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Bo Ma[1]
Chao Dong Li[1,2]
Fan Ma[3]
Zhan Bin Li[1]
Fa Qi Wu[2]

[1]State Key Laboratory of Soil Erosion and Dryland Farming on Loess Plateau, Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi, China
[2]College of Resources and Environment, Northwest A&F University, Yangling, China
[3]Institute of Desertification Control, Ningxia Academy of Agriculture and Forestry Science, Yinchuan, China

Research Article

Influences of Rainfall Intensity and Leaf Area on Corn Stemflow: Development of a Model

As an important pathway for movement of rainfall or sprinkler irrigation water through a crop canopy to the ground, stemflow is of great significance for utilization efficiency of sprinkler irrigation water and for crop growth. In this study, under simulated indoor artificial rainfall, the stemflow rates (SF) of corn plants (*Zea mays*) in different corn growth stages (V4 stage ∼ VT stage) under different rainfall intensities (*I*) were observed, and the relationships among stemflow, leaf area (LA), and *I* were analyzed. Based on these results, stemflow models were developed. The results showed that for all corn growth stages, the average SF of a single corn plant was about 55.69 mL/min, accounting for 45% of total rainfall. SF increased as a power function of corn LA and *I*, and the percentage of stemflow in total rainfall increased as a power function of corn LA. Theoretical, semi-empirical, and empirical models of corn SF and stemflow proportion (SR) of total rainfall were established by analyzing the relationships among LA, *I*, and stemflow. All three models were used to estimate SF and SR in different corn growth stages and achieved desired accuracy. The semi-empirical and empirical models were more accurate in predicting and simulating corn SF, but the calculation and application of the semi-empirical model was relatively simpler. The empirical model of SR enabled a more accurate calculation of the percentage of stemflow in total rainfall.

Keywords: Crops; Irrigation; Simulated rainfall; Stemflow prediction; Vertical projection area

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1 Introduction

The interception function of crop canopies changes the distribution of rain or sprinkler irrigation water considerably [1]. Rainwater is usually divided into four fractions by canopies: Throughfall; stemflow; interception storage; and evaporation from the canopy. Stemflow is the portion of water that is intercepted and collected by leaves and branches and flows down the stem to the soil surrounding the plant [2, 3]. Stemflow has an important impact on hydrological processes in fields and on other relevant processes such as soil water movement, solute transport, and soil erosion [2]. Some researchers have believed that stemflow can concentrate rainfall in the root zone and promote crop growth [2, 4], but others have suggested that a large amount of stemflow concentrated in the root zone can lead to leaching loss of fertilizers [5, 6]. Some scientists have pointed out that the role of stemflow in erosion may be negligible compared to that of throughfall [7, 8], but others have thought that stemflow causes soil erosion [4, 9]. The effects of stemflow vary with environmental conditions, and further studies of stemflow effects on crops are therefore needed.

Narrow-leaf crops such as wheat (*Triticum aestivum*), corn, and sugarcane (*Saccharum officinarum*) intercept most rainwater at the bottom of the leaf and ultimately convey it to the soil around the bottom of the stalk [10]. Because of their special structure, corn plants have a stronger capability to transform rainfall or spray irrigation into stemflow [11]. Under various circumstances, corn canopies can transform 12–57% of rainwater or spray irrigation into stemflow [3, 8, 9, 11–14]. In addition, corn stemflow has a certain impact on soil erosion. Corn stemflow can dissipate rainfall energy and has a potential capability for soil detachment [4, 8, 9]. These study results were almost obtained based on measurements of mature corn, and systematic results of stemflow in different corn growth stages have not been reported. It is difficult to observe the characteristics of stemflow throughout the growing season. The corn growing season is in spring and summer, with abundant rainfall. It is therefore necessary to study the variations of stemflow with leaf area (LA) and rainfall intensity (*I*) and to investigate the redistribution characteristics of rainfall through the corn canopy over the whole growing season.

Generally, stemflow has been measured with collecting devices fixed on the base of a plant [12, 15, 16]. This measurement method enables continuous observation of stemflow on a corn plant in different growth stages. However, the device used in this measurement method is difficult to install. Currently, some stemflow models have been developed [4, 6, 8, 17], but these models involve many parameters which are not easy to measure, which impedes their practical application. The first stemflow model for crop vegetation proposed by de Ploey was suitable for stemflow

Correspondence: Prof. F. Q. Wu, College of Resources and Environment, Northwest A&F University, Yangling 712100, China
E-mail: soilcrop@163.com

Abbreviations: **I**, rainfall intensity; **LA**, leaf area; **LAI**, leaf area index; **PA**, vertical projection area; **SR**, proportion of total rainfall; **SF**, stemflow rates.

calculations of grasses and tree canopies [18]. To predict the stemflow of corn plants precisely, van Elewijck revised the model. However, in these two models, the parameter calculations were complex [17]. For example, the required leaf-angle parameter was difficult to measure. In research and application areas related to hydrological processes, such as soil water movement, solute transport, soil erosion, and fertilization management, a simpler and more precise stemflow model is needed.

