water

MDPI

Article

A Rainfall Interception Model for Alfalfa Canopy under Simulated Sprinkler Irrigation

Jian Jiao, Derong Su *, Liliang Han and Yadong Wang

Research Center for Grassland Ecology and Resources, Beijing Forestry University, No. 35 Tsinghua East Road, Beijing 100083, China; jiaojian@bjfu.edu.cn (J.J.); hanliliang1024@126.com (L.H.); 13311010748@163.com (Y.W.)

* Correspondence: suderong@bjfu.edu.cn; Tel.: +86-10-6233-6284

Academic Editors: Tim Hess and Jerry Knox

Received: 19 October 2016; Accepted: 3 December 2016; Published: 15 December 2016

Abstract: Estimating canopy interception of water by plants during rainfall or sprinkler irrigation is a critical step for evaluating water-use efficiency. Most existing experimental studies and mathematic models of canopy interception have paid little attention to the interception losses of water by herbaceous plants. To better understand the canopy interception processes of herbaceous plants and to estimate the interception losses, a process-based dynamic interception model for alfalfa canopy was developed and validated by an experiment under conditions of simulated sprinkler irrigation. The parameters of the model included the maximum interception, the rate of interception of the alfalfa canopy, and the duration of sprinkler irrigation. The model demonstrated that the amount of interception increased rapidly with duration in the early stage of sprinkler irrigation, and then gradually leveled off until the maximum retention capacity of the canopy was reached. The maximum interception by the alfalfa canopy, ranging from 0.29 to 1.26 mm, increased nonlinearly with the increase of leaf area index (*LAI*) and sprinkling intensity. The rate of interception increased with the decrease of *LAI* and the increase of sprinkling intensities. Meanwhile, a nonlinear equation based on sprinkling intensity and plant height was proposed in order to more practically estimate the maximum interception by alfalfa canopy.

Keywords: canopy interception; sprinkler irrigation; alfalfa; leaf area index; sprinkling intensity

1. Introduction

The area of planted alfalfa in China has increased rapidly since 2012 [1]. Currently, there are over 4 million hectares of alfalfa, mainly distributed in northwestern and northern parts of the country [2]. These regions dominate alfalfa production in China because of the availability of large-sized lands with appropriate climatic and soil conditions. However, the major constraint to alfalfa growth in these arid and semiarid regions is the shortage of natural rainfall. Irrigation is essential for the production of alfalfa, and the center pivot is the most popular irrigation system [3,4]. A major concern about overhead sprinkler irrigation (like center-pivot systems) is the loss of water. While some water is lost due to wind drift and evaporation before reaching the plants and the soil [5,6], a significant amount of water can be intercepted by the canopy and then lost through evaporation [7,8].

Hydrological processes that occur during overhead sprinkler irrigation are similar to those during natural precipitation [9]. A portion of water reaches the ground directly through canopy gaps without hitting the canopy surfaces as free throughfall, and another portion of water drips from leaves, branches, and stems as released throughfall [10]. Some of the other water flowing down along branches and stems is the stemflow [11]. The rest of the water is intercepted by leaves. Although a fraction of the intercepted water can be absorbed by leaf tissues [12], the majority returns to the atmosphere by evaporation [13] and becomes the interception loss, which cannot be used by plants [14,15]. Therefore, estimating the loss of water by canopy interception under the conditions of sprinkler irrigation is crucial to guide the proper selection of a center-pivot irrigation system in order to increase the water-use efficiency in arid and semiarid areas.

Most research on canopy interception has focused on trees, shrubs, and tall crops [14,16]. Interception losses of water by shrubs accounted for 16.7%–22.3% of total annual precipitation in arid deserts [7] and 27.2% in semiarid areas [17]. The interception loss in forests accounted for 3%–24.2% of total annual precipitation [8,18]. A canopy mixed with shrubs and trees intercepted 15% of total precipitation in a year [19]. The aims of these studies were to understand the effects of canopy interception on hydrological processes of forest ecosystems [20–22]. However, studies on crop systems were more concerned with the decreases of water-use efficiency due to evaporation loss [5,23]. Lamm and Manges [24] measured the interception of water by maize canopy under the sprinkling of a center-pivot irrigation system and found the amount of intercepted water ranged from 1.85 to 2.06 mm, which was 1.13 mm higher than the values under natural rainfall conditions. Wang et al. [25] observed a maize interception of 3.6 mm under solid-set sprinkler irrigation, and concluded that leaf area and plant height were the most influencing factors on water interception. Mauch et al. [26] reported that the interception of water by maize canopy was between 1.0 and 2.3 mm at different vegetative stages under indoor sprinkler irrigation, and the increase in leaf area led to the increase in water interception. Under conditions of natural rainfalls, van Dijk and Bruijnzeel [27] studied the interception of water by a mixed canopy of cassava, maize, and rice. The percentage of total annual rainfall being intercepted was 8% and 18% in two different experimental seasons. Research on winter wheat reported that the minimum and maximum amounts of canopy intercepted water were 0.3 and 1.0 mm, respectively, during the growing season, and the maximum interception occurred during the blossoming stage [28].

