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Rainfall partitioning into throughfall, stemflow and interception loss by maize canopy on the semi-arid Loess Plateau of China

Jing Zheng[a], Junliang Fan[a,b,*], Fucang Zhang[a,b], Shicheng Yan[a], Youzhen Xiang[a]

[a] *Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas of Ministry of Education, Northwest A&F University, Yangling 712100, China*
[b] *Institute of Water-saving Agriculture in Arid Areas of China, Northwest A&F University, Yangling 712100, China*

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ABSTRACT

Rainfall or sprinkler irrigation water partitioning by the crop canopy is an important way of affecting the effective use of water by maize. To investigate the rainfall partitioning by maize canopy at different growth stages as well as its influencing factors on the water-limited Loess Plateau of China, the gross rainfall, throughfall and stemflow were measured during the growing seasons of 2015 and 2016. The effects of rainfall characteristics (gross rainfall and rainfall intensity) and canopy structure (leaf area index) on rainfall partitioning were further evaluated, based on which multiple regression models were developed to predict the partitioned rainfall components. Results showed that the measured throughfall, stemflow and derived interception loss accounted for 65.2%, 22.3% and 12.5% of cumulative gross rainfall during the whole growing season of maize, respectively. Specifically, the relative throughfall declined from 83.2% at the seedling stage to 52.2% at the tasseling stage, and then increased to 58.6% at the maturity stage. The relative stemflow and interception loss increased from 13.6% and 3.1% at the seedling stage to 30.6% and 17.3% at the tasseling stage, and then declined to 25.0% and 16.5% at the maturity stage, respectively. Smaller rainfall events contributed to a lower percentage of throughfall and stemflow but higher percentage of canopy interception loss. The percentages of stemflow and throughfall showed an increased tendency with increasing gross rainfall and rainfall intensity, while the increasing leaf area index resulted in a decrease in the relative throughfall but an increase in relative stemflow and interception loss. Generally, the amount of throughfall, stemflow and canopy interception loss can be predicted reasonably well using the developed multiple linear regression models, but the proportions of partitioned rainfall components generally had a relatively lower accuracy using the developed nonlinear models, especially for relative stemflow. This study can help to determine more precise irrigation schedule by the water balance method and give implications for the operation of sprinkler irrigation systems for higher irrigation water use efficiency.

1. Introduction

Rainfall or sprinkler irrigation water above the crop canopy is partitioned into three components as it moves towards the ground, i.e., throughfall, stemflow, and canopy interception loss. Throughfall reaches the ground directly through the canopy gaps without canopy interception or drips from the leaves after temporal storage in the canopy (Dunkerley, 2000; Fan et al., 2015). Stemflow is the portion of rainfall that flows down the plant stem and concentrates in the root zone around the stem base (Lamm and Manges, 2000; Liu et al., 2015). These rainfall partitioning processes affect the volume and also the spatial distribution of effective rainfall reaching the soil surface, representing the sum of throughfall and stemflow, which is often the major or even the sole source of soil water replenishment and can be of significance to the crop's survival in arid and semi-arid areas (Li et al., 2009; Zhang et al., 2015). Canopy interception loss refers to the part of rainfall that is intercepted, reserved and eventually evaporated back into the atmosphere during and after rainfall or sprinkler irrigation (Jackson, 2000; Fan et al., 2014), which reduces the availability of total water input to the field and can be a significant water loss in agricultural ecosystems.

Field and laboratory investigations have exhibited considerable variability in the partitioning of rainfall or sprinkler irrigation by crops, especially for maize plants. Steiner et al. (1983) measured the throughfall, stemflow and incident amount of water and calcu-

* Corresponding author at: College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling 712100, Shaanxi, China.
E-mail address: nwwfjl@gmail.com (J. Fan).

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lated the interception loss by maize canopy through a water budget method when the leaf area index exceeded 3.0 $m^2\ m^{-2}$. They found that throughfall and stemflow ranged from 31% to 55% and 35% to 64%, respectively, and canopy interception loss was about 10%. Zheng et al. (2012) found the average of throughfall, stemflow and interception loss occupied 65.68%, 26.79% and 7.53% during the whole growth period of maize by using a rainfall simulator, while the relative throughfall, stemflow and interception loss were 53.4%, 33.3% and 13.3% under natural rainfall conditions (Han et al., 2014). According to a literature reviewed by Paltineanu and Starr (2000), the throughfall generally ranged from 35% to 84% and the stemflow varied between 12% and 57% under sprinkler irrigation conditions. These studies indicate that there still exist large differences in the results of water partitioning by maize canopy, causing these results cannot be directly applied to other regions. Moreover, there are few studies focusing on the rainfall partitioning at different growth stages of maize, compared with the present studies mostly developed in matured maize.

