TRANSFORMATION OF RAINFALL BY A SOYBEAN CANOPY

B. Ma, W. J. Gale, F. Ma, F. Q. Wu, Z. B. Li, J. Wang

ABSTRACT. *The crop canopy significantly changes the distribution of rain water and irrigation water in the canopy and topsoil, thus potentially causing uneven distribution of surface soil water content and altering water use efficiency. In this study, simulated rainfall was used to measure soybean canopy stemflow and throughfall, and a spray method was used to observe canopy interception. The objectives were (1) to quantify stemflow, throughfall, and interception storage at different times during the soybean growing season and (2) to examine the spatial distribution of throughfall under a soybean canopy. Results showed that interception storage increased as soybean leaf area increased, reaching a maximum of 1.14 mm at the full-seed stage (R6). Stemflow, which was determined at rainfall intensities of 20 to 120 mm h^{-1}, increased as soybean leaf area and rainfall intensity increased. Depending on leaf area and rainfall intensity, stemflow accounted for 3% to 23% of incident rainfall. Throughfall, which was only determined at a rainfall intensity of 40 mm h^{-1}, decreased from 96% of incident rainfall at the second trifoliate (V2) stage to 75% of incident rainfall at the R6 stage. When soybean plants were small, throughfall was evenly distributed beneath the canopy. As the plants grew, throughfall was concentrated in the inter-row region. At the R6 stage, throughfall amounts in the center inter-row were up to 3.1 times those next to the soybean row. In summary, there were significant changes across time in the partitioning and spatial distribution of rainfall or sprinkler irrigation beneath a soybean canopy. This has important implications related to agrochemical applications as well as to erosion control and effective use of irrigation water on sloping land.*

Keywords. *Artificial rainfall, Interception storage, Stemflow, Throughfall.*

Water from rainfall or sprinkler irrigation is partitioned into four components as it passes through the crop canopy: stemflow, throughfall, interception storage, and in-canopy evaporation (Lamm and Manges, 2000). Stemflow is water that flows from the leaves to the stem and then down the stem to the soil surface. Throughfall is water that passes directly or indirectly through the plant canopy to the soil surface. Rainfall interception is the process by which rainfall is caught on plants and redistributed as stemflow, throughfall, and evaporation (Helvey and Patric, 1966). However, interception storage is the water remaining on the leaves and branches of a plant after rainfall or sprinkler irrigation. In-canopy evaporation is the amount of evaporation from the canopy surface during a rainfall or sprinkler irrigation event and is often negligible compared to the other three components (Steiner et al., 1983; Thompson et al., 1996; Lamm and Manges, 2000).

A number of studies have investigated the effect of crop canopies, especially maize (*Zea mays* L.), on the partitioning of rainwater or sprinkler irrigation (Haynes, 1940; Quinn and Laflen, 1983; Steiner et al., 1983; Van Elewijck, 1989a, 1989b; Parkin and Codling, 1990; Bui and Box, 1992; Paltineanu and Starr, 2000; van Dijk and Bruijnzeel, 2001a, 2001b; Li et al., 2003; Wang et al., 2006a; Ma et al., 2008b). Results indicated that 12% to 57% of incident rainfall in maize canopies reached the ground as stemflow, whereas 35% to 84% of water reached the ground as throughfall. Fewer studies have examined rainwater or sprinkler irrigation partitioning by crops other than maize. Bui and Box (1992) reported that stemflow accounted for 31% of incident rainfall in a mature sorghum [*Sorghum bicolor* (L.) Moench] canopy. Stemflow for soybeans [*Glycine max* (L.) Merr.] accounted for 9% to 21% of incident rainfall and throughfall for 46% to 65% (Haynes, 1940; Ma et al., 2008a; Bäse et al., 2012). Saffigna et al. (1976) reported that stemflow in a potato (*Solanum tuberosum* L.) canopy was 20% to 46% of total sprinkler irrigation water and 4% to 23% of total rainfall. Stemflow and throughfall in cotton (*Gossypium hirsutum* L.) accounted for 3% to 8% and 56% to 97% of total sprinkler irrigation water, respectively (Ayars et al., 1991). Crop canopies also affect the spatial distribution of throughfall beneath the canopy. This has important implications for crop survival, soil water and solute movement, runoff, and soil erosion (Glover and

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The authors are **Bo Ma,** Post-Doctoral Researcher, State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, and College of Resources and Environment, Northwest A&F University, Yangling, China; **William J. Gale,** Post-Doctoral Researcher, College of Resources and Environment, Northwest A&F University, Yangling, China; **Fan Ma,** Research Assistant, College of Resources and Environment, Northwest A&F University, Yangling, China, and Institute of Desertification Control, Ningxia Academy of Agriculture and Forestry Science, Yinchuan, China; **Faqi Wu,** Professor, College of Resources and Environment, Northwest A&F University, Yangling, China; **Zhanbin Li,** Professor, State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, China; and **Jian Wang,** Associate Professor, College of Resources and Environment, Northwest A&F University, Yangling, China. **Corresponding author:** Faqi Wu, College of Resources and Environment, Northwest A&F University, No. 3 Taicheng Road, Yangling, Shaanxi 712100, China; phone: +86-029-87015595; e-mail: wufaqi@263.net.