The widely adopted methodologies for measuring canopy interception of water have been water balance methods [7,17,24,29,30], micrometeorological methods [31,32], wiping method [28], and direct weighing method [26]. However, the applications of these methods are practically challenging [13], and under some circumstances could cause significant errors [13,24]. Therefore, developing interception models based on individual experimental observations to more accurately estimate canopy interception of water has become an important research direction. In 1919, Horton [33] published the first empirical interception function based on evaporation discharges during precipitation and water-holding capacity of a canopy. In 1971, an interception model based on physical processes was proposed by Rutter et al. [31], which was relatively easy to construct using water throughfall measurements and basic meteorological data. Anzhi et al. [34] developed an interception model for *Picea koraiensis* canopy, in which the predictive variables were leaf area index (*LAI*) and rainfall intensity. Research on pear and oak suggested *LAI* and meteorological factors could be used to model canopy interception of these plants [35]. The interception models of winter wheat were different for before and after blooming stages, but the *LAI* and plant height were suitable variables for both models [28].

While a great deal of effort has been made on modeling the canopy interception of trees and crops, few studies have targeted alfalfa. Fields of alfalfa are often characterized by high plant density, large leaf biomass, and high aboveground biomass. Furthermore, alfalfa is usually irrigated by center-pivot sprinkler irrigation systems in arid climates, so the water intercepted by alfalfa canopy could be substantial, and thus could have a significant influence on the water-use efficiency. In this study, our objectives are to: (1) construct a dynamic interception model for alfalfa canopy and validate it experimentally with a simulated sprinkler irrigation system during different vegetative stages and under different sprinkling intensities; and (2) estimate the maximum interception of water by alfalfa canopy based on the variables of morphological indices and sprinkling intensity.

2. Theoretical Considerations

Interception starts at the time when water reaches the canopy, and ends at the time when the water-holding capacity of the canopy is reached. In fact, the interception processes reflect the canopy water retention processes. These complex and dynamic mechanical equilibrium processes include dynamic equilibrium among adhesion, surface tension, deformation force, and gravity. Despite the complex nature of mechanical processes, the rate of interception should be higher in the initial period when the plant surfaces are relatively dry. With the increase of intercepted water, plant surfaces would reach the state of dynamic water equilibrium. Then, the rate of interception decreases gradually. Eventually, the interception will reach its maximum value. Physically, the dynamic interception should vary between zero (no interception) and maximum interception. Thus, a function can be assumed to indicate that at any time, the rate of interception is proportional to the difference between maximum interception and current interception:

$$\frac{dI}{dt} = k(I_m - I) \tag{1}$$

where t is the interception time duration (h), I is the dynamic interception at a given time (mm), I_m is the maximum interception (mm), and k is the exponential coefficient of the canopy interception.

Noting that when t = 0, the dynamic interception is considered to be 0 (i.e., I = 0), and the solution of Equation (1) is:

$$\alpha = \frac{I}{I_m} = 1 - e^{-kt},\ 0 < \alpha < 1,\ 0 < I < I_m \tag{2}$$

or

$$I = I_m(1 - e^{-kt}),\ 0 < I < I_m \tag{3}$$

where α is the interception ratio of canopy. Equation (2) or Equation (3) is the dynamic interception model, in which the parameters I_m and k can be determined experimentally.

Figure 1 shows the dynamics of interception ratios with different exponential coefficients corresponding to the model (Equation (2)). It demonstrates that the rate of interception (or the slope of the interception curves) is high at the initial low amounts of interception, and then gradually decreases toward the maximum interception.

