effect of rainfall intensity on splash erosion under a soybean canopy was weaker than for corn, which is largely attributable to the direct effects of rainfall intensity on splash erosion of bare soil between rows. However, the increase in rainfall intensity fortified randomness and uncertainty in the region where splash erosion was concentrated, thus enhancing the effects of splash erosion under the canopy.

The crop canopy has the positive effects of intercepting precipitation, reducing rainfall energy, protecting surface soil, and preventing splash erosion to a certain extent. As the crops grew rapidly, this resistant effect on splash erosion varied significantly during the different growth stages. The decrease of splash erosion under crop canopies occurred mainly because of energy dissipation in the canopies. By testing the kinetic energy of rainfall under corn and soybean canopies, we found that the number of raindrops decreased for both. However, the number of large drops was increased under the crop canopy, which led to an increase in the median diameter of the rain under the canopy. The corn canopy reduced rainfall kinetic energy by 65%–71% and the soybean canopy by 72%–75% (Ma, 2012). Because of the greater falling height from the crop canopy, the effect of the corn canopy on eliminating energy was slightly weaker than that of the soybean canopy. The large renewed drops (>2 mm) from the crop canopy affected splash erosion to a certain extent. By analyzing the relationship between splash detachment rates, large drops in canopy, and throughfall intensities under a crop canopy and combining this with experimental observation, it was found that large drops forming at the leaf edge and apex promoted splash erosion, caused an uneven distribution of splash rates, and represented an important source of energy which affected the generation and distribution of splash erosion. However, the quantitative relation between numbers of large drops, kinetic energy, and splash detachment rates is still uncertain. Further study and discussion are needed on the effects of crop species, planting density, and plant morphological structures to solve this problem.

4. Conclusions and discussion

Crop canopies can effectively reduce rainfall kinetic energy and protect soil surfaces from raindrop impact, thus inhibiting splash erosion. In general, splash detachment rates under crop canopies were smaller than those on bare lands. The results indicated that the average splash detachment rate under a corn canopy was 380.43 g m^{-2} h^{-1}, which represented a decrease of 62.33% compared with bare land. The average splash detachment rate for soybeans was 489.56 g m^{-2} h^{-1}, a reduction of 61.79% compared with bare land. Splash detachment rates under the canopy tended to decrease as LAI increased, but also tended to increase as rainfall intensity and throughfall increased. The spatial distribution of splash erosion under crop canopies became less uniform between rows, with splash erosion evidently tending to occur intensively in central row positions. There were good correspondences between the spatial distribution of throughfall and splash rates under crop and soybean canopies, meaning that regions of high throughfall intensities tend to generate serious splash erosion as well.

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