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Gwynne, 1962; Quinn and Laflen, 1983; Armstrong and Mitchell, 1987; Parkin and Codling, 1990; Paltineanu and Starr, 2000; Levia and Frost, 2003). Haynes (1940) reported that for soybeans, throughfall in the center inter-row was nearly twice that in the row position and observed that water passed from leaf to leaf toward the edge of the soybean canopy. Armstrong and Mitchell (1987) also found that throughfall under a soybean canopy was concentrated at the canopy edge but was periodically distributed under a maize canopy.

Erosion caused by stemflow is generally negligible, but the relationship between throughfall and erosion is closer, and the water dripping from leaf margins is an important influence. In WEPP, detailed information on the role of plants is needed to determine rill and inter-rill erosion. Throughfall and stemflow were introduced into a function to evaluate the total erosive rainfall in WEPP, but USLE and RUSLE only consider the role of throughfall in the cover subfactor. Although many researchers have observed and recorded stemflow, only de Ploey (1982, 1984) established a common stemflow model suitable for grass and trees. On this basis, Van Elewijck (1989a, 1989b) and Lamm and Manges (2000) built stemflow models suitable for maize. Maize canopy types and structures are quite different from those of soybean, and therefore the models built by Van Elewijck (1989a, 1989b) and Lamm and Manges (2000) cannot be used to evaluate stemflow and throughfall under soybean canopies. Interception storage is ignored in CREAMS. However, in KINEROS, interception is considered as a depth that has to be filled before rain can pass from the plant canopy to the ground (Morgan et al., 1998a and 1998b). In LISEM, interception storage is calculated as a function of the vegetation cover and cumulative rainfall, as proposed by Aston (1979). In EUROSEM, the amount of interception storage is modeled as a function of cumulative rainfall using the exponential relationship proposed by Merriam (1973), and the depth of stemflow is modeled as a function of the average acute angle of the plant stems to the ground surface using equations developed by Van Elewijck (1989a, 1989b). Maximum rainfall interception storage is in the range of 1.0 to 3.0 mm for a dense crop canopy in PRZM (EPA, 1998).

Currently, there are few methods for measuring interception by the crop canopy. Some researchers have suggested that canopy interception can be estimated from a water mass balance technique or algebraic closure (Seginer, 1967; Steiner et al., 1983; Lamm and Manges, 2000; Li and Rao, 2000; Wang et al., 2006b). Liu (1998) and van Dijk and Bruijnzeel (2001b) measured interception by the crop canopy using spraying and immersing methods, respectively. Interception by the canopy of dense crops, such as wheat, can be measured using the water wiping method (Wang et al., 2005; Kang et al., 2005). Stemflow is usually measured using the funnel method or funnel-like collecting devices (Saffigna et al., 1976; Bui and Box, 1992; Van Elewijck, 1989a; Lamm and Manges, 2000; Bäse et al., 2012). Additionally, the vase and collar methods were used by van Dijk and Bruijnzeel (2001b) to measure maize. However, these methods are mainly used to measure stemflow in maize and sorghum, but rarely in other crops. For dense crops, such as wheat, the stem is difficult to wrap due to its small diameter, and there is strong mutual influence between stems due to their close proximity. Therefore, no effective method has been developed for measuring the stemflow of such crops (Liu et al., 2007). In measurement of throughfall, rain collecting devices of a certain size are generally placed between the rows beneath the canopy. In field trials, the rain collecting devices commonly used are self-made square rain-collecting tanks (Ayars et al., 1991; Bäse et al., 2012) and rain gauges (Steiner et al., 1983; Lamm and Manges, 2000; Li and Rao, 2000; van Dijk and Bruijnzeel, 2001b).