The study aims to develop better stemflow models. In this research, the stemflow, LA, and vertical projection area (PA) of plants in different corn growth stages were systematically measured, stemflow variation with LA and *I* was investigated, the characteristics of rainfall redistribution by corn canopies were discussed, the relationships among stemflow on a single plant, *I*, LA, and vertical PA of the plant were explored, and theoretical, empirical, and semi-empirical models for stemflow on a single corn plant were developed. The objective of this study was to provide a simple model for stemflow prediction and a theoretical basis for water and fertilizer management in fields.

2 Materials and methods

2.1 Experimental design

The experiments in this study were conducted at the Soil and Water Conservation Engineering Laboratory of the Resources and Environment College, Northwest A & F University, Yangling, China. The corn variety used in the tests was Zhengdan 958, which was sown with a planting spacing of $60 \times 25\,cm^2$ on June 13, 2008. The planting spacing in this research was applied as a major and typical planting pattern for corn in Loess Plateau, China. During the growing season, measurements of stemflow, LA, and vertical plant PA were conducted nine times in various stages of corn growth. On each sampling date, four corn plants were cut at ground level. The corn plants were grown nearby the laboratory, so the corn plants could be taken into the laboratory immediately. Before testing, the incisions on the plants were immersed 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.

2.2 Stemflow collection and simulation devices

The stemflow collection device was a cylinder made of galvanized iron sheet with an oblique cover. The cylinder was 20 cm in diameter and 15 cm in height, and a 15-cm-long steel nail was welded at the center of the cylinder bottom to affix the corn plant (Fig. 1). The rainfall simulation device was an indoor fixed downward spraying simulator produced by the factory of the Institute of Soil and Water Conservation, Chinese Academy of Sciences and Ministry of Water Resources in Yangling, Shanxi Province.

The downward sprinkling rainfall simulation system was similar to that used by Jin et al. [19]. Four nozzles were positioned at a height of 4 m. The rainfall simulator consisted of two 3-m-long sprinkler booms with a spacing of 30 cm. On each sprinkler boom, two nozzles were fixed with a spacing of 1.5 m. Different *I* values were achieved through 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 [20]. The effective rainfall area of the simulator was $3 \times 3\,m^2$, and rainfall uniformity was >80%.

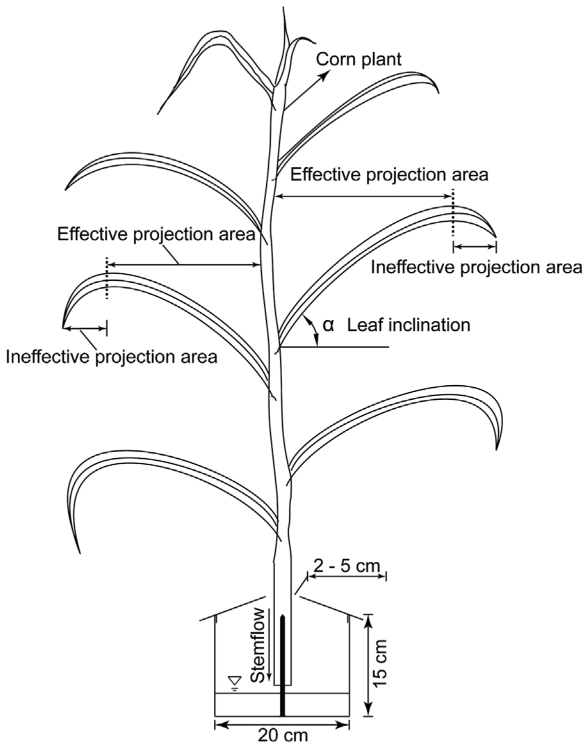

Figure 1. Stemflow collection cylinder for corn.

2.3 Measurement and calculation of the vertical PA of a single corn plant

The PA of a single corn plant was measured with a wooden frame and a movable laser head. As shown in Fig. 2, a nail was welded at the center of the bottom board to affix the corn plant. Before scanning, a piece of paper (A0) was laid onto the bottom board, and then a corn plant was fixed onto the nail. A laser head on the top of the frame moved on an aluminum rail. The laser head moved along the *Y*-direction with a step size of 2 cm, creating many parallel scan lines with 2-cm spacing on the paper on the bottom board. The laser head moved continuously on the rail along the *X*-direction at the end of every scan line. When it moved, the light spot also moved on the paper. Because of shading by the corn plant, some parts of a given scan line could not be seen on the paper, and these shaded parts were marked with a pencil. All shaded parts of all scanning lines jointly indicated the area shaded by the plant (Fig. 2). This area of the paper was cut off using scissors and weighed (*M*1). At the same time, a square area (100 square papers with each $100\,cm^2$) of the same paper was cut off and weighed (*M*2). With *M*2, *M*1, the shaded area, which was the vertical PA of the plant, could be determined. Four corn plants were measured in each measurement period, and the LA and vertical PA of a single plant was measured for one time.