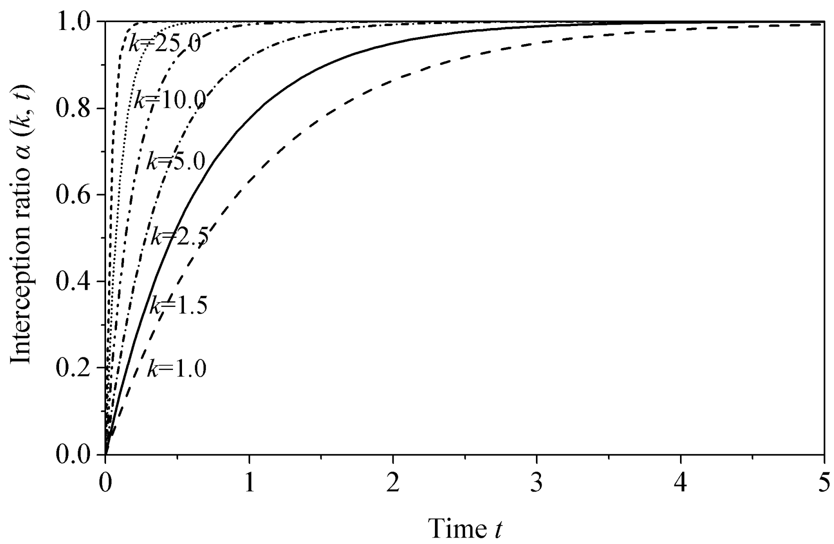

Figure 1. Dynamics of interception ratios with different exponential coefficients. k is the exponential coefficient; α is the interception ratio; t is the time duration of interception.

3. Materials and Methods

3.1. Experimental Site

The experiment was conducted in the grass experimental station of the Beijing Clover Grass Technology Development Center (116°61′ E, 39°88′ N, and 50 m above sea level (a.s.l.)) in 2015. The mean annual rainfall was about 600 mm. The alfalfa used for observing rainfall interception was planted at the site in 2014 with a row spacing of 15 cm and planting density of 1.5 g/m^2.

3.2. Measurement System

The interception measurement was carried out in a laboratory adjacent to the experimental field. The measuring system was as shown Figure 2. It was composed of four parts, including a set of simulated sprinklers and a water holding tank, an interception water collecting device, an electronic balance for weighing the water (Quintix5102-1CN, Sartorius AG, Göttingen, Niedersachsen, Germany, with an accuracy of 10 mg), and a computer for data recording. The simulated sprinkler was placed 1 m above the water-retention foam. The size of the water drops sprayed from the sprinkler varied between 1.15 and 4.12 mm in diameter and the velocity varied between 2.93 and 4.87 m/s. Both parameters were within the normal ranges of size and velocity of water drops generated by a commonly used fixed spray plate sprinkler (FSPS; model: Nelson D3000) for center pivots [36]. The water-collecting device was designed to hold the alfalfa plants, and collect and drain the water not being intercepted by the plant leaves when spraying. In order to keep the plants upright and fresh during experimentation, a leaking disc (25 cm in diameter) filled with water-retention foam was placed on top of the water-collecting device, and the water-retention foam was saturated with water prior to the experiment.

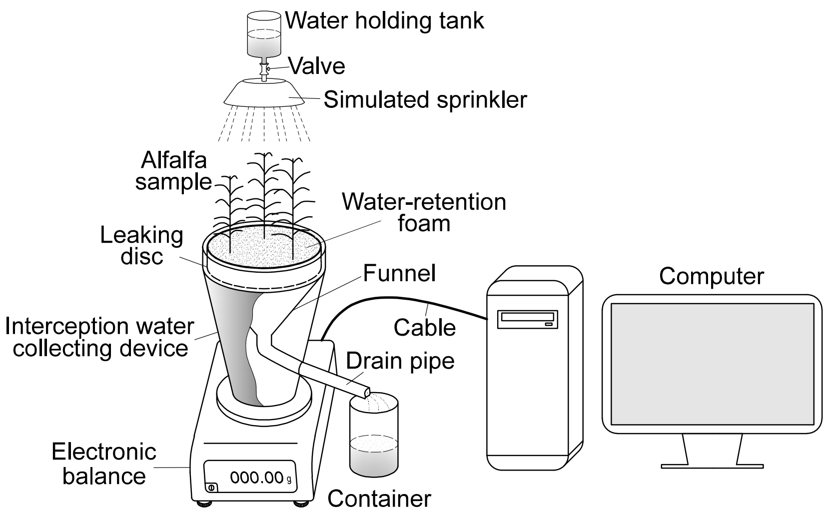

Figure 2. Schematic of the experimental system for measuring canopy interception during simulated spraying.