The crop canopy changes rain water distribution significantly between the top of the canopy and the soil surface. In the process of rainfall and irrigation, some water is intercepted and then evaporated, and thus part of the water does not reach the soil and cannot be absorbed by plant roots. This interception loss thus influences the water use efficiency (Seginer, 1967; McNaughton, 1981; Steiner et al., 1983). Because of the non-uniform infiltration caused by redistribution of rainfall and irrigation water under crop cover, the distribution of soil moisture in the surface soil tends to be uneven. Thus, irrigation and fertilization management will be changed accordingly, affecting crop growth and yield (Glover and Gwynne, 1962; Saffigna et al., 1976). Soybeans are one of the most valuable grain and oil crops and are widely planted worldwide. The world soybean area harvested increased by 2.96% annually during 2000-2010 and reached 102.39 million ha in 2010, according to FAOSTAT (FAO, 2013). In China, the soybean acreage has fluctuated around 9 million ha over the past decade with small changes, and production decreased 2.07% in the past decade (FAO, 2013). There are very few reports of transformational water for a soybean crop under rainfall or irrigation water. Researchers have developed stemflow and rainfall interception models for maize and sorghum canopies (Van Elewijck, 1989a, 1989b; Bui and Box, 1992; Lamm and Manges, 2000), but less is known about the effect of soybean canopies on rainfall or sprinkler irrigation partitioning. The objectives of this study were (1) to quantify stemflow, throughfall, and interception storage at different times during the soybean growing season and (2) to examine the spatial distribution of throughfall beneath a soybean canopy for improving soil, water, and crop management.

Materials and Methods

This article includes results from three experiments conducted during the 2008 and 2010 growing seasons at the Soil and Water Conservation Engineering Laboratory, Northwest A&F University, Yangling, Shaanxi Province, China. The soybean cultivar in this study was Zhonghuang-13, a determinate cultivar that is adaptable to high plant density and with an average plant height of 95 cm. Soybeans were planted in field plots during June of both years. Row spacing was 40 cm, and plant spacing was 20 cm. At different times during the two growing seasons, plants were cut at ground level and taken to the laboratory for determination of interception storage, stemflow, and throughfall, as

Table 1. Vegetative stage and average leaf area at each sampling date.

		Interception Storage		Stemflow		Throughfall	
Vegetative Stage[a]	Symbol	No. of Plants Sampled	Leaf area (cm^2 plant^{-1})	No. of Plants Sampled	Leaf Area (cm^2 plant^{-1})	No. of Plants Sampled	Leaf Area (cm^2 plant^{-1})
Second trifoliate	V2	10	660	16	660	18	640
Fourth trifoliate	V4	10	1370	16	1410	18	1460
Sixth trifoliate	V6	10	2190	16	2080	18	2160
Beginning flowering	R1	10	2810	16	2920	18	3050
Full flowering	R2	10	3800	16	3860	18	3840
Full pod	R4	10	4810	16	4820	18	4810
Full seed	R6	10	5600	16	5560	18	5520

[a] McWilliams et al. (1999).

described below. Leaf area of each plant was determined by the specific leaf weight method (table 1) (Pearce et al., 1969). The vegetative growth stages and average leaf area for each sample time are shown in table 1. There are three leaf area values for each growth stage because interception storage, stemflow, and throughfall were determined in three separate experiments in order to validate and better control the conditions.

The rainfall simulator in this study 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 was consisted of two 3 m long sprinkler booms, each positioned at a mutual distance of 30 cm. On each sprinkler boom, two nozzles were fixed at a mutual distance of 1.5 m. Different rainfall intensity was 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 about 75% of natural rainfall (Ma, 2009).The effective rainfall area of the simulator was 3 m × 3 m, and rainfall uniformity was >80%.

Interception Storage

Interception storage was measured during the 2010 growing season. An indication of the interception storage of soybean was obtained through experiments comparable to those described by Liu (1998) and van Dijk and Bruijnzeel (2001b). The maximum interception storage was estimated by spray method. On each sampling date, ten soybean plants were cut at ground level and immediately taken to the laboratory, where the cut stems were sealed with paraffin wax to prevent the gain or loss of water. In this process, all leaves were carefully treated so they were not wetted by water before the first spray experiment. The plants were fixed in an upright position and then sprayed from all sides by a vaporizer. Spraying was stopped when the water dripped from leaves, and then the plants were weighed (to the nearest 0.01 g). The maximum interception storage was calculated as the difference in the weight of the plants (to the nearest 0.01 g) before and after spraying.