2.4 Measurements of stemflow of corn plants

The stemflow of four corn plants was measured for *I* values of 0.033, 0.067, 0.100, and 0.133 cm/min as follows:

1) After the vertical PA had been measured, four corn plants were fixed in the collection cylinders and numbered and then placed at a spacing of $25\,cm \times 60\,cm$ under the rainfall simulator.

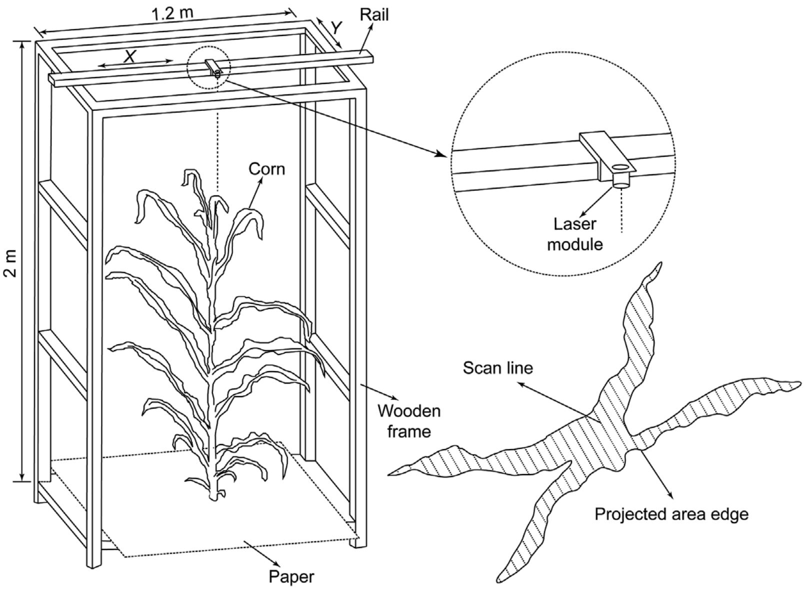

Figure 2. Measurement device for projected area of corn and scanned area.

2) Before the first rainfall experiment, the surface of the corn plants was wetted using the sprayer to ensure consistent conditions before each rainfall experiment. Rainfall with a designated intensity was applied for 10 min. Then the stemflow of every plant was measured with a graduated cylinder.
3) Four rain gauges with a diameter of 8.3 cm were put onto the positions where the collection cylinders had been placed to receive rainfall with the same intensity as before for 10 min to calculate actual intensities at every position.
4) The above procedures were repeated for each designated I.

The stemflow proportion (SR, %), which is defined as the ratio of stemflow rate (SF, mL/min) to total rainfall rate, can be calculated by dividing SF by the total rainfall rate as follows:

$$\mathrm{SR} = \frac{\mathrm{SF}}{I_{\mathrm{w}} R_{\mathrm{w}} I} \times 100\% \quad (1)$$

where I_{w} is the spacing between the plants (cm) and R_{w} is the row spacing (cm).

2.5 Measurement and calculation of corn LA

All leaves were cut from the collar to measure the length (L) and the maximum width (W). The total LA of a single corn plant (cm^2) can be calculated using Eq. (2) [21]:

$$\mathrm{LA} = \sum_{i=1}^{n} (k L_i W_i) \quad (2)$$

where k is a correction coefficient, 0.75, L_i is the length of the ith leaf (cm), W_i is the maximum width of the ith leaf (cm), and n is the number of leaves on a plant.

The leaf area index (LAI) was calculated as the green LA per unit ground area in broadleaf canopies can be calculated using Eq. (3) [22].

$$\mathrm{LAI} = \mathrm{LA}/A \quad (3)$$

where A is the average surface area land per corn plants occupied (cm^2).

2.6 Method of model evaluation

In this study, the R^2 and the Nash–Sutcliffe model efficiency (ME) coefficient were used to evaluate the simulated results from the various stemflow models. In a linear regression model, R^2 is a measure of the quality of fit of the regression equation. ME was used to evaluate the model simulation accuracy; it was first used by Nash and Sutcliffe [23]. ME is an effective way to evaluate model prediction capability by comparing measured with simulated values. The calculation formula is:

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n} (V_{\mathrm{m}} - V_{\mathrm{c}})^2}{\sum_{i=1}^{n} (V_{\mathrm{m}} - V)^2} \quad (4)$$

where V_{m} is the measured value, V_{c} is the calculated value, and V is the average of the measured values.

ME ranges from $-\infty$ to 1. $\mathrm{ME} = 1$ indicated that the response would be better if the model were matched more satisfactorily (the simulated value was equal to the measured value). $\mathrm{ME} = 0$ indicated that the model predictions were as accurate as the mean of the observed values. $\mathrm{ME} < 0$ indicated that the measured mean was a better predictor than the model. Essentially, the closer the model efficiency is to 1, the more accurate is the model [23].