3.3. Experimental Procedures

As a perennial forage, alfalfa is normally harvested multiple times a year from the field. It regenerates after each harvest and completes a growth cycle before the next harvest. In this experiment, we chose to use alfalfa between the second and third harvests to represent a full cycle of its vegetative growth. A total of four interception tests were performed at different times in order to examine the variation in the amount of canopy-intercepted water at different vegetative stages of alfalfa. Alfalfa plants used for the first, second, third, and fourth tests were collected from the field after they had grown for 5, 15, 30, and 45 days since the harvest, respectively.

Plants used for each test were randomly sampled from the field. To take alfalfa plants, a sampling ring with a diameter of 25 cm was placed firmly on the ground. All stems and leaves of the plant inside the ring were removed from the ground surface and transported to the laboratory, where temperature and relative humidity were maintained at 26 °C and 60%, respectively. After plants were inserted into the presaturated water-retention foam, sprinkling for interception measurement started immediately.

In each test, a total of five sprinkling intensities (2.5, 5.0, 10, 20, and 40 mm/h) were simulated to measure the amount of interception water. Each sprinkling intensity was repeated three times as replicates, and the plant samples for each repetition were always re-collected from the field. For each intensity, the total amount of sprayed water was kept at 0.49 L, equivalent to a water depth of

10 mm over the leaking disc. To achieve this fixed amount of water for different sprinkling intensities, experimental duration, spray intervals, spray times, and water volume for one spray were manipulated, as listed in Table 1.

Table 1. Detailed designs of sprinkling interception experiment.

Experimental Parameters	Sprinkling Intensity (mm/h)				
	2.5	5.0	10	20	40
Total spray volume (mm)	10	10	10	10	10
Experimental duration (min)	240	120	60	30	15
Spray intervals (min)	15	10	6	5	3
Spray times	16	12	10	6	5
Water volume for one spray (mm)	0.63	0.83	1.00	1.67	2.00

During spraying, a portion of the water was intercepted by plant leaves and the rest not being intercepted would drain through the leaking disc and flow into the container (Figure 2). Since the container was placed outside of the balance, the added weight measured by the balance was the amount of intercepted water. The amount of intercepted water was recorded in the computer as water depth over the area of the leaking disk.

3.4. Leaf Area Index

Immediately following each interception measurement, the alfalfa samples on the leaking disc were removed from the water-retention foam and the total number of plants (A) was counted. Ten plants were selected randomly from each sample and the number of leaves for each plant was counted in order to calculate the average leaf number ($\overline{N}$) for an individual plant. Then, 50 leaves (n) were chosen randomly from the 10 selected plants and the average leaf area (LA_i) was determined after digitally scanning the 50 leaves. Specifically, the pixel number of 50 leaves in the picture was calculated using image-processing software Photoshop 14.0 (Adobe System Inc., San Jose, CA, USA). Grid lines were inserted in the picture, and the number of pixels over a unit area (1 cm^2) was calculated using the software. The average leaf area was calculated as:

$$LA_i = \frac{p}{p_i \cdot n} \tag{4}$$

where LA_i is the average area (cm^2) for a single leaf, n = 50 is the number of scanned leaves, p is the total number of pixels for n leaves; and p_i is the pixel number per unit of leaf area (1 cm^2).

Therefore, the LAI can be calculated as:

$$LAI = \frac{LA_i \cdot \overline{N} \cdot A}{\mathrm{S}} \tag{5}$$

where the LA_i is the average area (cm^2) for a single leaf, $\overline{N}$ is the average leaf number for an individual plant, A is the total number of plants in the sample, and S is the area of the leaking disc.

Besides the LAI, the fresh weight of plants was measured as soon as the plant samples were cut. Plant height, the number of internodes, stem diameter, and leaf–stem ratio were determined after the simulated sprinkler irrigation was completed.

3.5. Statistical Analyses

Nonlinear regression was used to fit the model and experimental results to obtain the fitting coefficients I_m and k of the model, as well as the adjusted coefficient of determination (${R_a}^2$) and fitting significance (p). In addition, stepwise multiple linear regression was used to evaluate relative contribution of each variables (i.e., morphological indices and sprinkling intensities) to the estimation of maximum interception. The statistical analysis software used for these analyses was SPSS 22.0 (SPSS Inc., Chicago, IL, USA).

