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Investigation of canopy interception characteristics in slope protection grasses: A laboratory experiment

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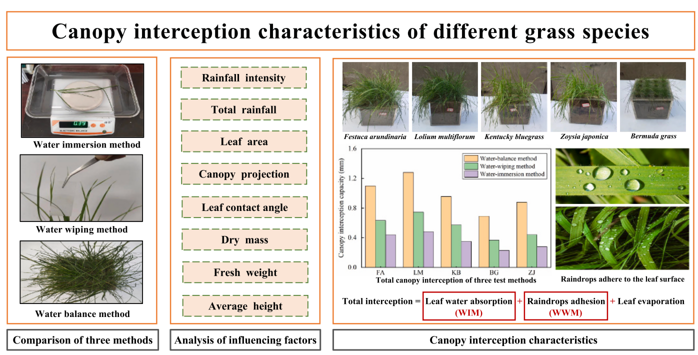
HIGHLIGHTS

- The effect of leaf contact angle of grass on the rainfall interception is explored.
- Three popular experimental methods for canopy interception of grass are compared.
- Assessed the contribution of rainfall and leaf characteristics to canopy interception
- A regression model is proposed to predict the canopy interception process of grass.

GRAPHICAL ABSTRACT



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ABSTRACT

Canopy interception significantly affects hydrological processes such as infiltration, runoff and evapotranspiration. Research on grass canopy interception remains limited, and the experimental methods employed differ substantially. To thoroughly investigate the canopy interception characteristics of grass and clarify the methodological differences, five commonly utilized slope protection grass species in temperate regions were cultivated in a laboratory setting, and their canopy interception characteristics were experimentally investigated using the water-balance method (WBM), the water-wiping method (WWM) and the water-immersion method (WIM), respectively. The results showed that the WBM is more accurate for measuring canopy interception in grass, whereas both the WWM and the WIM underestimate grass canopy interception capacity. The canopy interception capacity measured by the WBM was 1.61–2.09 times higher than that of the WWM and 1.93–3.47 times higher than that of the WIM. Grey correlation analysis of the eight evaluated factors indicated that leaf area is the most influential factor affecting canopy interception in grass, followed by rainfall amount, dry mass, rainfall intensity, canopy projection area, leaf contact angle, fresh weight, and average height. There is a negative power function relationship between the interception ratio and the rainfall amount. With increasing rainfall intensity, the canopy interception capacity initially increases and then decreases, peaking at rainfall intensities of 15 to 20 mm/h. Leaf contact angle is a key quantifiable parameter that explains the differences in canopy

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interception among different grass species, and the canopy interception per unit leaf area decreases as the leaf contact angle increases. This study demonstrates that the WBM provides the most accurate measurements of grass canopy interception compared to the WWM and WIM, and highlights the leaf contact angle as a key factor in explaining interspecies differences. These findings could enhance the understanding of grass canopy interception and guide the selection of experimental methods.

1. Introduction

Precipitation is intercepted and redistributed by the vegetation canopy before it reaches the ground. The rainwater intercepted during this process can account for 10 % - 50 % of the total rainfall (Sadeghi et al., 2020; Zheng and Jia, 2020; Zheng et al., 2018). Canopy interception plays a vital role in regulating water spatial distribution and improving ecological functions. For example, canopy interception reduces surface runoff by decreasing the amount of rainfall falling directly to the ground (Keim and Skaugset, 2004). Additionally, the vegetation canopy reduces soil erosion by diminishing the kinetic energy of rainwater (Vásquez-Méndez et al., 2010). Besides, canopy interception is also dynamically associated with other hydrological process, such as evaporation, infiltration and soil water transportation (Gerrits et al., 2010; Wu et al., 2016). Thus, investigating the canopy interception characteristics is of great significance for environmental protection and water resource management.

There are significant differences in canopy interception characteristics due to variations in vegetation species and growth conditions (Yuan et al., 2022). Currently, extensive investigations have been conducted on the canopy interception process of trees (Howard et al., 2022; Wei et al., 2020), shrubs (Snyder et al., 2022; Zhao et al., 2023), and crops (Lin et al., 2020; Zhang et al., 2023). Through monitoring the total rainfall, throughfall, and stemflow, the amount of canopy interception can be calculated using the water-balance method (WBM) of subtracting stemflow and throughfall from the total rainfall (Hassan et al., 2017). A meta-analysis of field studies on 68 woody plant species in drylands found that average interception, throughfall, and stemflow accounted for 24 %, 69.8 %, and 6.2 % of total rainfall, respectively (Magliano et al., 2019). Sadeghi et al. (2020) conducted a review of 644 observations across various climates and plant types, reporting that relative throughfall was highest in forests, followed by shrubs, crops, and grasses, whereas relative stemflow was highest in grasses, followed by crops, shrubs, and forests. Unlike trees and shrubs, it is challenging to directly monitor throughfall and stemflow in grass due to its low height, soft stem structure and dense leaves (Demir et al., 2022). In addition, grasslands usually intercept less rain than tall vegetation such as forests and shrubs (Madani et al., 2018). Consequently, research on rainfall interception of grasses has not received adequate attention (Gordon et al., 2020). However, grassland is one of the most essential terrestrial ecosystem types on earth, accounting for about 25 % of the total land area (Zhao et al., 2020). An investigation in New South Wales, Australia, has found that the canopy interception of the striped Mitchell grassland can reach 32 % of annual rainfall (Dunkerley and Booth, 1999). In arid regions, some grassland communities grow densely and close to the ground, and the interception loss can exceed 35 % of the annual rainfall (Dunkerley, 2000). Therefore, the rainfall interception effect of grass cannot be ignored, especially in arid areas with less rainfall and lush grass growth.

Grasses are also widely used for soil and water conservation, and ecological protection on slopes (Pan and Ma, 2020; Tu et al., 2021). The protective effect of grass on soil slope is achieved by both the root system and canopy interception. Numerous studies have shown that the root system of grass can enhance the shear strength of the slope (Ma et al., 2021). Additionally, root growth occupies soil pores, reducing soil infiltration capacity and improves the soil water retention capacity (Song et al., 2017). Moreover, grasses are prone to forming dense communities on the slope surface, which improves land cover. Therefore, the interception effect of grass canopy can weaken the rainfall erosion on the slope surface and reduce rainfall infiltration to improve the slope stability (Li and Pan, 2018). Evidence indicates that the runoff of the slope after implementing grass protection is significantly smaller than that of the exposed slope (Liu et al., 2022).

Due to the small branches and soft structure of the stems, there has been no standardized experimental method for measuring canopy interception of grass. At present, the water-immersion method (WIM), the water-wiping method (WWM), and the WBM are commonly used to measure the canopy interception of grass (Yu et al., 2012). The WIM is to cut off the above ground part of grass and determine the interception capacity of grass by measuring the weight difference between the leaves before and after water-immersion (Wohlfahrt et al., 2006; Xiong et al., 2019). The WIM is convenient, however, cutting off leaves prevents the assessment of the effect of canopy structure on canopy interception. Moreover, the interception characteristics under different rain conditions are also unable to be examined. The WWM refers to the use of highly absorbent materials to absorb the accumulated rainwater on grass leaves after rain and weigh them (Kang et al., 2005; Wang et al., 2006). This method can preserve the original canopy structure of the grass, but there are large operational errors, and the dynamic process of canopy interception is not investigable. The WBM is considered a more appropriate method for measuring the canopy interception of grass without damaging the vegetation structure and can monitor the dynamic changes of canopy interception (Demir et al., 2022). Similar to monitoring canopy interception in forests, canopy interception in grasses can also be obtained by monitoring total rainfall, throughfall and stemflow, respectively. Due to the inconspicuous stems of grasses, some researchers have attempted to seal the soil surface before simulating rainfall (Li et al., 2009). All the throughfall and stemflow are collected in the form of surface runoff, and then the canopy interception is determined based on the difference between total rainfall and surface runoff. The WBM is more complex than the WIM and the WWM, but it is more in line with the definition of canopy interception. These three methods have been widely used in investigating canopy interception of grass, and each has benefits and drawbacks. However, the comparison of measurement results and the causes for the differences between the three experimental methods are still poorly understood.

Canopy interception is a complex process, which is influenced by multiple factors such as meteorological conditions (i.e., rainfall, temperature, wind speed and humidity) and plant characteristics (i.e., species, leaf area, canopy coverage, height and biomass) (Holder and Gibbes, 2017; Livesley et al., 2014). Numerous investigations have shown that the canopy interception is primarily affected by rainfall characteristics and canopy structure features, which determine the input of rainwater and the carrying capacity of the canopy, respectively (Grunicke et al., 2020). There has been extensive exploration regarding the effect of elements like rainfall amount, rainfall intensity, rainfall duration, leaf area, biomass, and canopy coverage on canopy interception (Grunicke et al., 2020; Nakayoshi et al., 2009). Unfortunately, the majority of these studies focused on trees and small shrubs, while the effects of various factors on grass were inadequately examined. Leaves are the primary organ for canopy interception in grasses, since most of the rainwater intercepted during rainfall is adsorbed on the leaf surface (Yang et al., 2019). Raindrops on leaves of different plants display a variety of shapes, such as spherical, hemispherical, and water film (Xiong et al., 2018), indicating different wetting properties of the leaves. The wettability of leaves is usually measured by calculating the contact angle between sessile water droplets and the leaf surface. The rainwater tends to spread into a water film on the leaf surface with small contact angle, which is not susceptible to external disturbance. Conversely, rainwater is prone to forming water droplets on leaf surfaces with large contact angles, which can easily leave the leaf surface under the action of wind and gravity (Holder, 2013; Holder and Gibbes, 2017). Leaf wettability reflects the affinity of leaves to water and may directly affect the rainwater interception ability of vegetation canopy. However, the role of leaf contact angle is rarely considered in research on canopy interception. Moreover, research on the factors affecting canopy interception is largely confined to single-factor investigations, and there is a lack of comparative studies on the extent to which various factors affect the canopy interception of grasses.

At present, many empirical and theoretical models have also been developed in view of the correlation between canopy interception and various influencing factors (Baiamonte, 2021; Muzylo et al., 2009; Vrugt et al., 2003). The inference process of the theoretical model is rigorous, but it usually requires a large number of parameters and is difficult to solve. Therefore, empirical or semi-theoretical models are preferred in practical applications as they require fewer parameters and can provide practical estimation of canopy interception. The most commonly used models are the Gash model (Gash, 1979) and the Rutter model (Rutter et al., 1972). Nevertheless, these models are mostly applicable to estimating canopy interception of different forest and crop species (Muzylo et al., 2009; Nazari et al., 2020), while there is less research on models applied to grass species (Liu et al., 2024), especially for the prediction of interception process of grass. The inadequate understanding on canopy interception in grass and the lack of corresponding mathematical model has promoted the development of this study.