3 Results and discussion

3.1 SF of a single corn plant

According to the SF, I, LA, and vertical PA of corn plants at different growth stages (Tab. 1), during the whole growing season, the average SF was about 55.69 mL/min, which was 44.55% of the total rainfall amount. The SF values were extremely different at every stage. SF was 9.01 mL/min in the V4 stage (7.29% of total rainfall) and

Table 1. General characteristics of stemflow from corn in different phases

Growth stage	LAI	Single plant LA range (cm^2)	Vertical PA of a single plant (cm^2)	I (cm/min)			SF (mL/min)			Stemflow ratio (%)	
				Min	Max	Mean	Min	Max	Mean	Mean	Coefficient of variation
V4	0.41	400–760	300	0.035	0.144	0.082	3.10	18.80	9.01	7.29	0.17
V5	0.77	790–1330	480	0.030	0.141	0.080	4.90	26.20	14.42	11.22	0.12
V6	1.33	1330–2460	820	0.030	0.133	0.081	2.50	60.70	35.64	28.23	0.12
V7	1.92	2330–3450	1140	0.037	0.144	0.085	14.60	86.20	46.38	36.49	0.06
V8	2.16	3040–3470	1380	0.030	0.156	0.082	10.80	114.20	57.36	46.11	0.12
V9	2.54	3480–4400	1560	0.026	0.133	0.080	22.50	113.30	72.21	57.43	0.15
V12	3.23	4400–5220	1770	0.030	0.133	0.080	23.50	142.40	74.47	60.28	0.19
V14	3.54	4490–6250	2000	0.030	0.141	0.077	30.10	158.90	92.80	74.17	0.10
VT	3.67	5240–5930	2180	0.033	0.141	0.082	42.30	154.30	98.89	79.70	0.12
Average	2.17	3260	1290	0.031	0.141	0.081	17.14	97.22	55.69	44.55	0.13

V(n) was nth leaf with collar visible stage ($n = 4$–14).

98.89 mL/min in the tasseling stage, the VT stage (79.70% of total rainfall), indicating that the stemflow of corn increased gradually as the plant grew and reached its highest value in the VT stage. During the rainfall experiment, limp would not occur because rainfall water adhering to the leaves surface would be absorbed by the corn plants. Therefore, there might be no difference in experimental results between living and limp plants.

3.2 Relationship between SF and LA of a single corn plant

In this study, the obtained SF data corresponded to LA data and I data per stem. The amount of stemflow from a single plant/min was defined as the SF (mL/min · per stem). To discuss the relationship between SF and LA, the SF data should be divided by I to obtain ratio of SF to I ($R_{SF/I}$, mL/min per · stem). There was a positive correlation between $R_{SF/I}$ and LA for a single plant (Fig. 3), and the relationship was best described by a power function ($R_{SF/I} = 0.095\ LA^{1.096}$). Another important phenomenon in the V4 and V5 stages ($LA < 1200\ cm^2$) was that the data points of $R_{SF/I}$ for the same plant under different intensities were similar, and different I values showed no significant difference ($p > 0.1$), indicating that the $R_{SF/I}$ for the same plant under different I were almost the same. As the LA of a single plant increased, especially after the V9 stage, the data points of $R_{SF/I}$ presented an obviously increasing trend of discrete degrees, indicating that the difference in $R_{SF/I}$ for the same plant under different I gradually increased with increasing LA. This difference reached a significant level ($p < 0.01$). In other words, when LA was large, SF per plant did not necessarily increase with I. One reason for this phenomenon was probably that SF changed with I followed a nonlinear relationship (see Section 3.3). The second reason might be that when the corn plant grew and the leaf size became large enough to intercept rainfall more efficiently, it took more time for rainwater to reach the base of the plant after the interception storage capacity was saturated. Different I values might have different impacts on this process. Another reason might be that as opportunities for overlapping of leaves from different plants increased during the growing season, rainwater intercepted by one plant could possibly be transferred to another plant and even become stemflow of another plant. For different I values, this mutual transfer relationship among plants could become very complex and lead to irregular fluctuations in SF with changing I.

3.3 Relationship between SF and *I*

To discuss the relationship between SF and I, the SF data should be divided by the LA of a single plant to obtain the ratio of SF to LA ($R_{SF/LA}$, mL/min · cm^2). According to the relationship between $R_{SF/LA}$ and I (Fig. 4), $R_{SF/LA}$ increased with the increase in I, the relationship

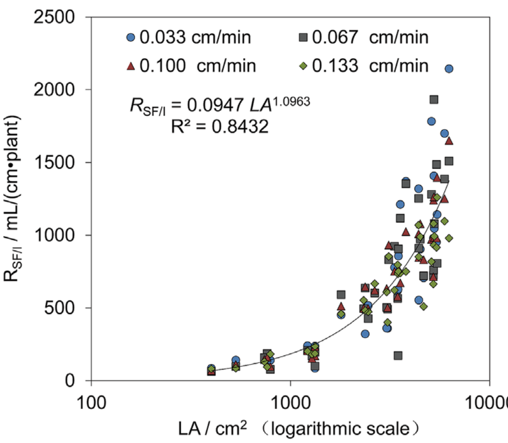

Figure 3. Relationship between $R_{SF/I}$ and LA per plant.