Stemflow

Stemflow was determined during the 2009 growing season. On each sampling date, 16 soybean plants were cut at ground level. The soybeans were grown nearby, so the plants could be taken into the laboratory within a short time. Before testing, the incisions on the plants were im-

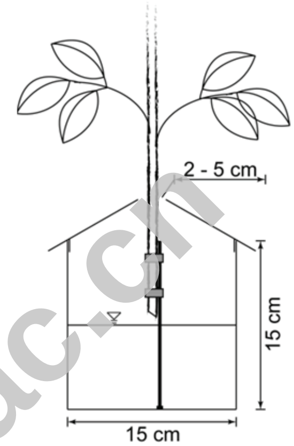

Figure 1. Setup for stemflow collection from soybean plant.

mersed in water for >30 min to prevent wilting. Water adhering to the incisions was absorbed using soft tissue before the plants were impaled in stemflow collection cylinders. The 16 freshly cut soybean plants were impaled in upright positions on nails welded to the bottom of a galvanized metal collection cylinder (15 cm diameter) (fig. 1). These self-made collection cylinders were constructed to measure stemflow of maize in 2008 (Ma et al., 2008b). The soybean stem diameter was in the range of 0.32 to 1.04 cm during the growing season. Lids with different hole diameters (2 to 5 cm) were selected according to the soybean stem diameter at different stages in order to ensure a distance of at least approximately 1 cm between the stems and the hole edges. The collection cylinders were then arranged to simulate 40 cm between rows and 20 cm between plants within a row. Before the first rainfall experiment, the surface of the soybean plants was wetted using the sprayer to ensure consistent conditions before each rainfall experiment. The plants were exposed to 30 min of rainfall at intensities of 20, 40, 60, 80, 100, and 120 mm h^{-1}. The actual rainfall intensity at each position in the grid was determined prior to the run. By adopting this method, the stemflow amount per unit time (S_a, mm h^{-1}) at each vegetative growth stage was calculated. The ratio of stemflow amount to rainfall was calculated as the stemflow ratio (S_r, %).

Throughfall

Throughfall was measured during the 2008 growing season using 60 rain gauges arranged under the soybean canopy, spanning two rows of soybean plants, similar to the method of Steiner et al. (1983) for maize canopies. On each

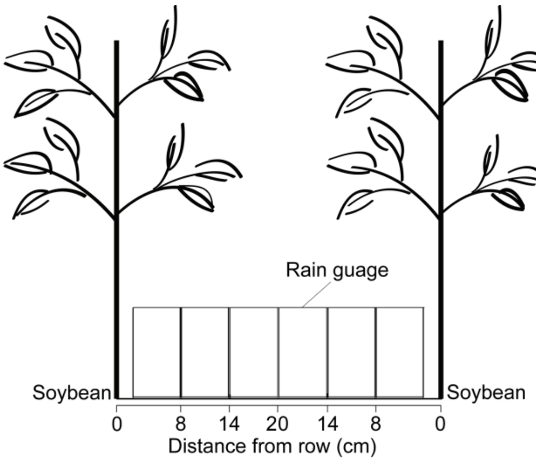

Figure 2. Setup for measuring interception by soybean canopy.

sampling date, 18 freshly cut soybean plants were impaled in upright positions on nails welded to a steel grid. The setup was arranged to simulate 40 cm between rows and 20 cm between plants (fig. 2). Six rows of rain gauges (6 cm diameter) were placed between the two rows of soybean plants. Each row contained ten gauges. Before the first rainfall experiment, the surface of the soybean plants was wetted using the sprayer to ensure consistent conditions before each rainfall experiment. The plants were exposed to a rainfall intensity of 40 mm h^{-1} for 10 min. Throughfall intensity (mm h^{-1}) was determined from the amount of water collected in the rain gauges.

RESULTS AND DISCUSSION

INTERCEPTION STORAGE

The maximum interception storage ranged from 0.06 mm at the V2 stage to 1.14 mm at the R6 stage (fig. 3), the average interception storage was 0.48 mm. Interception storage increased with the increase in leaf area throughout the growing season. With the growth of the soybean plants, branches and leaves in the canopy grew rapidly, and the leaf area rapidly increased, thus increasing the canopy surface area capable of holding rainfall. There was a significant ($p < 0.01$) positive correlation between maximum interception storage and leaf area, and the relationship was best described by a power function:

$$I_a = 0.0001\ A_L^{1.030}$$

$$(R^2 = 0.748,\ F = 800.172,\ p < 0.0001)$$

where I_a is the maximum interception storage (mm) and A_L is soybean leaf area (cm^2).

Additionally, the large leaves of soybean are conducive to holding and adsorbing rainfall to improve interception storage. We found few published reports that quantified interception storage in soybean canopies, although simulation models such as EPIC and PRZM typically use values of 2 to 2.5 mm for interception storage in soybean canopies with moderate cover (EPA, 1998). In addition, the value of maximum interception storage for mature soybean plants was 0.7 mm in EUROSEM (Morgan et al., 1998a. However, the observation method was not mentioned in these studies. Reported values for interception storage in mature maize canopies were in the range of 1.8 to 3.6 mm, as estimated by water balance (Steiner et al., 1983; Lamm and Manges, 2000; Wang et al., 2006a).