Therefore, the objectives of this paper were to (1) identify the differences in the results of three commonly used experimental methods for canopy interception of grasses and investigate the reasons for the differences; (2) reveal the influence of rainfall characteristics, canopy features, and leaf contact angle on the canopy interception of grass, and quantitatively analyze the contribution of each factor to the canopy interception; (3) explore the canopy interception process of grasses and establish a regression model to predict it. We hypothesised that canopy interception measured by the WBM would be higher compared to the WBM and the WIM, and that canopy interception would decrease with increasing leaf contact angle.

2. Material and methods

2.1. Grass species and cultivation

Five commonly used slope protection grass species in temperate regions (Brummitt et al., 2001), namely *Festuca arundinaria* (FA), *Lolium multiflorum* (LM), *Kentucky bluegrass* (KB), *Bermuda grass* (BG), and *Zoysia japonica* (ZJ), were utilized to investigate the characteristics of canopy interception. FA, LM and KB are cool-season grasses with strong resistance to cold and drought environments. BG and ZJ are warm-season grasses that are resistant to high air temperatures and humidity. Due to their excellent environmental adaptability, simple maintenance, and low cost, these five kinds of grass have a wide range of applications in urban greening, soil and water conservation, and ecological protection of slopes (Tu et al., 2021). According to the thousand grain weight of different kinds of grass seed, FA and LM are sown at 35 g/m^2, while KB, BG, and ZJ are sown at 25 g/m^2. As shown in Fig. 1, these grasses are planted in the holes on the top cover of the cultivation box in the laboratory. Holes are created to facilitate the sealing of the soil surface while performing experiments using the WBM and the WWM. To enhance the reliability of the experimental results, each grass species was seeded in five identical cultivation boxes as replicate samples. The size of the cultivation box is 20 cm × 20 cm × 20 cm. The soil used for cultivating grass was silty fine sand. The air temperature in the laboratory was maintained at 24 ± 2.7 °C and the relative humidity was 60 ± 5 %, which was beneficial for the germination and growth of these grass species (Butler et al., 2017). Canopy interception experiments were conducted after 90 days of cultivation. Sampling revealed that the alteration in leaf area with grass growth was <0.3 % during the experiment.

2.2. Experimental design

To compare the performance of different experimental methods and investigate the interception process, the canopy interception characteristics of five grass species were investigated using the WBM, the WWM, and the WIM, respectively. Specifically, the WBM and the WWM employed artificial rainfall simulation method, while the WIM utilized the immersion method. For the five replicate cultivation boxes of each grass species, canopy interception experiments were independently conducted. The WBM was first used to conduct interception experiments at eight different rainfall intensities (5, 10, 15, 20, 25, 30, 40, and 50 mm/h). These rainfall intensities were selected with reference to previous studies on similar rainfall interception experiments (Dunkerley, 2015; Snyder et al., 2022). Following the WBM experiments, the investigation proceeded with the WWM, where the rainfall intensities was maintained consistent with the WBM. Subsequently, all the leaves of the grasses were cut off along the top cover of the cultivation box, and the amount of water absorbed by the leaves was then determined using the WIM. To avoid water ingress into the interior, the slice planes of stems were sealed with wax.

The WBM and the WWM were carried out using a self-designed rainfall simulation device, as shown in Fig. 2. The rainfall intensity was adjusted by controlling the flow rate of the pump. The rainfall area is 25 × 25 cm^2, which ensures that all leaves are within the rainfall range. The gaps between the holes and the grass stems were sealed with a waterproof material (*Niuyuan*) before the canopy interception experiment to avoid rainwater infiltrate into the soil of the cultivation box during the experiment. To avoid wilting of the grasses from long time water shortage, the soil in the cultivation box was thoroughly irrigated prior to sealing the gaps, ensuring that the grasses had sufficient water

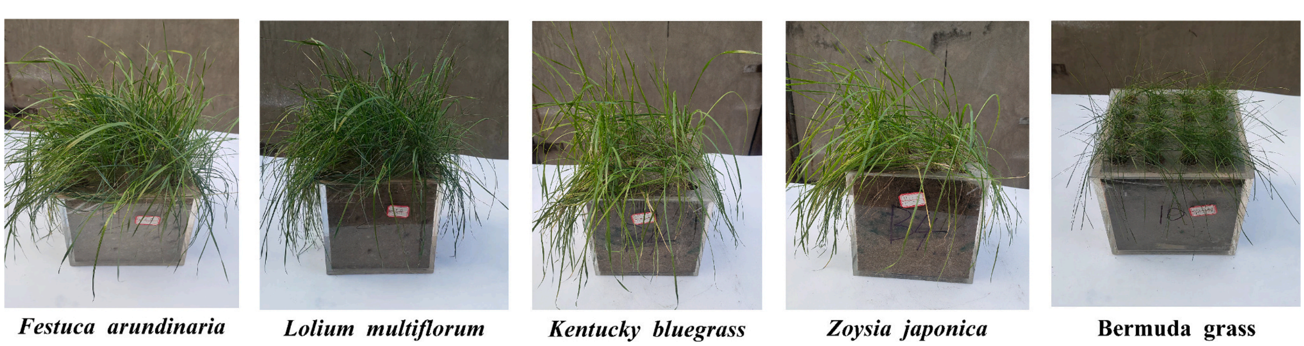

Fig. 1. Planting and growth of five grass species in the cultivation box.

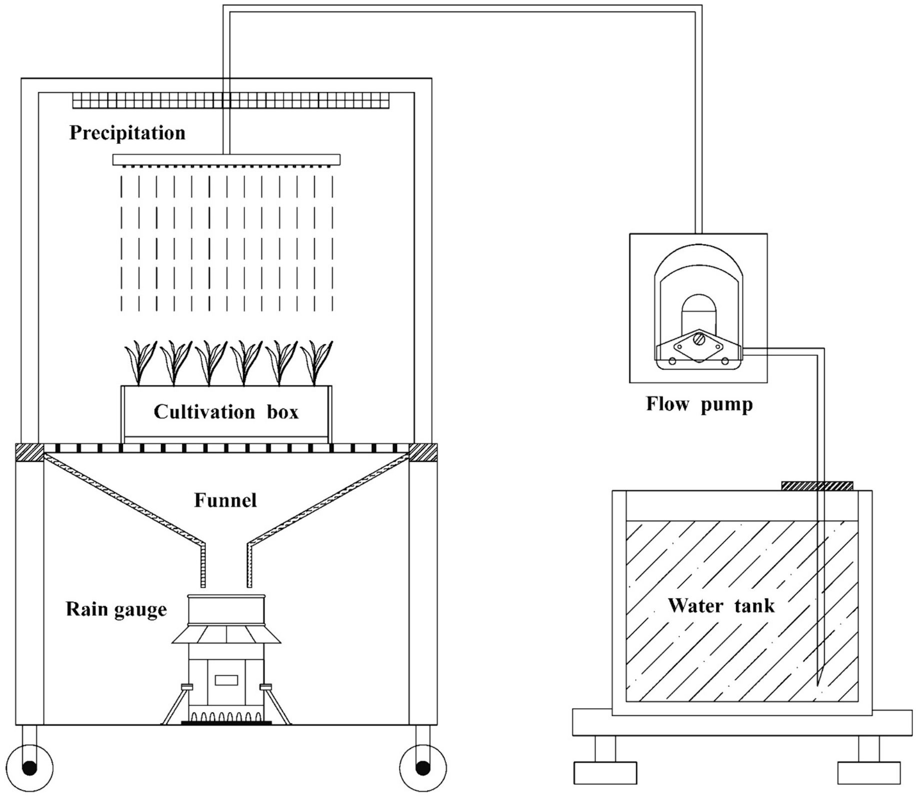

Fig. 2. Schematic diagram of rainfall simulation device.

supply throughout the experiment. Placing the cultivation box on the funnel at a slight angle to prevent rainwater from accumulating on the top cover. Weighing the cultivation box revealed that its weight returned to the initial level after 6 h of rest following the simulated rainfall experiment. Therefore, the same cultivation box was allowed to stand for 6 h after each test before conducting the next set of tests. This practice ensures that the drying state of the leaves remains constant across consecutive tests, minimizing any potential variations in the experimental conditions.

Pre-testing was conducted at eight rainfall intensities (5, 10, 15, 20, 25, 30, 40, 50 mm/h) in a sealed cultivation box without grass. The total rainfall in different rainfall intensities was 10 mm. Available research has shown that a rainfall of 10 mm can achieve maximum interception of vegetation canopy (Pypker et al., 2005). The pre-tests were used, on the one hand, to calibrate the rainfall intensity using a rain gauge. Additionally, a small amount of rainwater will adhere to the surface of the device during the rainfall process. Ignoring this portion of interception may result in an overestimation of canopy interception when applying the WBM experiments. The pre-tests allowed for the determination of the dynamic changes in the amount of water adhered on the surface of the device at different rainfall intensities. Therefore, the accuracy of the measurement results can be improved by subtracting this part of adhered water when conducting the canopy interception experiment. Each rainfall intensity was subjected to three pre-tests, with the results being averaged.

2.3. Measurement of leaf parameters

When the experiments finished, the projection information of the grass canopy in each cultivation box was recorded through photography, and the software of Image J was utilized to calculate the canopy projection area. To prevent leaf dehydration, leaf area of each cultivation box was immediately measured using a leaf area analyzer (LD-YMJ-S, China) after the completion of the water-immersion experiment. Subsequently, 30 leaves were randomly selected for each grass species, and the contact angle between the 2 μl water droplet and the leaf front surfaces was measured using a contact angle goniometer (DSA 100S, Germany). The average height of the grass was calculated by dividing the projected area of the main view of the grass canopy (above the top cover) by the width of the top cover. The fresh weight of the leaves was measured before the water-immersion experiment. After the water immersion experiment, the dry mass of the leaves was determined after drying for 24 h in an oven at 60 °C. An electronic scale with an accuracy of 0.001 g was used to weigh the leaf mass.

2.4. Experimental methods

2.4.1. Water-balance method (WBM)

The throughfall and stemflow were converted into surface runoff, which was monitored by the rain gauge (HC-YL9072, China). To analyze the dynamic changes in grass canopy interception over time, data from the rain gauge was recorded every 1 min. The test was stopped when the increase in surface runoff monitored by the rain gauge reached a steady state. The expression of canopy interception measured by the WBM was represented by Eq. (1).

$$I_b = P - T_r - S \tag{1}$$

where I_b is the amount of canopy interception measured based on the WBM (mm). P is the total rainfall (mm). T_r is the amount of rainfall being monitored by the rain gauge as the sum of the throughfall and stemflow (mm). S is the amount of rainfall adhered on the surface of the device (mm).