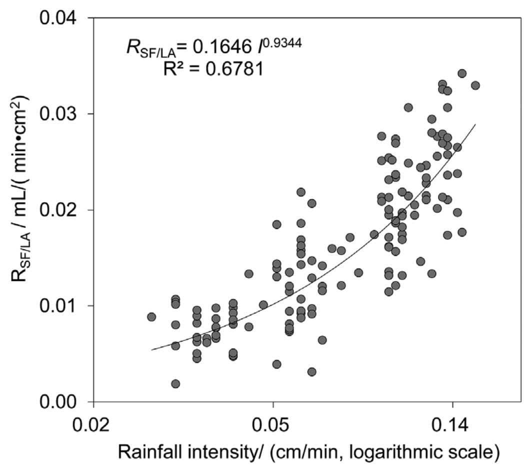

Figure 4. Relationship between $R_{SF/LA}$ and I.

was best described by a power function ($R_{SF/LA} = 0.165\,I^{0.934}$), and the regression equation reached a significant level ($p < 0.01$). As I increased, the degree of discreteness of the data points for $R_{SF/LA}$ also increased, indicating that the differences among the $R_{SF/LA}$ of plants of different sizes with the same I gradually increased as I increased. This increase might have been caused by the nonlinear relationship between SF and LA. Moreover, the kinetic energy of raindrops increased with I, and leaves shook more strongly, exerting an impact on rainwater concentration and transfer. Plants of different sizes responded differently to rainfall impact at the same intensity, resulting in fluctuations of SF.

3.4 Relationship between stemflow proportion (SR) and corn LA

The sum of the stemflow of four plants in 10 min was converted to water depth over the field area of a single plant ($0.15\,m^2 \times 4 = 0.60\,m^2$) that the plants occupied and then divided by the total rainfall amount (average intensity at four positions × rainfall duration) over the same area to obtain the ratio of collective stemflow to total rainfall. Analysis of variance showed that canopy LAI had a significant effect ($p < 0.01$) on the ratio of collective stemflow to total rainfall, but that I had no significant effect ($p > 0.05$). The relationship between the ratio of collective stemflow to total rainfall and canopy LAI is shown in Fig. 5. The ratio of collective stemflow to total rainfall increased significantly with canopy LAI. In the V8 stage, when LAI was 2.16, the portion of stemflow could reach 40–50%, and in the V14 stage, with LAI >3.54, the ratio became >70%, which was slightly higher than the values measured by other researchers [2, 3, 7, 24, 25]. The corn used in this study was a "compact shape" variety planted at high density. Corn plants reached their highest stemflow collection capacity in the VT stage, when the plant was like a funnel.

3.5 Establishment of stemflow model for a single corn plant

Corn plants can effectively convert rainfall into stemflow due to their special shape. The stemflow process was deeply investigated in this study. In the stemflow process, rainwater first reaches the leaves, then flows downward along leaves to the stem, and finally reaches the base of the plant. The most obvious feature of a corn plant is its funnel shape. For the "compact shape" variety used in this study, the ideal stemflow process can be described as follows: Raindrops fall vertically onto leaves and are then transferred to the stem. The rainfall interception and collection area is the vertical PA of the plant. All raindrops that fall onto the PA can possibly be converted into stemflow, ideally. Under constant I, according to Eq. (5), stemflow collected by a single corn plant theoretically equals the rainfall amount on the PA/min, which is the product of I and PA:

$$\mathrm{SF} = I \times \mathrm{PA} \tag{5}$$

All 36 plants tested were sequenced by their PA, and 18 of them were randomly selected to establish the model. The relationship between measured and calculated SF (Fig. 6a) indicated that the calculated values were closely related to the measured values, but the slope of the regression equation was 1.726 and the intercept was 14.669, indicating that Eq. (5) overestimated SF. The reason was that the entire PA is not involved in stemflow collection. For example, the tips of leaves often droop, and rainwater falling on the tip cannot be converted into stemflow, but rather becomes throughfall. The PA contributing to stemflow collection is the effective PA (Fig. 1), and therefore Eq. (5) should be revised as follows:

$$\mathrm{SF} = a \cdot I \cdot \mathrm{PA} \tag{6}$$

where a is a correction factor for the stemflow model.

The reciprocal of the slope in Fig. 6a basically represents the ratio of effective PA to total PA. The correction factor a was 0.579, which is equal to the reciprocal of 1.726, and the stemflow model was revised as:

$$\mathrm{SF} = 0.579 \cdot I \cdot \mathrm{PA} \tag{7}$$

Equation (7) was used to calculate the SF of the other 18 plants used to validate the models. The relationship between measured and calculated values is shown in Fig. 6b. The slope is 1.067, which is close to one, and R^2 is 0.936. Eq. (7) can be used to calculate stemflow on a single corn plant. This model can also be used to calculate SF under different I in different corn growth stages. This model demonstrated the correctness of the physical relationships and the need for the correction factor a.