The semi-arid Loess Plateau of China is an important region for food production in China, where maize (*Zea mays* L.) is one of most popular grain crops. This region experiences approximately 200 mm to 750 mm of annual rainfall, with approximately 70% of which falling between June and September (Ren et al., 2008). Droughts occur frequently and water scarcity is becoming a major problem during the maize growing season. The key to increase agricultural productivity lies in how to maximize the utilization of limited and erratic rainwater resources, and how to plan precise irrigation schedule during the whole growing season of maize. In high evaporative potential regions such as the Loess Plateau, rainfall of less than 5 mm per event was mostly considered to be ineffective or unproductive rainfall (Wu et al., 2016), with the rest as effective rainfall. The effective rainfall was also estimated by using a simple utilization coefficient (Rajak et al., 2006; Zheng et al., 2013). However, the interception loss caused by the crop canopy during larger rainfall or sprinkler irrigation events has always been overlooked when planning the irrigation schedule by the water balance method, which is expected to underestimate the actual amount of irrigation water required by the crop, and thus causes the reduction in grain yield.

Thus, throughfall, stemflow and canopy interception loss at different growth stages of maize were systematically measured in this study. The main influencing factors on rainfall partitioning were further explored, based on which multiple regression models were developed to predict the partitioned rainfall components. This study was expected to provide a simple model for canopy interception loss prediction, which was further used to determine more precise irrigation schedule by water balance method. The study also tended to have implications for the operation of sprinkler irrigation systems at different growth stages of maize to improve the irrigation water use efficiency.

2. Materials & methods

2.1. Site description

Field experiments were carried out in 2015 and 2016 at the Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Area sponsored by Ministry of Education (34°18′N, 108°24′E; 521.0 m above sea level), at Northwest A&F University, in Yangling, Shaanxi Province of China. This area, classified as a semi-arid zone, has a warm temperate and monsoon climate (Dong et al., 2013). Mean annual precipitation is 560 mm (1995–2014), with 65% of rain falling between June and September with a coefficient of variation of 29.7%. The annual mean air temperature at the site is 12.9 °C and the annual mean pan evaporation is 1500 mm (Gu et al., 2016). The total annual sunshine hour is 2196 h and the frost-free period is 220 d.

2.2. Experimental design

The plastic film-mulched ridge and the bare furrow planting system was adopted in this experiment as a common agronomic practice on the Loess Plateau to improve the rainwater use efficiency (Ren et al., 2008; Liu et al., 2016). Each experimental plot was 10 m long and 6 m wide with three replications, which were separated by a 1.5 m wide zone surrounding each plot to minimize the mutual effects of adjacent plots. The maize hybrid of "Zhengdan 958" was used in this study as it is a high-yielding maize variety and widely grown by local farmers. The maize was sown with a row and plant spacing of 60 cm × 25 cm on 15 June 2015 and 12 June 2016, which is a typical planting pattern for maize. Before the maize was sown, all plots received a basal fertilizer of 180 kg ha^{-1} N, 120 kg ha^{-1} P_2O_5 and 60 kg ha^{-1} K_2O. There was no irrigation and fertilization during the maize growing season in both years. According to the maize growth characteristics in the two years, the entire growing season was roughly divided into four growth stages, i.e., seedling (from 20 June to 10 July), jointing (from 11 July to 31 July), tasseling (from 1 August to 31 August) and maturity (from 1 September to 1 October).

2.3. Collection of gross rainfall and other meteorological variables

The gross rainfall (P, mm) was recorded by a standard ticking-bucket rain gauge with an accuracy of 0.1 mm and a mini logger recording 60-min rainfall amount from an automatic weather station (HOBO event logger, USA) located in a nearby clearing at a distance of 25 m. Four collecting containers (10 cm in diameter and 15 cm in height) were also placed around the experimental plot to obtain average gross rainfall. The rainfall volume from collecting containers was measured right after each rainfall event. A rainfall event was defined as a rainfall period from preceding and succeeding rainfall being separated by at least 6 h without rainfall. The average rainfall intensity (RI, mm/h) during each rainfall event was estimated by the weighted mean hourly rainfall intensity:

$$RI = \sum_{i=1}^{n} \frac{R_i}{G} \times RI_i \quad (1)$$

where n is the number of hours recorded by the rain gauge during a rainfall event, R_i is the rainfall amount (mm) at the i^{th} hour, and G is the gross rainfall during a rainfall event.

Air temperature and relative humidity were measured every an hour and 10-min averages of wind speed at 10 m were also recorded by the weather station. To comprehensively reflect the synergistic effect of air temperature and relative humidity, we adopted the index of vapor pressure deficit (VPD, kPa) which was calculated as:

$$VPD = 0.611 \cdot e^{[17.502T_a/(T_a+240.97)]} \cdot (1\text{-}RH) \quad (2)$$

where T_a is the air temperature (°C) and RH is the relative humidity (%).

2.4. Collection of throughfall and stemflow

The throughfall (T, mm) was collected by 15 containers located beneath four adjacent maize plants at each experimental plot (Fig. 1). Their sites were randomly chosen and ensured that these containers covered a ground area representative of the row and plant spacings. Throughfall volume was measured manually right after the cessation of individual rainfall and converted to an average equivalent depth by dividing the horizontal cross-sectional area of the container (Tanaka et al., 2015). Each throughfall measurement