2.4.2. Water-wiping method (WWM)

A large number of raindrops adheres on the grass leaves during the rainfall process. When the rain stops, carefully absorb the rainwater adhering to the leaves with highly absorbent paper. An electronic scale with an accuracy of 0.001 g was used to weigh all the absorbent papers (before and after wiping). The canopy interception of the canopy can be calculated by the weight difference of the absorbent paper before and after absorbing water.

$$I_w = \frac{10 \times (M_{pa} - M_{pb})}{\rho \cdot G} \tag{2}$$

where I_w is the amount of canopy interception measured based on the WWM (mm). M_{pb} is the weight of absorbent paper before wiping rainwater (g). M_{pa} is the weight of absorbent paper after wiping rainwater (g). ρ is the density of water, 1 g/cm^3. G is the rainfall area.

2.4.3. Water-immersion method (WIM)

The leaves were weighed immediately after sealing the slice planes of stems with wax and then submerged in water. The leaves were weighed every 10 min, and the amount of water absorbed was calculated by the difference in leaf mass. An electronic balance with an accuracy of 0.001 g was used to weigh the leaf mass (before and after immersion). With each measurement, the leaves were carefully wiped with absorbent paper to eliminate any excess water. The entire procedure typically took <1 min, minimizing water loss by evaporation. The test was finished until eventually there were no more changes in the leaf weight.

$$I_i = \frac{10 \times (M_{ia} - M_{ib})}{\rho \cdot G} \tag{3}$$

where I_i is the amount of canopy interception measured based on the WIM (mm). M_{ia} is the weight of grass leaves before it absorbs water (g). M_{ib} is the weight of grass leaves after absorbing water (g).

Canopy interception capacity is the maximum amount of rainwater that grass can absorbed and retained by leaves during precipitation events. The canopy interception capacity measured by the WBM and the WIM was determined by the maximum values recorded during the monitoring process, while for the WWM, it was taken as the value at the end of the experiment.

2.5. Statistical analysis

The leaf area, contact angle, average height, biomass, canopy projection area and canopy interception of different grass species were analyzed by one-way analysis of variance (ANOVA) to determine whether there were significant differences between grass species. Similarly, ANOVA was also employed to analyze whether there were significant differences among three different experimental methods. When ANOVA indicated significant differences, multiple comparisons among group means were conducted using the least significant difference (LSD) method. Pearson's product moment correlation and least squares regression analysis were adopted to assess the degree of linear association between leaf area, canopy projection area, contact angle, rainfall amount, and rainfall intensity with canopy interception. All statistical tests were considered significant at $p < 0.05$. Data analyses were conducted using IBM SPSS Statistics 26.0 software. Determining the contribution of various factors to canopy interception helps to promote understanding of interception mechanisms, and is a crucial basis for developing canopy interception prediction models. The grey correlation analysis method was employed to investigate the factors influencing canopy interception, aiming to gain insights into the significance of these factors in the context of grass canopy interception. Multiple regression analyses were used to explore the relationship between maximum canopy interception and rainfall characteristics and canopy features.

3. Results

3.1. Vegetation characteristics

Table 1 shows the measured vegetation characteristics and their standard deviations for each grass species. ANOVA indicated that there were statistical differences in leaf area, contact angle, fresh weight, dry mass and canopy projection area among five grass species. Average heights of FA, LM, and ZJ were significantly different from KB and BG. LM has the fastest growth rate, with the largest mean leaf area, fresh weight, dry mass, and canopy projection area. These characteristics suggest that LM has a more extensive and denser canopy, which could contribute to enhanced canopy interception. On the contrary, the smallest leaf area, fresh weight, dry mass and canopy projection area were recorded for BG. The leaf area of LM is approximately twice that of BG, and the dry mass of LM is about 1.7 times that of BG. The average height of the five grass species ranged from 11.94 cm for KB to 17.11 cm for LM. Furthermore, the contact angles of the three cool-season grasses, FA, LM, and KB, were measured at 110.2°, 123.7°, and 97.6°, respectively. These values were significantly smaller than the contact angles observed for the warm-season grasses, BG, and ZJ, which had contact angles of 133.9° and 141.4°, respectively. The smaller contact angles indicate that the leaf surfaces of cool-season grasses may be more hydrophilic than those of warm-season grasses, which could contribute to their ability to intercept and retain rainwater more effectively.

Table 1
Leaf characteristics for the five cultivation boxes of each grass species.

Species	L_a (cm^2)	C_a (°)	H (cm)	W_f (g)	M_d (g)	C_{pa} (cm^2)
FA	1144.97 ± 49.71b	110.2 ± 2.7d	15.79 ± 0.31a	109.82 ± 6.71b	60.34 ± 4.63b	459.19 ± 13.60b
LM	1392.88 ± 59.16a	123.7 ± 2.1c	17.11 ± 0.35a	120.05 ± 7.39a	64.51 ± 5.64a	481.61 ± 14.75a
KB	965.72 ± 31.63d	97.6 ± 5.0e	11.94 ± 0.23b	64.44 ± 5.12d	40.03 ± 3.40d	397.46 ± 10.52d
BG	787.52 ± 30.66e	133.9 ± 5.6b	12.56 ± 0.19b	59.16 ± 3.99e	37.92 ± 3.48e	359.85 ± 7.18e
ZJ	1034.68 ± 34.13c	141.4 ± 3.3a	15.12 ± 0.37a	79.21 ± 5.92c	45.47 ± 4.26c	424.72 ± 14.35c

Notes: Leaf area (L_a); contact angle (C_a); average height (H); fresh weight (W_f); dry mass (M_d); canopy projection area (C_{pa}). Data in the table are mean values ± standard deviation, and different lowercase letters indicates significant differences at $p < 0.05$ between different grass species.

3.2. Comparison of the three experimental methods

Fig. 3 illustrates the canopy interception capacity for each grass species measured using the three experimental methods. Affected by the measurement methods, the canopy interception capacity measured by the WIM remains constant for each grass species, while that measured by the WBM and the WWM varies with different rainfall intensities. The results of ANOVA indicate statistical differences ($p < 0.05$) in canopy interception measured by the three methods. For example, the canopy interception capacity measured under the eight rainfall intensities for LM, which had the highest canopy interception capacity, ranged from 0.92 mm (Fig. 3(h)) to 1.39 mm (Fig. 3(d)) using the WBM, 0.57 mm (Fig. 3(h)) to 0.82 mm (Fig. 3(d)) using the WWM, and only 0.48 mm using the WIM. For the FA, KB, BG, and ZJ, the canopy interception capacity measured by the WBM under 8 rainfall intensity conditions was also significantly higher than that of the WIM, and the WWM were between the WBM and the WIM. Specifically, the canopy interception capacity measured by the WBM was 1.93 times (LM at 50 mm/h) to 3.47 times (ZJ at 15 mm/h) higher than that measured by the WIM, and 1.61 times (KB at 15 mm/h) to 2.09 times (ZJ at 20 mm/h) higher than that the WWM. Furthermore, the canopy interception capacity measured by the WWM was 1.29 times (FA at 5 mm/h) to 1.80 times (KB at 20 mm/h) higher than that measured by the WIM. The results indicate that the WBM recorded the largest canopy interception capacity, while the WIM had the lowest, across different rainfall intensities and with various grass species. Additionally, ANOVA also showed statistically significant differences among the five grass species ($p < 0.05$). Following the same

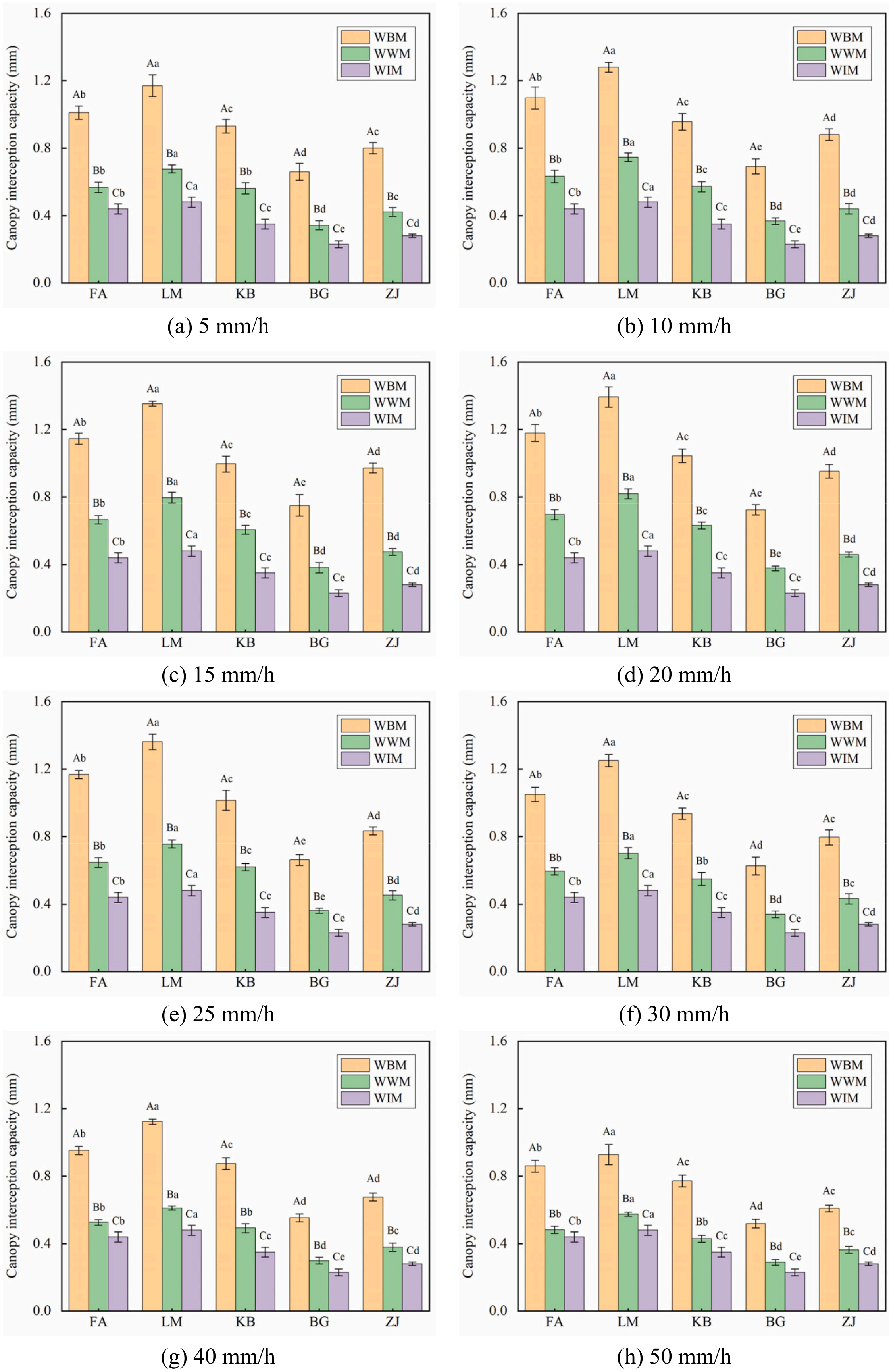

Fig. 3. Comparison of canopy interception capacity for the three experimental methods. Different capital letters indicate significant differences ($p < 0.05$) between different experimental methods for the same grass species. Different lowercase letters indicate significant differences ($p < 0.05$) between different grass species for the same experimental method.

experimental procedure, the canopy interception capacity for the five grass species ranked as LM > FA > KB > ZJ > BG.