The maximum interception storage per plant showed large changes when the leaf area was large ($A_L \geq$ 3500 cm^2), fluctuating within 0.62 to 1.14 mm (fig. 3). Such fluctuations were caused to some extent by the particularity of soybean plant morphology. The stretching direction of the soybean leaves differed, with some stretching upward and some sagging. These different directions greatly affected the adhesion and retention of water droplets on the leaf surface. Hypothetically, two soybean plants could have the same leaf area, but the number of leaves with different stretching directions may be quite different between them, so that the maximum interception storage of the two plants could differ greatly. In addition, since soybean leaves are large, they might bend down after full adsorption of water due to the weight, so that the water originally attached to the leaf surface is only temporarily intercepted throughfall, thus reducing the maximum interception storage. However, the bending extent of leaves differs due to individual characteristics of each plant and thus is highly random. All these factors resulted in the large fluctuations in maximum interception storage per soybean plant. Young leaves were an important place for water storage due to the pubescence covering their surface. Moreover, the pods were an important place of interception when soybean entered the R4 stage. The pubescence covered the pod surface, the pods were flat and clustered, and the spacing between the pods was small, long, and narrow; thus, more rain water could be attached by surface tension forces, resulting in a high water retention capacity.

Relative to the high canopy interception of 15% to 35% in the Loess Plateau (Wu and Yang, 1998), the soybean canopy interception, as part of rainfall redistribution by the crop canopy, is low. The interception capacity of crops increases with crop growth but is limited under a fixed leaf area. Once interception reaches its limit, it remains relatively stable and rainfall intensity exerts no further impact on interception storage. Nonetheless, the mechanisms and function of canopy interception still exist, and rain collected by the leaves and branches will be converted to stemflow and throughfall.

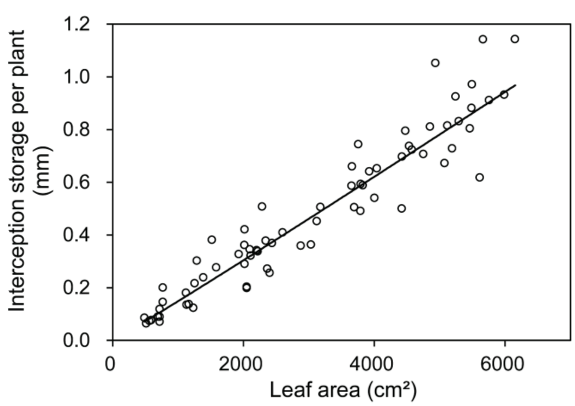

Figure 3. Relationship between maximum interception storage and soybean leaf area.

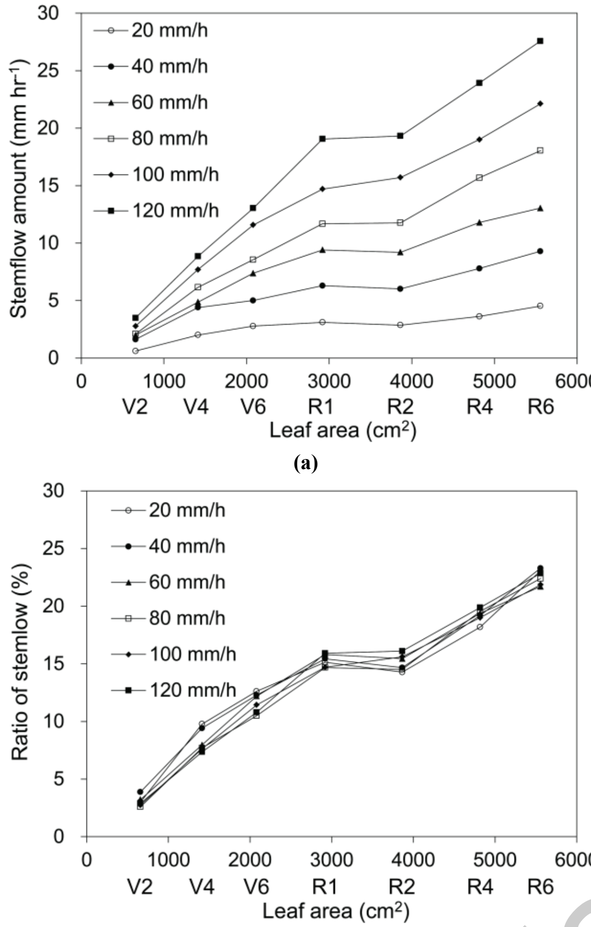

Figure 4. Relationship between stemflow and leaf area.