The theoretical model of SR was obtained by substituting Eq. (7) into Eq. (2):

$$\mathrm{SR} = \frac{0.579\ \mathrm{PA}}{I_w \cdot R_w} \times 100\% \tag{8}$$

Equation (8) was used to calculate the SR of the selected 18 plants to validate the models. According to the relationship between measured and calculated values (Fig. 6c), the slope is 1.0009, which is very close to 1, and R^2 is 0.783, indicating that Eq. (8) can predict SF well. According to Eq. (8), SR is a single-factor function of the vertical PA of corn plants. The factor I was neglected, as SR did not vary significantly with I over the whole growing stage.

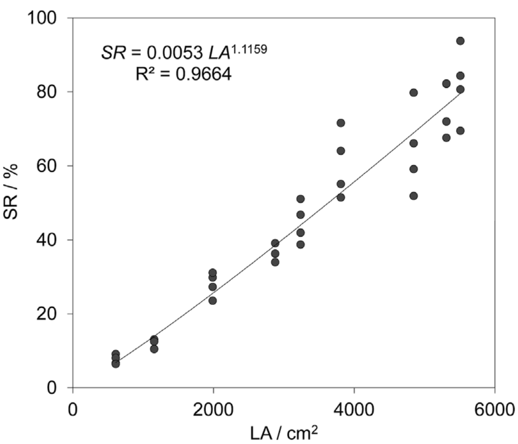

Figure 5. Relationship between the SR and corn LA.

3.6 Semi-empirical model for stemflow on corn

From the analysis described above, the theoretical model showed high simulation accuracy for stemflow prediction, but it was

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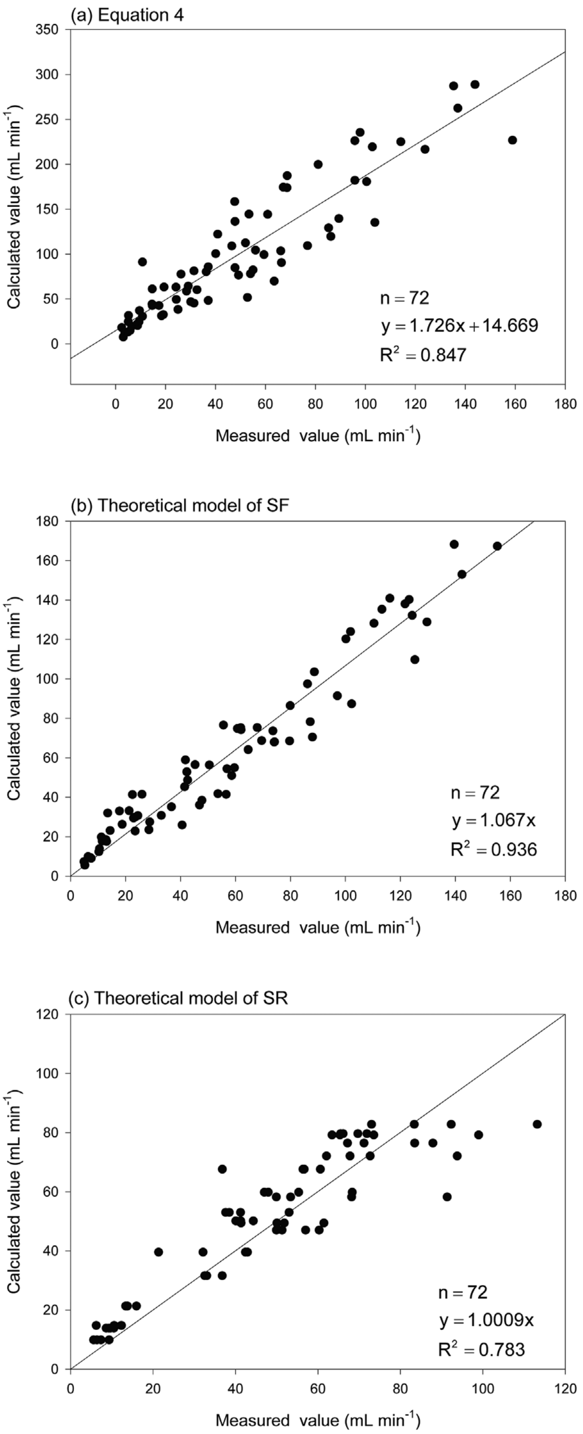

Figure 6. Comparison between measured and calculated values from theoretical models.

difficult to measure the vertical PA. In this study, vertical PA was found to be closely related to LA. A semi-empirical model based on LA could therefore be developed. The relationship between vertical PA and LA was obtained using data for 18 randomly selected plants:

$$\mathrm{PA} = 0.356\mathrm{LA} + 109.74; R^2 = 0.929 \quad (9)$$

The semi-empirical model was obtained by substituting Eq. (9) into Eq. (7):

$$\mathrm{SF} = (0.21\ \mathrm{LA} + 63.65)I \quad (10)$$

Stemflow data for the remaining 18 plants were validated using Eq. (10) to obtain the relationship between calculated and measured values (Fig. 7a). The slope of the regression line was 1.072, which is close to 1, indicating that Eq. (10) can predict SF well. The semi-empirical model can also be used to calculate SF of corn in different stages and for different *I*. In addition, it is simpler than the theoretical model.