3.3. Dynamic processes of canopy interception

There was a consistent trend in canopy interception variation with rainfall duration for the five grass species based on WBM. Fig. 4 illustrates the variation process of the average canopy interception for the five grass species under different rainfall intensities, as measured by the WBM. It is evident that the interception process can be divided into three stages: rapid period, slow period and saturation period. The corresponding time of the three stages in the five grass species are shown in Table 2. For the WBM, the leaves were relatively dry at the beginning of rainfall, and the rainwater could be quickly adhered and stored on the surface of the leaves. The amount of rain intercepted during the rapid period was relatively large, but the duration was relatively short. FA, LM, KB, BG and ZJ intercepted 83.98 %, 81.69 %, 87.91 %, 69.33 % and 76.77 % of the canopy interception capacity at 12 min, 6 min, 3 min, 23

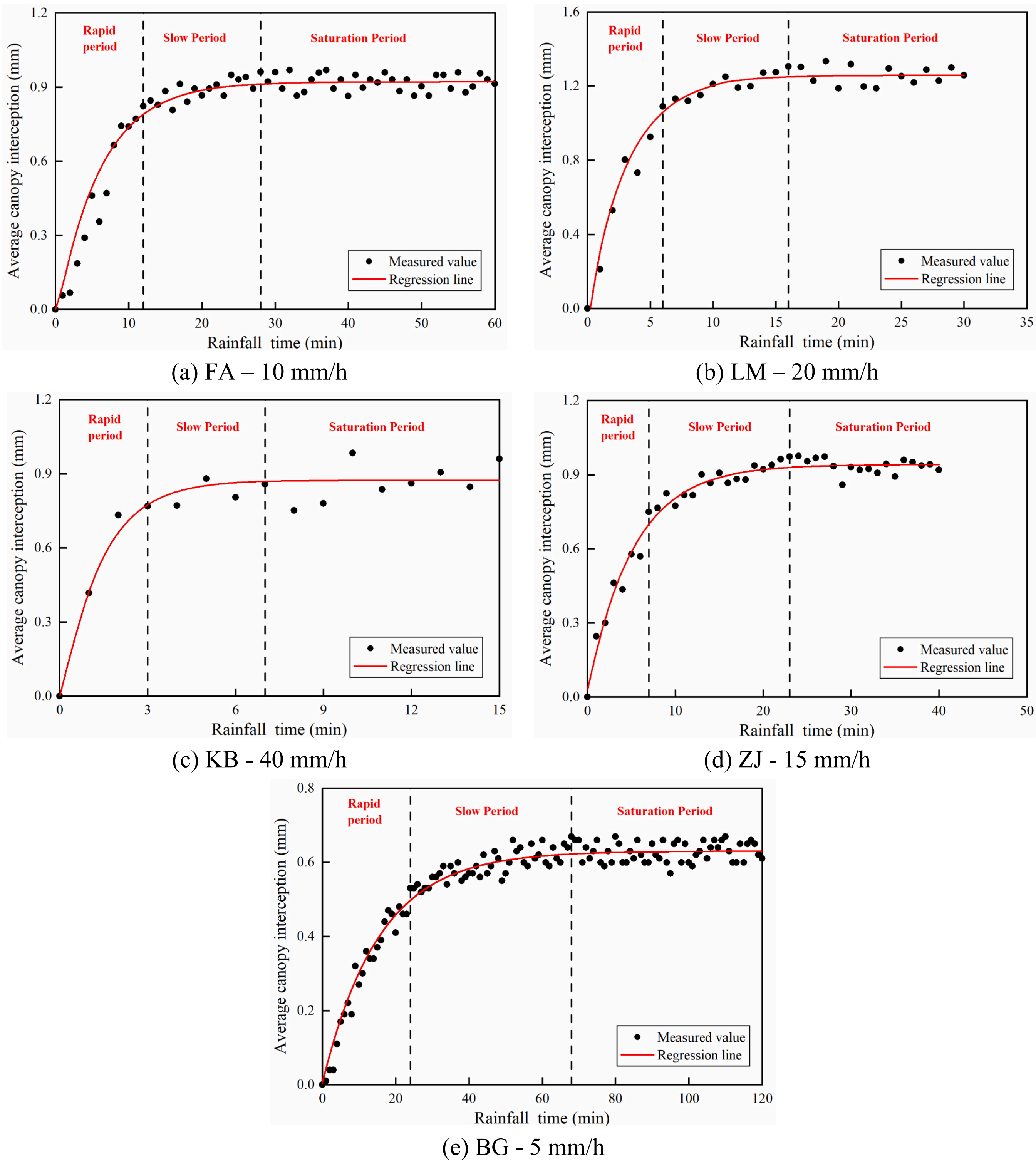

Fig. 4. The variation of average canopy interception under different rainfall intensities based on WBM.

Table 2
The stages of canopy interception variation in different grass species.

Species	WBM			WIM		
	Rapid period (min)	Slow period (min)	Saturation period (min)	Rapid period (min)	Slow period (min)	Saturation period (min)
FA	0–12	12–28	≥28	0–30	30–120	≥110
LM	0–6	6–16	≥16	0–30	30–110	≥120
KB	0–3	3–7	≥7	0–30	30–120	≥120
BG	0–23	23–68	≥68	0–30	30–140	≥140
ZJ	0–7	7–23	≥23	0–30	30–130	≥130

min and 7 min, respectively. As rainfall continued, the leaves became wetter and nearly saturation, which slowed down the interception ratio in the canopy. The duration of the slow period was longer, but the amount of rainwater intercepted was less because the area of the leaves to which raindrops can adhere was reduced and most of the leaves were saturated. During the slow interception period, the interception time consumed by FA, LM, KB, BG and ZJ was 16 min, 10 min, 4 min, 45 min and 16 min, respectively, but the intercepted rainwater only accounted for 14.52 %, 16.21 %, 10.27 %, 29.65 % and 23.01 % of the canopy interception capacity. When the leaves were fully saturated, some of adhered raindrops will fall to the ground under the splash effect of other raindrops and the influence of their own gravity, resulting in slight fluctuations in the intercepted rainfall during the saturation period. In addition, significant differences were observed in the durations of the rapid and slow interception periods of the five grass species under varying rainfall intensities. It was found that a longer duration was required for the canopy to reach saturation under lower rainfall intensities.

As shown in Fig. 5, the average canopy interception of five grass species measured by the WIM with immersion time had the same three stages of rapid, slow and saturated periods. During the rapid period, FA, LM, KB, BG and ZJ absorbed 72.76 %, 75.79 %, 68.13 %, 64.39 % and 61.51 % of the canopy interception capacity, respectively. While in the slow period, FA, LM, KB, BG and ZJ only absorbed 25.97 %, 23.75 %, 31.51 %, 34.60 % and 37.36 % of the canopy interception capacity, respectively. This is consistent with the variation in interception at different periods as measured by the WBM. As shown in Table 2, there is no difference in the time of rapid period among the five grass species, all of which are 30 min. Nevertheless, the time required for canopy saturation varied significantly among the five grass species, ranging from 110 min for FA to 140 min for BG. Additionally, it is obvious that the WBM requires a noticeably shorter duration for canopy to achieve saturation compared to the WIM, and the difference in the time required for canopy saturation between the two methods is greater at higher rainfall intensities.

3.4. Effect of leaf contact angle on canopy interception

Fig. 6 illustrates the relationship between canopy interception per unit leaf area and leaf contact angle for five grass species. As depicted in Fig. 6(a) and (b), the canopy interception per unit leaf area under constant rainfall intensity is as follows: KB > FA > LM > BG > ZJ. Consequently, the canopy interception per unit leaf area measured by the WBM and the WWM was negatively correlated to the leaf contact angle. However, the canopy interception per unit leaf area obtained by the WIM does not exhibit a declining trend with the increase of leaf contact angles. Within the WIM, FA shows the maximum canopy interception per unit leaf area, quantified as 0.000394 mm/cm^2. The canopy interception per unit leaf area for KB, LM, and BG remains substantially identical, and ZJ exhibits the minimum canopy interception, recording at 0.000289 mm/cm^2. Due to the rainfall intercepted by the WBM and the WWM primarily adheres to the leaf surface in the form of raindrops, while canopy interception measured by the WIM is mainly absorbed by the leaves. Therefore, the differences in the variation trends of the WIM compared to the WBM and the WWM indicate that the leaf contact angle exerted a vital influence on the adhesion and accumulation of raindrops on the leaf surface, but has little effect on leaf water absorption.

As shown in Fig. 6(a) and (b), KB with the smallest leaf contact angle has the highest canopy interception per unit leaf area, whereas ZJ with the largest leaf contact angle has the lowest canopy interception per unit leaf area. The differences in canopy interception per unit leaf area measured by the WBM for KB and ZJ under rainfall intensities of 5, 10, 15, 20, 25, 30, 40, and 50 mm/h were 0.000127, 0.000120, 0.000132, 0.000182, 0.000209, 0.000159, 0.000118, and 0.000101 mm/cm^2, respectively. Meanwhile, the difference in canopy interception per unit leaf area between KB and ZJ measured using the WWM was 0.000164, 0.000166, 0.000169, 0.000210, 0.000205, 0.000151, 0.000143, and 0.000093 mm/cm^2, respectively. Consequently, a discernible trend is observed wherein the effect of the leaf contact angle on canopy interception demonstrates an initial increment followed by a subsequent reduction as rainfall intensity increase. The most pronounced deviations are notably observed at rainfall intensities of 20 mm/h and 25 mm/h. Furthermore, as the rainfall intensity exceeds 25 mm/h, the difference in canopy interception per unit leaf area between KB and ZJ decreases as the rainfall intensity increases, and the impact of leaf contact angle on canopy interception is reduced.