4. Results and Discussion

4.1. Dynamic Canopy Interception

As shown in Figure 3, at each sprinkling intensity, the interception increased rapidly during the initial phase and then leveled off gradually until it became relatively stabilized at the maximum value. This indicated that a large part of water in the initial period of irrigation was captured by the canopy, which is consistent with observations under natural rainfall events [7,37,38]. Across different vegetative stages of alfalfa under the same sprinkling intensity, the rate of interception and the maximum interception tended to increase as the vegetative stage at cutting increased. When the irrigation volume and vegetative stage were kept the same, it took less time for interception to reach maximum value at the higher sprinkling intensities.

As for Equation (3), the model coefficients I_m and k represent the maximum interception and the rate of interception, respectively. The fitting curves of dynamic interception are shown in Figure 3, and the values of I_m, k, and $R_a{}^2$ of the model are listed in Table 2.

Table 2. Coefficients of the dynamic interception model of alfalfa canopy.

Sprinkling Intensity (mm/h)	Vegetative Stage (Days)	Model: $I = I_m\ (1 - e^{-kt})$		
		I_m	k	$R_a{}^2$
2.5	5	0.292	2.793	0.997
	15	0.444	1.490	0.992
	30	0.616	1.600	0.999
	45	0.666	1.712	0.993
5.0	5	0.336	3.632	0.981
	15	0.600	2.438	0.987
	30	0.801	2.738	0.988
	45	0.787	2.934	0.999
10.0	5	0.453	6.824	0.996
	15	0.624	5.498	0.992
	30	0.881	5.171	0.991
	45	0.941	5.905	0.997
20.0	5	0.506	13.306	0.977
	15	0.707	10.519	0.993
	30	1.041	9.317	0.993
	45	1.106	10.380	0.995
40.0	5	0.578	23.929	0.995
	15	0.774	21.034	0.996
	30	0.990	19.703	0.998
	45	1.256	18.455	0.998

Notes: I, the dynamic interception at a given time; I_m, the maximum interception; k, the exponential coefficient of the canopy interception; t, the interception time duration; $R_a{}^2$, adjusted coefficients of determination. The vegetative stages indicate the days after the most recent harvest of alfalfa.

The results showed that the values of I_m and k varied significantly with the changes of the vegetative stages and sprinkling intensities. Overall, values of $R_a{}^2$ ranged from 0.977 to 0.999, and p values were below 0.001. These results indicated that the derived model and observed results fit well.