The semi-empirical model of SR was obtained by substituting Eq. (10) into Eq. (2):

$$\mathrm{SR} = \frac{0.21\ \mathrm{LA} + 63.65}{I_{\mathrm{w}} R_{\mathrm{w}}} \times 100\% \quad (11)$$

SR data for the remaining 18 plants were used in Eq. (11) to validate the relationship between calculated and measured values (Fig. 7b). The regression line indicated that this equation could be used to calculate SR based on LA. The model is easy to use for calculation.

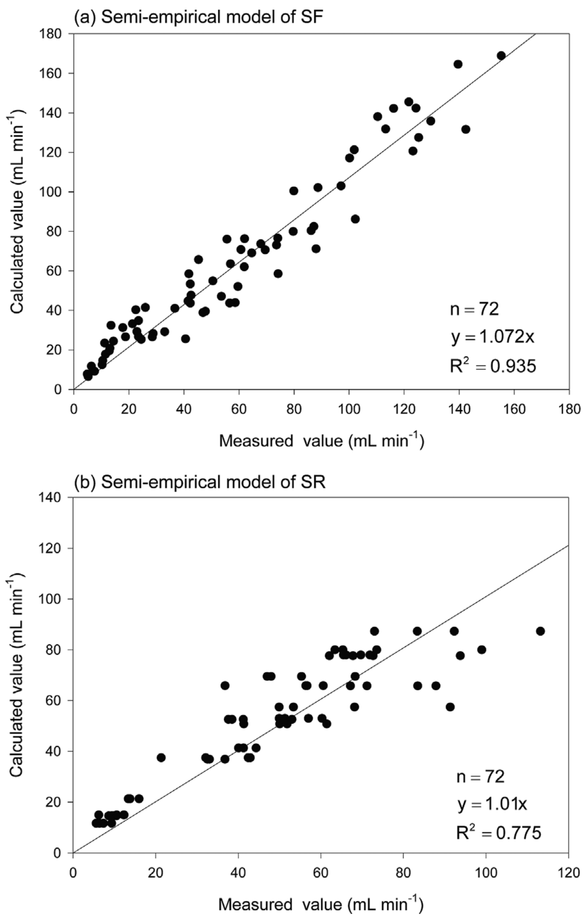

Figure 7. Comparison between measured and calculated values from the semi-empirical models.

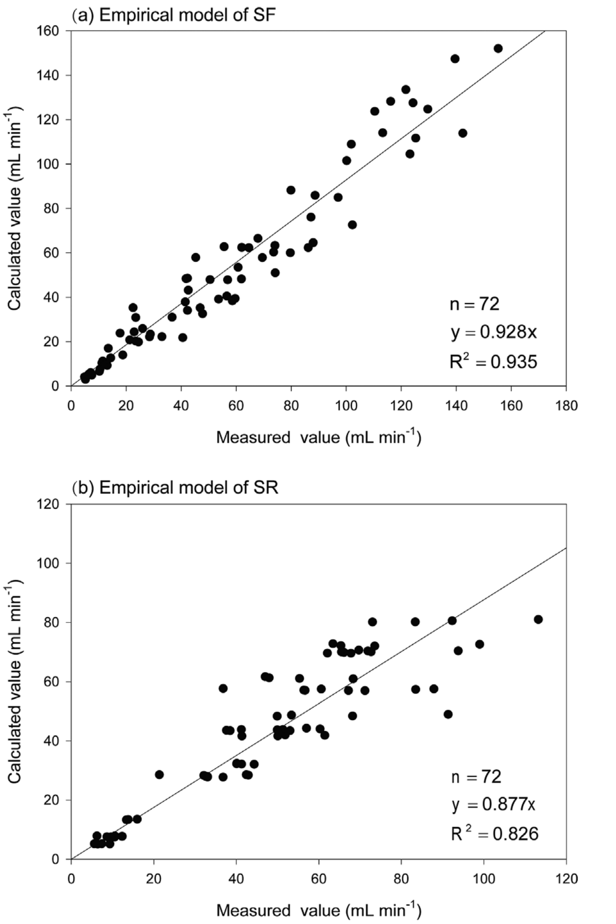

Figure 8. Comparison between measured and calculated values from the empirical models.

3.7 Empirical model for stemflow on corn

SF on a single corn plant was found to increase with LA and I, and SF on a single corn plant was closely related to LA and I. Directly predicting stemflow based on LA and I was therefore feasible. Eighteen plants were randomly selected to establish the model. By regression analysis, the relationship among SF, LA, and I could be expressed as follows:

$$\mathrm{SF} = 0.062I^{0.991}\mathrm{LA}^{1.134}; R^2 = 0.875 \quad (12)$$

The remaining 18 plants were used to validate the model. According to the relationship between calculated and measured values (Fig. 8a), the values calculated with Eq. (12) and the measured values exhibited a linear relationship. The slope of the regression line in Fig. 8a was 0.928, which is close to 1, and R^2 is 0.935, indicating that this empirical model is a practical tool for SF prediction when accuracy requirements are low.