3.5. Effect of rainfall characteristics on canopy interception in grass canopy

Fig. 7 illustrates the canopy interception capacity measured for the five grass species at eight rainfall intensities. It can be observed that the canopy interception capacity measured by both the WBM and the WWM initially increased and then decreased with the increasing rainfall intensity for all five grass species. There was a peak canopy interception capacity, and the rainfall intensity corresponding to this peak was identical for the same grass species measured using both the WBM and the WWM. Specifically, the canopy interception capacity peaked for FA, LM, and KB at a rainfall intensity of 20 mm/h, while BG and ZJ showed the peak interception at a rainfall intensity of 15 mm/h. Additionally, it is noteworthy that the canopy interception capacity at lower rainfall intensities of 5 mm/h, 10 mm/h, 15 mm/h, and 20 mm/h surpassed that observed at higher rainfall intensities of 30 mm/h, 40 mm/h, and 50 mm/h. As is widely recognized, lower rainfall intensity corresponds to longer rainfall duration when the total rainfall remains constant. Consequently, grass canopy exhibits a greater capacity for intercepting rainfall under conditions of lower intensity and longer duration rainfall events.

The relationship between canopy interception ratio and total rainfall is illustrated in Fig. 8. When the rainfall amount is minimal, the majority of rainfall can be intercepted by the grass canopy. For instance, at a total rainfall of 1 mm, the canopy interception ratios for FA, LM, KB, BG, and ZJ were recorded at 83.16 %, 85.37 %, 80.46 %, 75.1 %, and 79.6 %, respectively. As total rainfall increases, canopy interception ratios for the five grass species exhibit a decline. As shown in Table 3, regression analysis findings indicated that the correlation between canopy interception ratio and total rainfall conforms to a negative power function. When the total rainfall reached 10 mm, the canopy interception ratio of five grass species varied from 7.91 % for BG to 13.17 % for LM.

3.6. Effect of leaf characteristics on canopy interception

Leaf area and canopy projection area are critical parameters to characterize the canopy interception capacity of vegetation, particularly in grasslands where the interception of leaves is a key process in the canopy interception due to the absence of stems and branches. Fig. 9 depicts the correlation between canopy interception capacity and leaf area as well as canopy projection area. It can be observed that there is a significant positive correlation between canopy interception capacity

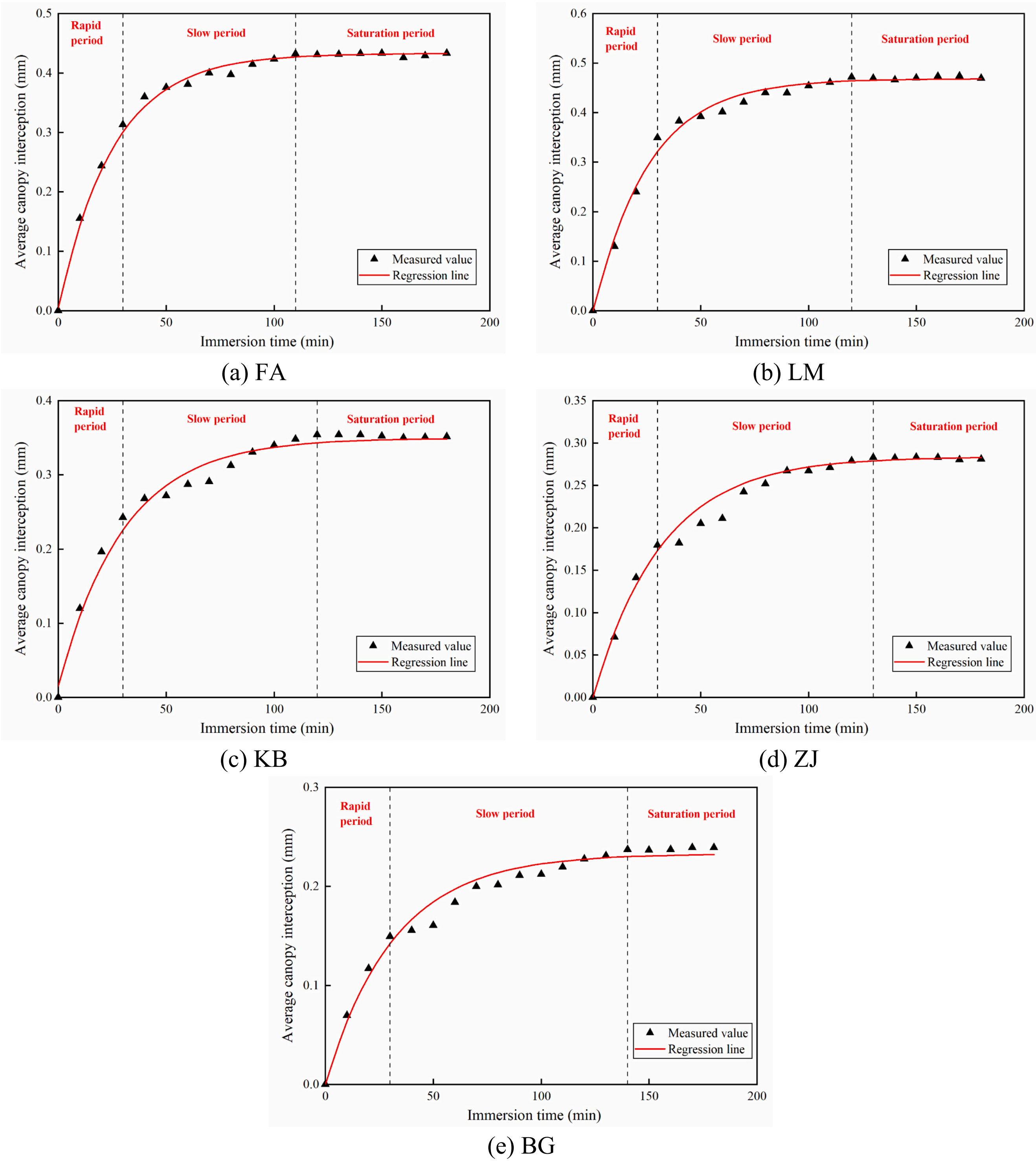

Fig. 5. The variation of average canopy interception measured by WIM with immersion time.

and both leaf area and canopy projection area. Pearson statistical analysis revealed that the correlations between canopy interception capacity and leaf area measured by the WBM, WWM, and WIM were 0.755, 0.719, and 0.692, respectively. Similarly, the correlations between canopy interception capacity and canopy projection area measured by the WBM, WWM, and WIM were 0.727, 0.685, and 0.701, respectively. Furthermore, the determination coefficients R^2 of the regression analysis of leaf area and canopy interception capacity were 0.931, 0.859 and 0.827 respectively, in comparison to 0.886, 0.803 and 0.819, respectively, for the regression analysis of canopy projection area and canopy interception capacity. Consequently, the linear relationship between leaf area and canopy interception capacity is more evident than the canopy projection area.

It is worth mentioning that there were notable disparities in canopy interception capacity among various grass species, even when leaf areas and canopy projection areas were similar. For example, ZJ had a canopy interception capacity of 0.92 mm (WBM) at a leaf area of 988.1 cm^2, whereas KB recorded a canopy interception capacity of 1.04 mm (WBM) at a leaf area of 986.5 cm^2; Similarly, the canopy interception capacity corresponding to FA at a projected area of 469.8 cm^2 was 0.68 mm

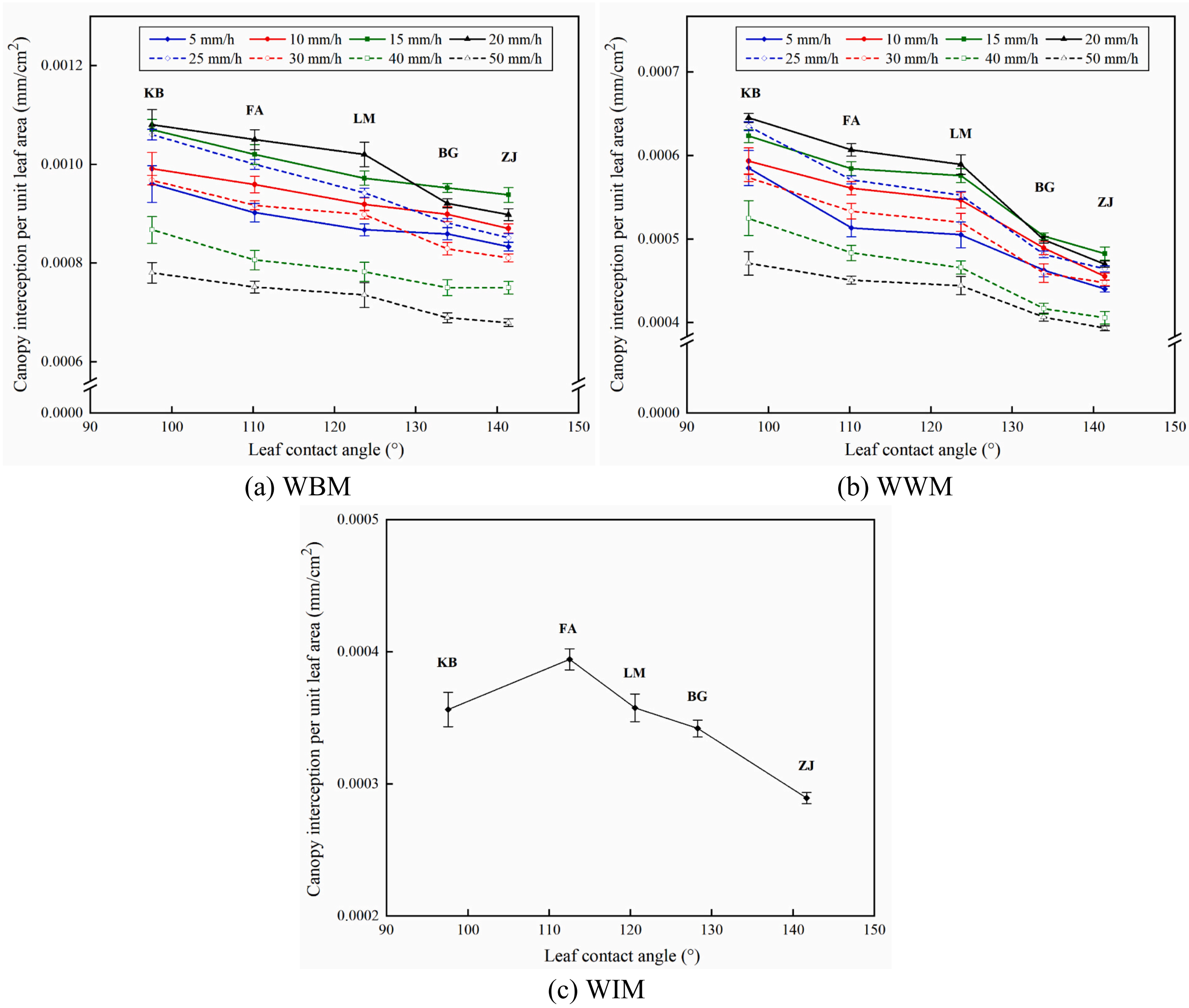

Fig. 6. Relationship between leaf contact angle and canopy interception per unit leaf area.