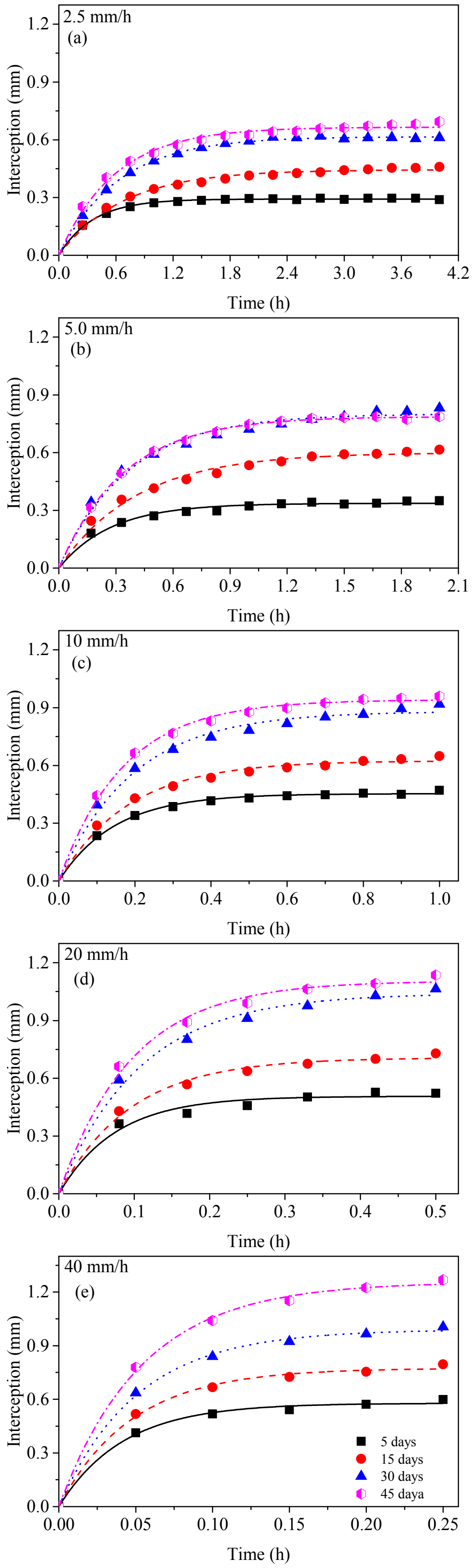

Figure 3. Canopy dynamic interception of alfalfa at different sprinkling intensities (2.5 (**a**), 5.0 (**b**), 10 (**c**), 20 (**d**), and 40 mm/h (**e**)) during different vegetative stages. The dots indicate the observed values, and the curves are the fitting results. The legend (5, 15, 30, and 45 days) indicates the number of days after the most recent harvest of alfalfa.

4.2. Model Coefficients

The model coefficients listed in Table 2 show that I_m and k were controlled by vegetative stages and sprinkling intensities.

I_m ranged from 0.29 to 1.26 mm, tending to increase with the growth of alfalfa and increasing sprinkling intensity (Figure 4a). When alfalfa was at the earlier vegetative stages and the sprinkling intensity was lower, the changes of the vegetative stages and sprinkling intensity influenced the value of I_m more significantly. However, the changes of the vegetative stages and sprinkling intensity had little influence on the value of I_m when alfalfa had developed towards the later vegetative stages and when sprinkling intensity was higher.

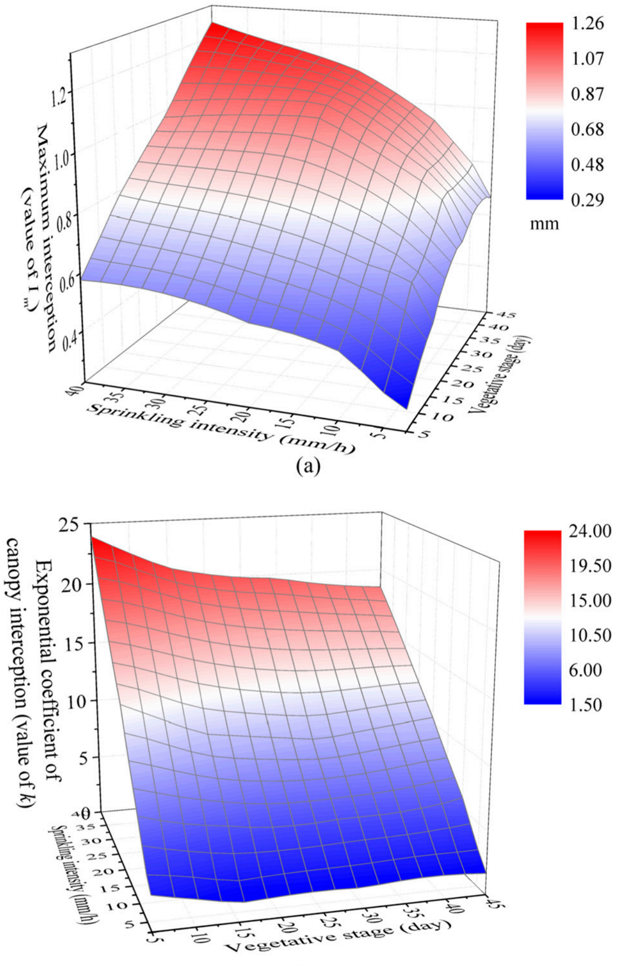

Figure 4. Variation tendencies of model coefficients I_m (**a**) and k (**b**) with the variations of sprinkling intensities and vegetative stages (days after the most recent harvest of alfalfa). I_m is the maximum interception, and k is the exponential coefficient of the canopy interception.

The value of k ranged from 1.49 to 23.93, tending to increase with the increase in sprinkling intensity and to decrease with the development of vegetative stages (Figure 4b). Previous results also demonstrated that under higher rainfall intensities it took less time to reach maximum interception by the canopy of forests [39,40] and shrubs [7]. The difference between the highest and lowest values of k was greater than that of I_m, demonstrating that the rate of interception changed more drastically than did the maximum interception across different vegetative stages and sprinkling intensities. Variation of k showed no clear trend along the vegetative stages of alfalfa when the sprinkling intensity was low, but k values tended to decrease with the growth of plants when the sprinkling intensity was at higher levels (Figure 4b). This suggests that how the rate of interception changes from one vegetative stage to another is dependent on the levels of sprinkling intensity.