STEMFLOW

Stemflow amounts generally increased as leaf area and rainfall intensity increased, although there was generally a slight decline in stemflow between the R1 and R2 stages (fig. 4a). However, from R1 to R2, stemflow showed a downward trend for rainfall intensity ≤60 mm h^{-1} but slowly increased for rainfall intensity ≥80 mm h^{-1} (fig. 4a). This may be because the production of stemflow during soybean growth may also be influenced by other uncertainties, such as crop morphology, strength of branches and leaves, leaf toughness, and angle of leaf inclination. Depending on rainfall intensity, stemflow was in the range of 0.6 to 3.5 mm at the V2 stage and 4.5 to 27.6 mm at R6. These stemflow amounts represented 2.6% to 3.9% of incident rainfall at the V2 stage and 21.7% to 23.3% at R6 (fig. 4b). Rainfall intensity generally had no significant effect on stemflow expressed as a percentage of total rainfall (S_r, %).

Data from all runs were combined to establish equations that described the effect of leaf area and rainfall intensity on total stemflow amount (S_a) and the stemflow to total rainfall ratio (S_r) (table 2).

Stemflow declined slightly after the R1 stage, suggesting an interaction between rainfall intensity and the soybean canopy. The partitioning of rainfall or sprinkler irrigation into stemflow, throughfall, or interception storage is affected by canopy characteristics, including the angle of leaf inclination, the bending extent of leaves under raindrop impact, and the condition of the leaf surface (Kitanosono, 1972).

Table 2. Regression equations and coefficient value between stemflow and rainfall intensity and leaf area of soybean.

	Equation[a]	R^2	F Value	p Value
Stemflow amount	$S_a = I^{0.955} A_L^{0.862} e^{-8.706}$	0.938	5045.863	<0.0001
Stemflow ratio	$S_r = 0.014 A_L^{0.862}$	0.893	5576.266	<0.0001

[a] S_a is stemflow amount (mm h^{-1}), S_r is stemflow to total rainfall ratio (%), I is rainfall intensity (mm h^{-1}), A_L is leaf area (cm^2), and e is natural logarithmic base (e = 2.718).

Rainfall intensity and leaf area both caused changes in soybean stemflow, but their influence varied at different growth stages. Between the V2 and R1 stages, the soybean plant was relatively weak, with relatively small and few leaves, so that leaves had a relatively small influence on stemflow. In contrast, in terms of rainfall intensity, because of the beating of raindrops on soybean leaves and the weight of rainfall, combined with the weak and small leaves, the leaves and petioles bent downward, so that the effective rain-receiving area of the plant was reduced, which is not conducive to the formation of stemflow. Rainfall energy had a negative effect on stemflow, but sustained rainfall greatly increased the stemflow. Soybean stemflow showed a significant upward trend between the V2 and R1 stages. The canopy contained many large, soft, and thin leaves at the R1 and R2 stages. The increase of leaves substantially increased the coverage and overlap in the canopy, and large and thin leaves were very prone to bending under the beating of raindrops, so that the effective rain-receiving area of the plant showed no significant changes. When the rainfall intensity was low (i.e., 20, 40, and 60 mm h^{-1}), the supply from rainfall to stemflow was small, and stemflow declined. When the rainfall intensity was high (i.e., 80, 100, and 120 mm h^{-1}), the supply from rainfall to stemflow was relatively enhanced, and stemflow showed an upward trend. From the R2 to R6 stages, the most important feature of leaf changes was that the increased leaf area was accompanied by significant thickening of leaves. This enhanced the capability of leaves to resist bending and thus increased the effective rain-receiving area, so the influence of leaves on stemflow was enhanced. As a result, stemflow always showed an upward trend at different rainfall intensities. We also observed that the large leaf area intercepted more rainwater and channeled it to the stem. The influence of leaf area on stemflow, in essence, is the direct influence of the effective rain-receiving area of the soybean canopy on the formation of stemflow. The effective rain-receiving area refers to the total leaf area that can channel rainwater on the leaf surface to the petiole and so to run down along the stem. However, this part of leaf area varies with individual differences in plants, such as the differences in morphology, and is formed in the process of rainfall. Therefore, it is difficult to distinguish it from the total leaf area and measure it in actual observations.

THROUGHFALL

Throughfall was measured at 40 mm h^{-1} rainfall intensity. As expected, throughfall amounts generally decreased across the growing season, although there was a slight increase between the R1 and R2 stages. Throughfall accounted for 96%, 92%, 88%, 83%, 82%, 77%, and 75% of the incident rainfall at the V2, V4, V6, R1, R2, R4, and R6 stages, respectively. Throughfall decreased as the soybean canopy developed and was negatively correlated with stemflow.