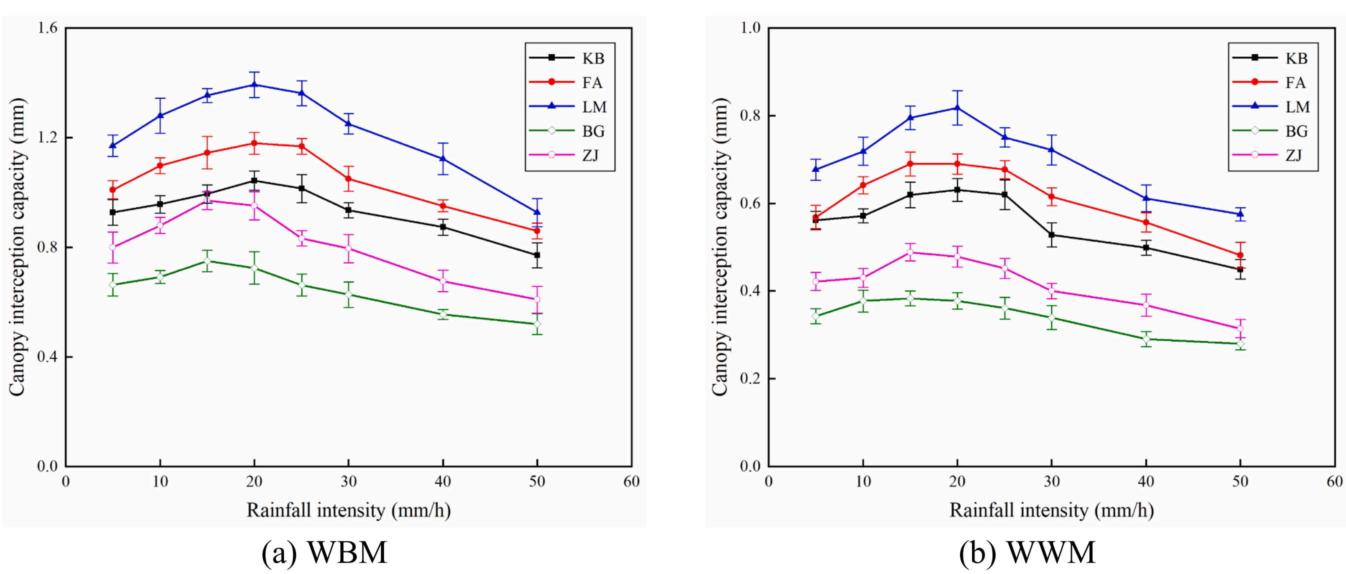

Fig. 7. The maximum canopy interception of five grass species under different rainfall intensities.

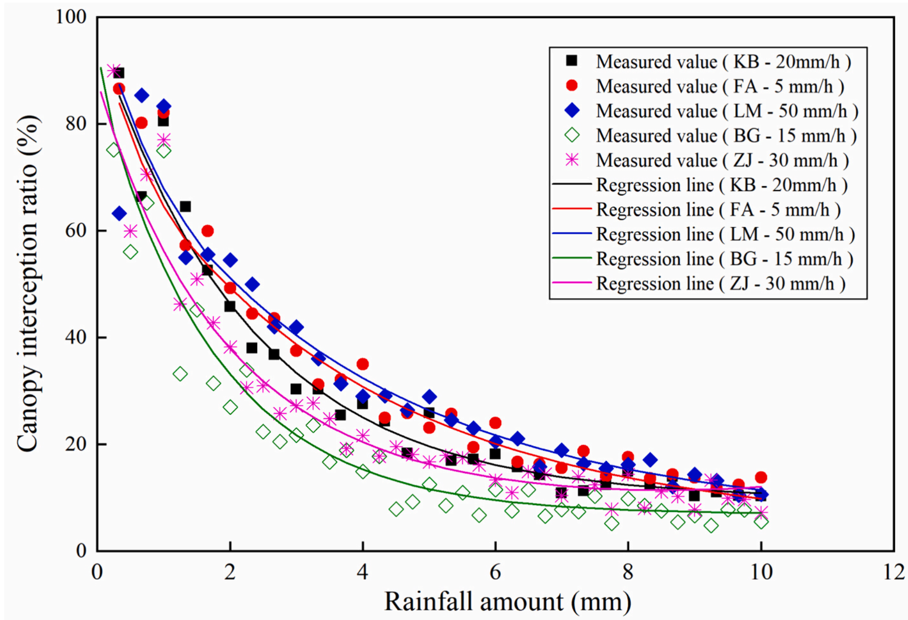

Fig. 8. The relationship between canopy interception ratio and total rainfall.

Table 3
Regression analysis of total rainfall and canopy interception ratio.

Species	Regression equation	R^2	sig.
FA	$I_P = 37.31 * P^{-0.342}$	0.783	0.001
LM	$I_P = 39.22 * P^{-0.340}$	0.780	0.001
KB	$I_P = 35.31 * P^{-0.364}$	0.831	0.001
BG	$I_P = 34.06 * P^{-0.397}$	0.796	0.001
ZJ	$I_P = 38.16 * P^{-0.348}$	0.778	0.001

Notes: I_P is the canopy interception ratio. P is the total rainfall (mm).

(WWM), while the canopy interception capacity corresponding to LM at a projected area of 472.6 cm^2 was 0.77 mm (WWM). These distinctions highlight that canopy interception capacity in grass is influenced by additional canopy structure characteristics, such as leaf contact angle.

3.7. Comprehensive analysis of factors affecting canopy interception in grass

The above analysis reveals that canopy interception is an intricate process, which is affected by multiple factors such as rainfall, canopy structure and leaf surface characteristics. Based on the comparison of three experimental methods, it is shown that the canopy interception measured by the WBM is more in line with the actual interception (Section 3.2), and the WBM can reveal the effects of rainfall intensity, total rainfall, contact angle, and grass height on canopy interception. Therefore, to fully quantitatively evaluate the contribution of different factors to the canopy interception of grass, the grey correlation analysis was conducted to analyze the relevance between the canopy interception measured by the WBM and the different influencing variables. The canopy interception is a dynamic process that varies with rainfall time (rainfall amount) and can be divided into three stages: rapid period, slow period, and saturation period. Therefore, analysis of the correlation between rainfall amount and canopy interception was based on the monitoring values during the canopy interception process.

Analysis of the grey correlation revealed that the correlation coefficients of leaf area, rainfall amount, dry mass, rainfall intensity, canopy projection area, leaf contact angle, fresh weight and average height were 0.8552, 0.8190, 0.7882, 0.7723, 0.7559, 0.7235, 0.7067 and 0.6496 respectively (Table 4). Evidently, leaf area is the most influential factor affecting canopy interception in grasses. Leaf contact angle had a correlation coefficient of 0.7235, which was more prominent than 0.7067 for fresh weight and 0.6496 for average height. The grey correlation analysis also confirmed that the correlation between leaf area and canopy interception was more powerful than the correlation between canopy projection area, which was consistent with the findings of regression analysis (Section 3.6). In assessing vegetation biomass, both dry mass and fresh weight emerge as crucial factor. However, compared to the fresh weight of leaves, the results showed that the dry mass of leaves had a greater effect on canopy interception. This disparity in influence might be attributed to the intricate interplay between dry mass and the leaf water content.

3.8. Prediction of canopy interception process

Referring to pertinent previous studies (Keim et al., 2006; Liang et al., 2009) and the variations in canopy interception with rainfall time for five grass species (Section 3.3), the canopy interception process can be represented with the following equation:

$$I = I_m\left(1 - e^{-kT}\right) \tag{4}$$

where I_m is the canopy interception capacity (mm), T is the rainfall time (min), and k is a fitting parameter, reflecting the growth rate of canopy interception.

The canopy interception capacity of five grass species under different rainfall intensities can be referred to Fig. 7. Fig. 10 illustrates the k variation pattern for each grass species under eight different rainfall intensities. Variance analysis indicated that k exhibited significant statistical variations among different rainfall intensities and different grass species ($p < 0.05$). Regression analysis showed that the relationship between k and rainfall intensity and leaf contact angle was well fitted by the following equation:

$$k = 0.015R_i - 0.003C_a + 0.386 \tag{5}$$

where R_i is the rainfall intensity (mm/h), and C_a is the leaf contact angle (°).

The determination coefficient (R^2) of the regression equation is 0.965; $p = 0.001$ and $F = 506.42 > F_{0.05}\,(2, 37) = 3.252$, indicating that the regression Eq. (5) is statistically significant, and the variation of k