For the empirical SR model, another regression analysis was performed among SR, I, and LA data for 18 randomly selected plants, resulting in Eq. (13):

$$\mathrm{SR} = 0.004\mathrm{LA}^{1.134}I^{-0.009}; R^2 = 0.996 \quad (13)$$

However, Eq. (12) reflects only the results under row and plant spacing of $60 \times 25\,\mathrm{cm}^2$. The empirical SR model was obtained by substituting Eq. (12) into Eq. (2):

$$\mathrm{SR} = \frac{0.062\ \mathrm{LA}^{1.134}I^{-0.009}}{I_\mathrm{w}R_\mathrm{w}} \times 100\% \quad (14)$$

The data for the remaining 18 plants were used to validate this model, and the relationship between calculated and measured values is shown in Fig. 8b. The slope and R^2 of the regression line from Fig. 8b suggest that the accuracy of Eq. (14) is higher than that of the semi-empirical model.

Values of ME efficiency and R^2 for the stemflow models are shown in Tab. 2. The ME efficiencies of the SF and SR models based on Eq. (5) form were −1.81 and −1.67, respectively. This indicates that the simulated data are higher than the measured data and that the models based on the Eq. (5) form give poor model simulation results. The ME efficiencies of the theoretical, semi-empirical, and empirical SF models are 0.91, 0.91, and 0.92, respectively, which are similar and close to 1. This indicates that the simulated results from these three models are consistent with measured results. However, it is difficult to measure the PA of corn plants. Judging from their R^2, the semi-empirical and empirical models of SF are applicable to predict and calculate SF in different corn growth stages. As for the SR models, the ME efficiencies of the theoretical, semi-empirical, and empirical models are 0.83, 0.82, and 0.82, respectively. The obtained simulation accuracy is slightly lower than from the SF models. However, the three models still have high ME efficiency, indicating that the simulated results from these three models are consistent with measured results. Compared to the empirical model, the semi-empirical model offers easy SR calculation and application.

Corn plants, especially in regard to the close planting, can transform a considerable portion of rain or sprinkler irrigation water into stemflow. Under these circumstances, the average SF over the whole growing season was found to be 55.69 mL/min, representing 44.55% of total rainfall, and reached its highest level in the VT stage. SF was closely related to both LA and I, but SR was significantly influenced only by LA, not by I. When a large portion of rainwater transformed to stemflow, it not only increased water utilization efficiency, but also significantly reduced throughfall of large raindrops as well as kinetic energy. This change had an

Table 2. ME efficiency of the models

Stemflow	Comparison	$I \cdot$PA model	Theoretical model	Semi-empirical model	Empirical model
SF	ME	−1.81	0.91	0.91	0.92
	R^2	0.847	0.936	0.935	0.935
Stemflow ratio	ME	−1.67	0.83	0.82	0.82
	R^2	0.572	0.783	0.775	0.826

important impact on splash detachment, runoff, and sediment yield processes. From the perspective of soil erosion, stemflow from corn plants on slopes partly does become surface runoff and lead to erosion. The protective effect of corn cover for the soil surface is probably offset by the stemflow effect, indicating that certain measures, such as contour farming, should be adopted to control erosion caused by stemflow. From the perspective of fertilizer and sprinkler irrigation management, the impact of uneven infiltration of irrigation water caused by stemflow on corn plants must be considered. Particularly on fast-infiltrating soil, fertilizers should not be applied near the base of corn plants to avoid strong leaching of chemicals to the root zone and underground water pollution. According to these management requirements, it is necessary to estimate stemflow effects on corn in different growth stages correctly and to design a suitable irrigation and fertilization plan combined with water and fertilizer requirements for corn, as well as a theory of soil water and solution transport.

The models presented in this study provided relatively accurate predicted values of stemflow in different growth stages of corn. Nonetheless, to develop more universal models, precise measurements of plant shape parameters, such as leaf angle and the ratio of LA of drooping leaves account to the total LA, should be conducted to calculate the actual rainwater collection area. In different growth stages, the ratio of actual collection area to total LA is changing. This change may be the intrinsic reason for the nonlinear relationship between SF and LA.

4 Concluding remarks

In this study, three models for the prediction of stemflow from corn plants were established based on LA, vertical PA, and *I*. Validation of these models indicated that they were suitable for calculations of SF and SR of corn in different growth stages. Among the three models, the semi-empirical model was the simplest and has high calculation precision to estimate SF. This study was conducted based on a single corn variety, and therefore variations in plant shape could not be considered. However, the theoretical model framework (Eq. (6)) was desirable, and the impact of different varieties was directly reflected in the correction parameter *a*. The determination of parameter *a* significantly affected the theoretical model and the accuracy of the semi-empirical model and was the key step in the establishment of stemflow models.

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