The distribution of throughfall changed significantly during the soybean growing season (fig. 5). Throughfall was evenly distributed across the soil surface at the V2 stage. At the V6 stage, there was a reduction in throughfall in the 0 to 8 cm band nearest to the soybean plants, and throughfall distribution in the 6 to 20 cm band became more irregular. At the R1 stage, the band of reduced throughfall became larger, covering an area 0 to 14 cm away from the soybean plants. At the same time, there was significant concentration of throughfall in the 14 to 20 cm band. Throughfall became more concentrated in the center of the inter-row in the remainder of the growing season. At the R6 stage, throughfall in the 14 to 20 cm band was 3.1 and 2.2 times that in the 0 to 8 cm and 8 to 14 cm bands, respectively. These findings are in agreement with Haynes (1940), who observed that rainwater moved across the surface of soybean leaves to the canopy edge and then fell to the soil surface.

Throughfall was composed of the water directly falling on the ground through the canopy gap and that falling from the leaf edge and apex onto the ground after being intercepted by the canopy; these cannot be measured separately in actual observations. When the crop plants were small (V2 to V6 stages), the canopy did not completely cover the land between the rows, so most throughfall came from raindrops directly falling to the ground. As many raindrops directly struck the bare soil, this indicated that coverage and protection of the soil by soybean plants at the vegetative growth stages was limited. Soybean plants could completely cover the soil between the rows when in vigorous growth (R1 to R6 stages). However, leaves of the lower stem shifted farther from the stem and closer to the center of the inter-row space in the growth process. During rainfall, these leaves bent down under raindrop impact and so reduced the coverage and increased the bare soil between rows. Moreover, raindrops falling from the leaf edge and apex in the upper canopy to the bent leaves also ran to the leaf edge and apex, further increasing the throughfall between the soybean rows. This transformation process is confirmed in figure 5. As raindrops that fell from the leaf edge and apex were pooled from raindrops on the leaves, they had a large diameter. These large raindrops not only affected splash erosion beneath the canopy but also increased the turbulence of runoff between the rows, resulting in a possible influence on runoff and sediment.

In this study, only one rainfall intensity (40 mm h^{-1}) was used, so the influence of changes in rainfall intensity on throughfall under the soybean canopy remains unknown. Further studies should investigate the effect of raindrop impact on the partitioning of rainwater in terms of both rainfall intensity, where the overall rainfall energy is changed, and raindrop velocity, where the energy of the raindrops is changed. The sum of stemflow, throughfall, and interception storage did not equal the rainfall amount due to experimental error, and the maximum interception storage using the spray method caused higher measurement results, which led to the imbalance in water balance. Furthermore, using the same number of plants for each part of the experiment would be statistically more appropriate in any future study. Amounts of stemflow, throughfall, and interception storage were measured at different times and on different plants, which aimed to determine the variation of these three individual factors with crop growth. Therefore, water balance was not considered in the present study. In soil erosion research and water management, understanding the temporal and spatial distribution of stemflow and throughfall would be far more important than interception storage. If water balance is to be studied, the differences between treatments need to be minimized, and another method of measuring interception storage is needed.

Conclusions

The goal of this study was to quantitatively evaluate the process of rainfall transformation under crop cover and the effects of leaf area and rainfall intensity, and provide a reference to evaluate water use efficiency. This study was unique in attempting to characterize changes in the partitioning and spatial distribution of rainfall or sprinkler irrigation by a soybean canopy during the growing season. Various methods were used to measure throughfall, stemflow, and interception under soybean canopies in the laboratory, and empirical equations were established. The data used to build the model were collected under "no wind" conditions in the laboratory. Water drop diameter, drop height, and incident angle under rainfall were all different from sprinkler conditions. Consequently, the derived equations need to be revised for use in outdoor windy conditions and sprinkler irrigation conditions. The derived equations are practical and applicable to estimate the quantity of throughfall, stemflow, and interception in different growth stages of soybean. Regression equations indicated that throughfall and stemflow were closely related to rainfall intensity and soybean growth. Throughfall decreased with increased leaf area and with decreased rainfall intensity. Meanwhile, stemflow increased with increased leaf area and with increased rainfall intensity. Canopy interception increased with increased leaf area index. During the soybean growing season, stemflow accounted for an average of 14% of total rainfall, and approximately 85% of rainfall reached the ground as throughfall. Interception storage amounts were relatively small, never exceeding 1.2 mm. In the typical plant spacing of soybean fields, throughfall is the main flow path to the surface soil, and stemflow is relatively small.