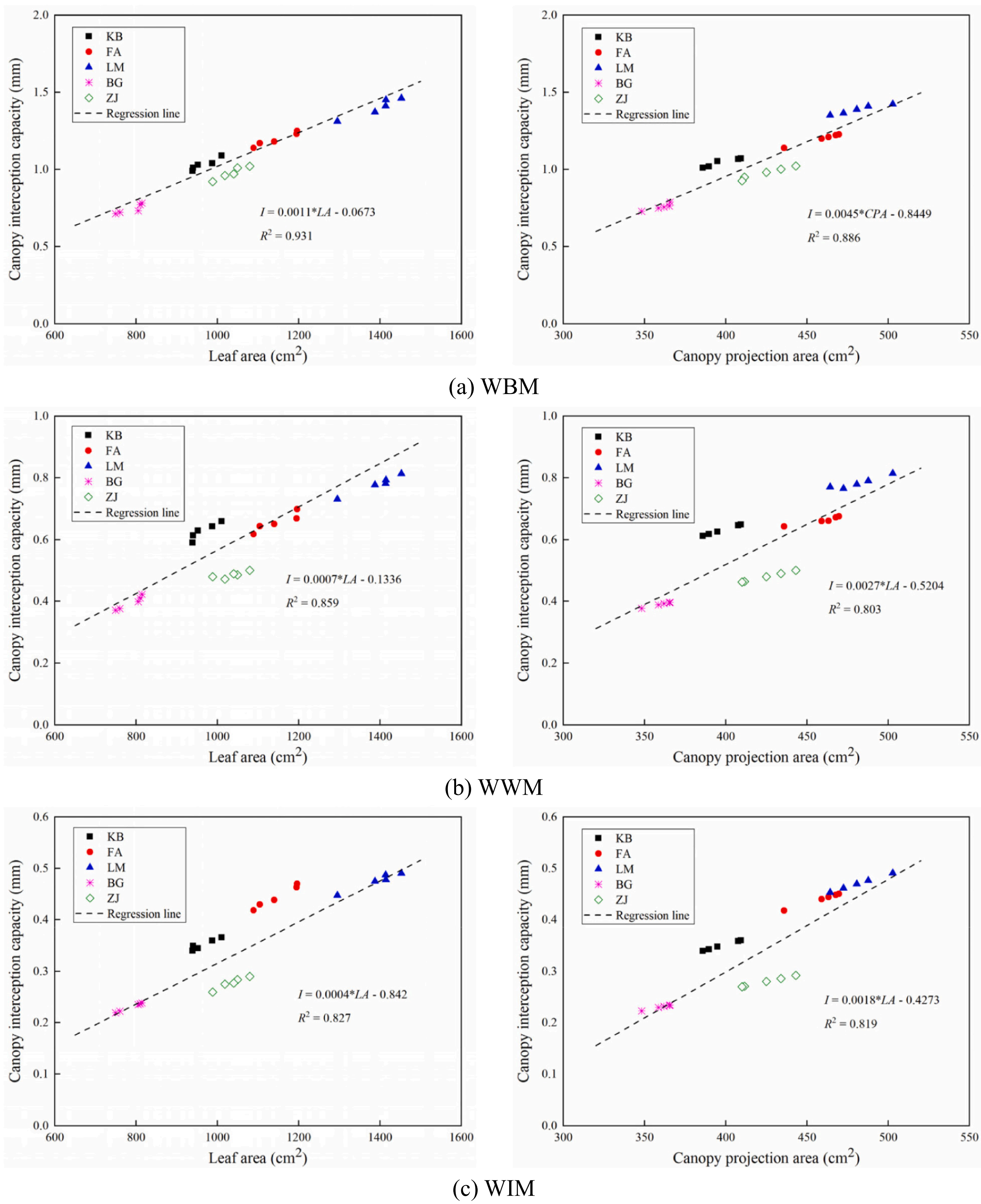

Fig. 9. Analysis of canopy interception capacity in relation to leaf area and canopy projection area.

with rainfall intensity and leaf contact angle can be well described by this regression model.

Substituting Eq. (5) into Eq. (4), the canopy interception process can be expressed as:

$$I = I_m\left[1 - e^{-(0.015R_i - 0.003C_a + 0.386)T}\right] \quad (6)$$

k reflects the growth rate of canopy interception. In Eq. (5), the coefficient of R_i is positive and the coefficient of C_a is negative. Thus, the growth rate of canopy interception increases with rainfall intensity in the same grass species, and the increase rate of canopy interception is faster in grass with a small leaf contact angle at a given rainfall intensity.

G.X. Wang et al. (2012) developed a multivariate regression model for canopy interception process in alpine swamp and alpine meadow, by statistically analyzing the relationship between canopy interception and various factors:

Table 4
The grey correlation degree of interception and factors influencing interception.

Parameter	Grass species					Mean value
	FA	LM	KB	BG	ZJ	
Leaf area (cm^2)	0.8761	0.8385	0.8659	0.8361	0.8596	0.8552
Rainfall amount (mm)	0.8366	0.8289	0.8027	0.8019	0.8247	0.8190
Dry mass (g)	0.8092	0.7719	0.7989	0.7691	0.7921	0.7882
Rainfall intensity (mm/h)	0.7855	0.7712	0.7820	0.7635	0.7591	0.7723
Canopy projection (cm^2)	0.7530	0.7987	0.7781	0.7212	0.7284	0.7559
Leaf contact angle (°)	0.7327	0.7113	0.7152	0.7151	0.7433	0.7235
Fresh weight (g)	0.7187	0.6881	0.7370	0.6835	0.7063	0.7067
Average height (cm)	0.6582	0.6591	0.6635	0.6272	0.6399	0.6496

$$I = a \cdot F_c \cdot R_i^{\,b} \cdot T^c \tag{7}$$

where F_c is vegetation cover, which is equal to the ratio of the canopy projection area of to the area covered by vegetation. R_i is rainfall intensity (mm/h), and T is rainfall time. a, b and c are fitting parameters.

To validate the accuracy of Eq. (6), both Eqs. (6) and (7) were used to fit the canopy interception process of the five grass species under random rainfall intensities. Due to the differences in fitting coefficients among different grass species in Eq. (7), the best fitting coefficients a, b, and c for five grass species under different rainfall intensities were first determined based on the lsqcurvefit function of Matlab 2019. The fitting results are shown in Fig. 11 and Table 5. It can be seen that the expression of Eq. (6) is more accurate than Eq. (7), as it has lower errors and a higher coefficient of determination. At the initial stage of rainfall, the prediction accuracy of Eq. (7) was close to that of Eq. (6). However, as the rainfall time increased, the canopy interception predicted by Eq. (7) continued to increase, which was inconsistent with the existence of saturated interception in the canopy, resulting in a progressive increase in the prediction errors.

4. Discussion

Previous studies had explored the difference between the WBM and the WIM. For example, Yu et al. (2012) estimated the canopy interception of non-degraded grassland by the WBM and the WIM as 0.979 ± 0.32 mm and 0.612 ± 0.08 mm, respectively. Wohlfahrt et al.'s (2006) investigation on the water storage capacity of leaves and stems of nine species of plants in a mountain meadow also showed that the canopy interception measured by the WIM was significantly lower than that measured by the WBM. Both studies demonstrate that the WBM is a more accurate method for measuring canopy interception, as the WIM underestimate the results. Our experimental results are consistent with these investigations, which revealed that the canopy interception capacity measured by the WBM is 1.93–3.47 times that measured by the WIM. Currently, there are also studies utilizing the WWM to investigate canopy interception characteristics (Kang et al., 2005; Wang et al., 2006), but rarely involving the comparison of the WWM, the WBM and the WIM. In this study, we found that the canopy interception capacity measured by the WBM was 1.37–2.07 times that measured by the WWM, while the canopy interception capacity measured by the WWM is 1.29–1.80 times that measured by the WIM. The difference in experimental results can be attributed to the multifaceted nature of canopy interception in grass, including leaf water absorption, raindrops adhesion to the leaves, and evaporation. During the rainfall process, a substantial accumulation of adhered raindrops occurs on the leaf surface (Ou et al., 2023; Prata et al., 2011). The eventual loss of these adhered raindrops and the ensuing evaporation contribute to the significant reduction in canopy interception measurements achieved via the WIM. Therefore, the canopy interception measured by the WIM is actually the maximum water storage capacity when the leaves are saturated with water absorption, rather than the actual canopy interception capacity. The measurement result of the WWM is the amount of rainfall adhered to leaves minus the amount of evaporation. However, employing absorbent paper to extract rainwater from the leaf surface proves to be a somewhat intricate process, as it can result in the detachment of raindrops (Llorens and Domingo, 2007). Furthermore, the loss of water absorption and potential experimental errors contribute to lower canopy interception measurements obtained through the WWM compared to those obtained from the WBM. Therefore, the WBM is more in line with the definition of canopy interception and provides a more accurate assessment of canopy interception, while the measurement results of the WWM and the WIM are smaller than the actual values. Additionally, the canopy interception obtained through the WWM is greater than that obtained by the WIM, indicating that the rainfall intercepted by the grass canopy mainly adheres to the grass leaves in the form of raindrops, rather than being absorbed by the leaves.

There are significant interspecific differences in the interception

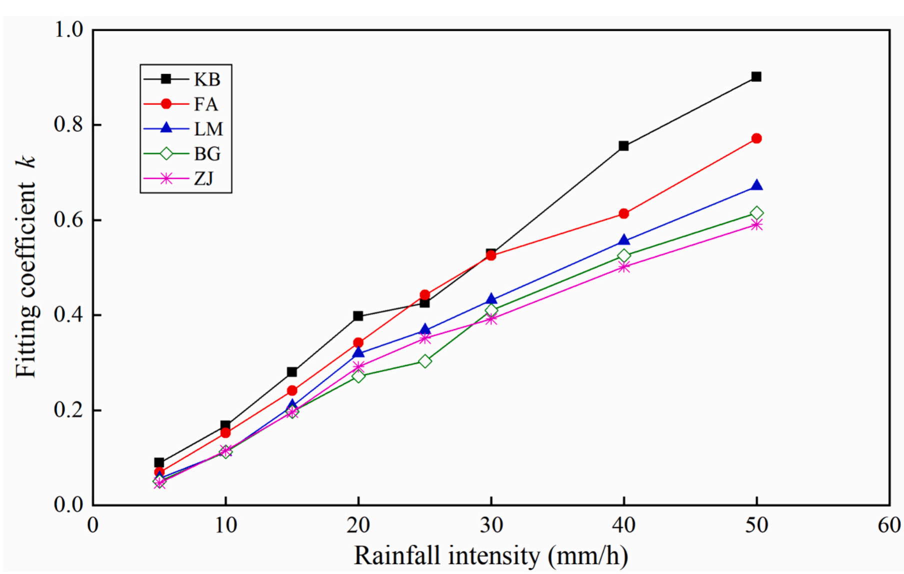

Fig. 10. The variation of fitting coefficient k of five grass species with rainfall intensity.

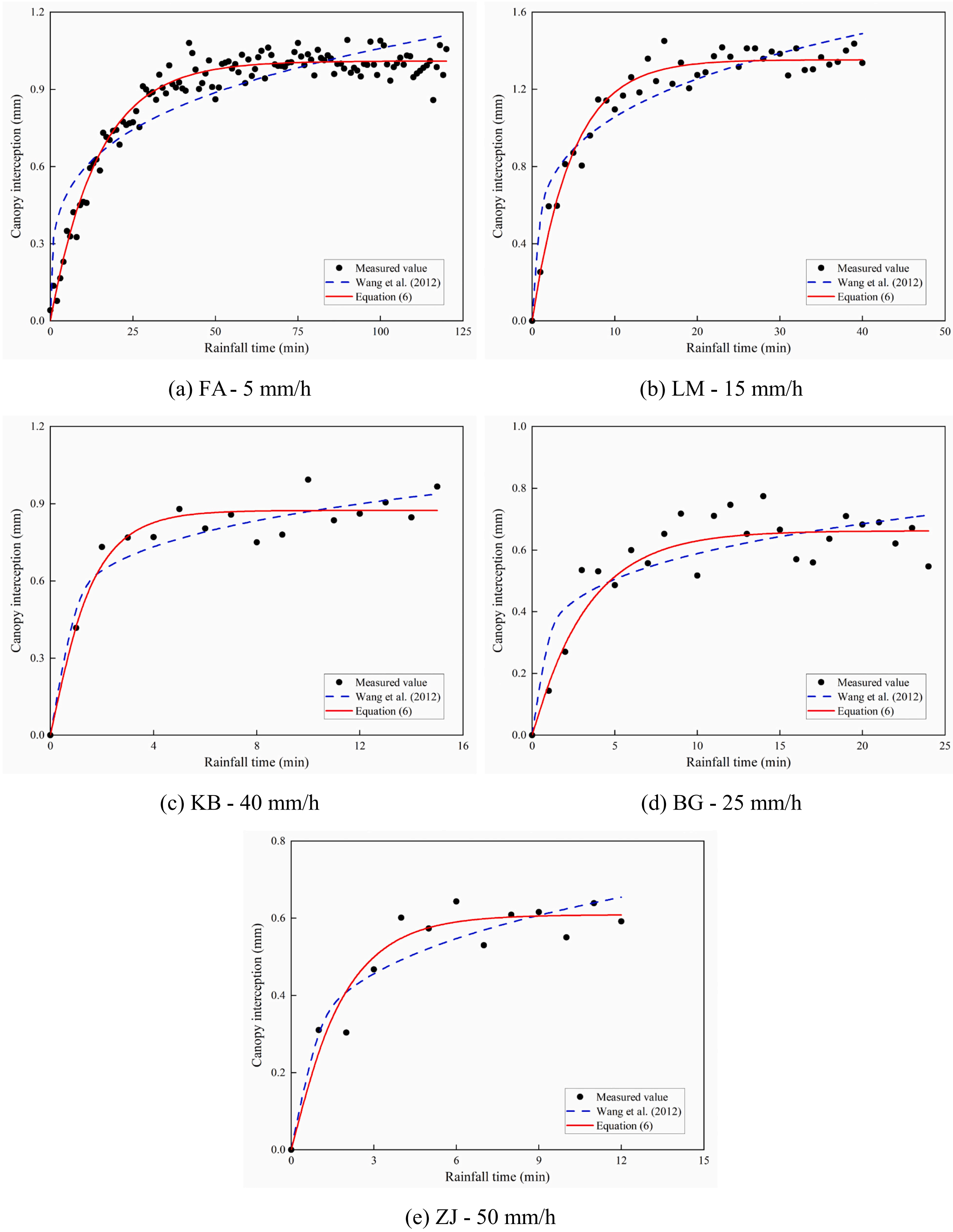

Fig. 11. Comparisons between model predictions and experiment measurements.

characteristics of grass canopy. Under the same rainfall conditions, the canopy interception per unit leaf area was KB > FA > LM > BG > ZJ. The canopy interception per unit leaf area decreases with the increase of leaf contact angle. This result has also been validated in other vegetations, such as the rainfall simulation experiments conducted on seven tree species in Colorado, USA also showed that the order of leaf surface storage capacity of each tree species corresponds to the order of leaf hydrophobicity (Holder, 2013). The variation in the impact of leaf contact angle is principally attributed to the distinct interception mechanisms of the three methods. In the context of rainfall simulation

Table 5
The results of the error analysis of the prediction model.

Species	Formulation		R^2	RMSE
FA (5 mm/h)	Eq. (6)	$I = 1.01 * [1 - e^{-(0.015Ri-0.003Ca+0.386)T}]$	0.959	0.0022
	G.X. Wang et al. (2012)	$I = 0.54F_c \cdot R_i^{-0.26} \cdot T^{0.27}$	0.812	0.0097
LM (15 mm/h)	Eq. (6)	$I = 1.35 * [1 - e^{-(0.015Ri-0.003Ca+0.386)T}]$	0.937	0.0043
	G.X. Wang et al. (2012)	$I = 0.87F_c \cdot R_i^{-012} \cdot T^{0.25}$	0.872	0.0131
KB (40 mm/h)	Eq. (6)	$I = 0.87 * [1 - e^{-(0.015Ri-0.003Ca+0.386)T}]$	0.924	0.0039
	G.X. Wang et al. (2012)	$I = 0.82F_c \cdot R_i^{-0.046} \cdot T^{0.19}$	0.901	0.0057
BG (25 mm/h)	Eq. (6)	$I = 0.66 * [1 - e^{-(0.015Ri-0.003Ca+0.386)T}]$	0.861	0.0049
	G.X. Wang et al. (2012)	$I = 0.55F_c \cdot R_i^{-0.073} \cdot T^{0.22}$	0.696	0.0088
ZJ (50 mm/h)	Eq. (6)	$I = 0.61 * [1 - e^{-(0.015Ri-0.003Ca+0.386)T}]$	0.903	0.0024
	G.X. Wang et al. (2012)	$I = 0.48F_c \cdot R_i^{-0.053} \cdot T^{0.26}$	0.850	0.0037

experiments employing the WBM and the WWM, an abundance of small raindrops adhered to the leaf surface. Smaller contact angles of leaves make it easier for raindrops to adhere and accumulate on the leaf surface, thereby wetting the leaves and increasing interception capacity (Xiong et al., 2018). However, as the leaf contact angle increases, raindrops with larger diameters are difficult to adhere on the leaf surface under the impact of their own gravity (Holder, 2012), causing most of the raindrops to fall to the ground. This attenuation weakens the effectiveness of the canopy interception. Leaf hydrophobicity is commonly measured by calculating the contact angle of a sessile water drop and the leaf surface. Leaf contact angle is an important plant functional trait that varies widely among species (Holder and Gibbes, 2017; Xiong et al., 2018). In this study, we found that there were notable disparities in canopy interception capacity among various grass species, even when leaf areas and canopy projection areas were similar. Therefore, leaf contact angle may be a key quantifiable parameter to explain the differences in canopy interception characteristic of different grass species with constant leaf area or canopy structure, as grasses with small leaf contact angles can intercept more rainfall under the same unit leaf area conditions.

Leaf area is the primary factor affecting the canopy interception of grass. In addition, this study also found that the linear correlation between leaf area and canopy interception was stronger than that between canopy projection area. Studies on shrubs has also found that the leaf area can better predict the canopy interception capacity compared to the canopy projection area (X.P. Wang et al., 2012). Similarly, the results of canopy interception experiments on four common trees in northern China also indicate a high correlation between leaf area and canopy interception (Li et al., 2016). The amount of total rainfall constitutes the second pivotal factor influencing canopy interception since it governs the volume of rainwater supplied to the canopy. However, it mainly affects canopy interception in the rapid and slow periods. When the grass canopy is saturated, the interception is almost stable despite the continuous increase in rainfall. The canopy interception capacity initially increased and then decreased with the increasing rainfall intensity for all five grass species. This phenomenon is attributed to the cumulative effect of leaf surface characteristics, raindrop size and rain kinetic energy. The mean diameter and kinetic energy of raindrops increase with the increase of rainfall intensity (Meshesha et al., 2019; Yakubu et al., 2016). When the rainfall intensity is low, raindrops tend to be smaller in size and have less kinetic energy, allowing most of them to adhere to the leaf surface and be intercepted by the canopy. However, as rainfall intensity increases, larger raindrops are difficult to adhere on the leaf surface, and the impact of falling raindrops on the leaf surface is enhanced, resulting in most of the rain falling from the leaf surface to the ground (Zabret et al., 2017). Dry mass and fresh weight are important parameters representing vegetation biomass. It has also been reported in relevant studies that fresh weight is the index with the highest correlation with canopy interception (Garcia-Estringana et al., 2010). However, the results of this study show that dry mass has a stronger effect on canopy interception. Keim et al. (2006) also showed that plant fresh weight is not a good indicator of the different interception abilities of different species. The reason for this difference may be related to the water content of the leaves. The difference in leaf water content leads to changes in both the water absorption capacity of the leaves and the adhesion of raindrops to the leaf surface (Brewer and Nuñez, 2007; Li et al., 2023). The leaf water content is influenced by various factors, such as air temperature and humidity, duration of lighting, leaf water retention properties, and soil water content. In this study, we controlled the air temperature and humidity within the laboratory environment, and maintained consistent soil and light conditions for the grass cultivation. Additionally, it was observed from the weighing cultivation boxes that its weight returned to the initial level after 6 h of rest following the simulated rainfall experiment. Therefore, to ensure consistent leaf water content across consecutive tests, the same cultivation boxes were allowed to rest for six hours after each test before proceeding to the next set of experiments. These measures minimised errors due to differences in pre-experimental environmental conditions.

5. Conclusion

This study investigated the canopy interception characteristics of five typical slope protection grass species in temperate regions using the WBM, the WWM, and the WIM, respectively. The results demonstrate that the WBM is more in line with the definition of canopy interception and provides a more accurate assessment of canopy interception capacity. The canopy interception measured by the WBM significantly exceeded that obtained through the WWM and the WIM, with the WIM recording the lowest interception. Specifically, the canopy interception capacity measured by the WBM was 1.61–2.09 times higher than that measured by the WWM, and 1.93–3.47 times higher than that the WIM. Under the conditions of the three experimental methods, the canopy interception capacities of the five grass species were consistently ranked as LM > FA > KB > ZJ > BG.

Leaf contact angle is a key quantifiable parameter to explain the differences in canopy interception among different grass species with constant leaf area or canopy structure. It plays a vital role in affecting the adhesion and accumulation of raindrops on the leaf surface, but has little effect on leaf water absorption. The canopy interception per unit leaf area decreases with the increase of leaf contact angle. Among the eight factors evaluated (leaf area, rainfall amount, dry mass, rainfall intensity, canopy projection area, leaf contact angle, fresh weight, and average height), the results of the grey correlation analysis indicate that leaf area is the most influential factor affecting canopy interception in grasses. As rainfall intensity increases, the canopy interception capacity initially increases and then decreases, with the peak interception capacity occurring at rainfall intensities of 15–20 mm/h. Furthermore, the relationship between the interception ratio and rainfall amount follows a negative power function. Under a total rainfall of 10 mm, the interception ratio of the five grass species ranged from 7.91 % in BG to 13.17 % in LM. These findings will improve the understanding of canopy interception characteristics in temperate grasses, clarify the differences of commonly used experimental methods for grass canopy interception, and inform species selection for slope ecological protection.

CRediT authorship contribution statement

Xu-Guang Gao: Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation. **Ji-Peng Wang:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition. **Shangqi Ge:** Writing – review & editing, Validation, Investigation, Formal analysis. **Shuai-Kang Su:** Writing – original draft, Investigation. **Mo-Han Bai:** Investigation, Formal analysis, Data curation. **Bertrand Francois:** Writing – review & editing, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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