The reduction in throughfall and increase in stemflow are significant for reducing soil erosion on sloping land. The crop canopy can cushion the impact of rainfall, reducing rainfall kinetic energy and transforming it into stemflow and throughfall with lower energy. The throughfall intensity beneath a soybean canopy was high. Although

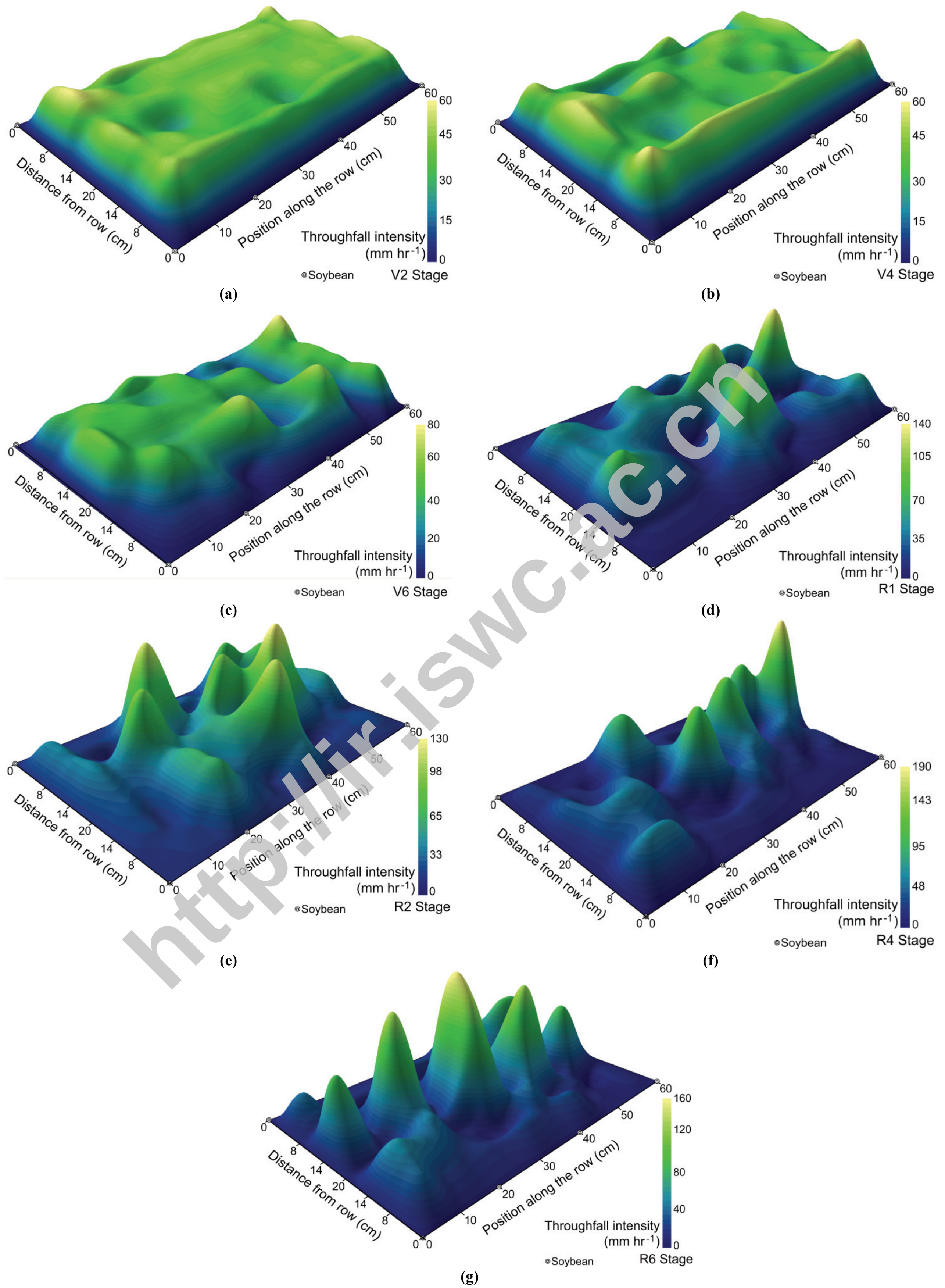

Figure 5. Throughfall distributions beneath the soybean canopy at seven growth stages during the growing season. Rainfall intensity was 40 mm h^{-1}. Plants were positioned to simulate 40 cm between rows and 20 cm between plants within a row.

the large leaves and low plants provided high ground coverage, most throughfall was concentrated in the center of the inter-row space due to the soft leaves, which would influence runoff and erosion between the rows. The height of the rainfall simulator in this study was 4 m, and the final raindrop velocity, raindrop energy, and rainfall kinetic energy differed from natural rainfall. Future studies should consider the effect of precipitation parameters on the process of rainfall redistribution under soybean canopies, such as rainfall kinetic energy, rainfall type, and rainfall amount. Furthermore, the derived equations do not consider the effects of planting density, plant height, and stem diameter on water volume of each component. Future studies should consider the role of these parameters in throughfall, stemflow, and canopy interception.

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