It has been reported that maximum interception increased from earlier to later vegetative stages [28] and with increasing rainfall intensities [7]. The maximum interception by alfalfa canopy (reflected by I_m (0.29–1.26 mm)) was lower than that of maize (1.85–3.9 mm) [24,25], shrubs (0.36–5.29 mm) [7], and forests (0.3–5 mm) [8]. The higher interception rates observed in other studies was likely due to a higher canopy surface area of those plants, since the surface area of the plant is often considered as a significant factor influencing the amounts of interception [8,9,28]. The interception we measured for alfalfa was slightly higher than that of winter wheat canopy (0.3–1.0 mm) [28]. The reason might be that our tests were performed in laboratory without wind, and wind could potentially decrease the canopy interception [28,30]. Besides, alfalfa leaves have relatively high hydrophobicity [6], and this would decrease the amount of water intercepted by canopy [41].

In this study, we observed a positive relationship between maximum interception and sprinkling intensities for alfalfa canopy under sprinkler irrigation. This pattern is consistent with the findings of some previous studies under natural rainfall conditions. These studies reported that maximum interception by shrub canopy was positively correlated with rainfall intensity [7,42]. However, some other studies showed that the maximum interception decreased with the increase in rainfall intensities [43,44]. In addition, a study conducted in spruce forest reported no clear relationship between maximum interception and intensities [45]. Thus, the role of rainfall intensity in determining the maximum interception is still uncertain [46]. We argue that the relationship between maximum interception and sprinkling intensity depends on the range of intensity values, as suggested by a few other researchers [39,46,47]. Further study with a broader range of sprinkling intensities is needed in order to fully understand the mechanism of how rainfall intensity affects the maximum interception.

4.3. Maximum Interception Estimation

Since the maximum interception of alfalfa canopy was influenced by sprinkling intensity and vegetative stages, we obtained the two following equations based on the output of linear stepwise regression analysis:

$$I_m = 0.261 + 0.078LAI,\ {R_a}^2 = 0.701,\ p < 0.001 \quad (6)$$

$$I_m = 0.157 + 0.075LAI + 0.008R,\ {R_a}^2 = 0.890,\ p < 0.001 \quad (7)$$

where I_m is the maximum interception (mm), LAI is leaf area index, R is sprinkling intensity (mm/h), ${R_a}^2$ is the adjusted coefficient of determination, and p is regression significance. The results indicated that the LAI and the sprinkling intensity were the most influential variables. Furthermore, based on Equations (6) and (7), the combination of LAI and sprinkling intensity predicted I_m better than LAI did alone.

We also estimated I_m by a nonlinear regression relationship:

$$I_m = 0.284 + 0.092LAI(1 - e^{-0.231R}),\ {R_a}^2 = 0.969,\ p < 0.001 \quad (8)$$

The plant height of alfalfa is an indicator more readily available than LAI, so an equation based on plant height for estimating I_m could be more practical. As shown in Figure 5, there was a significant linear relationship between LAI and plant height.

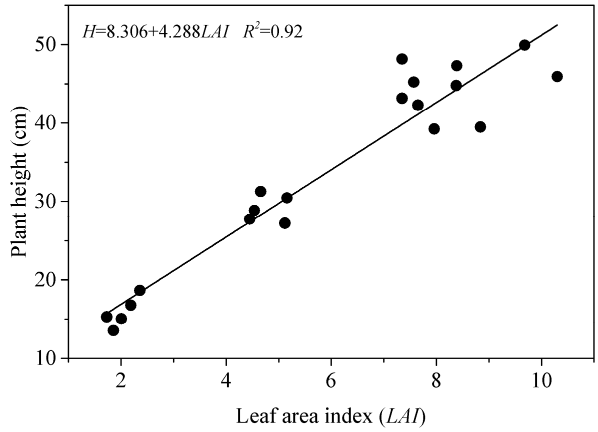

Figure 5. Relationship between plant height (H) and leaf area index (LAI).

After the variable LAI was replaced with plant height (H) in Equation (8), the nonlinear regression result became:

$$I_m = 0.194 + 0.019H(1 - e^{-0.230R}), {R_a}^2 = 0.932, p < 0.001 \quad (9)$$

Comparison of four estimation equations of I_m are shown in Figure 6.

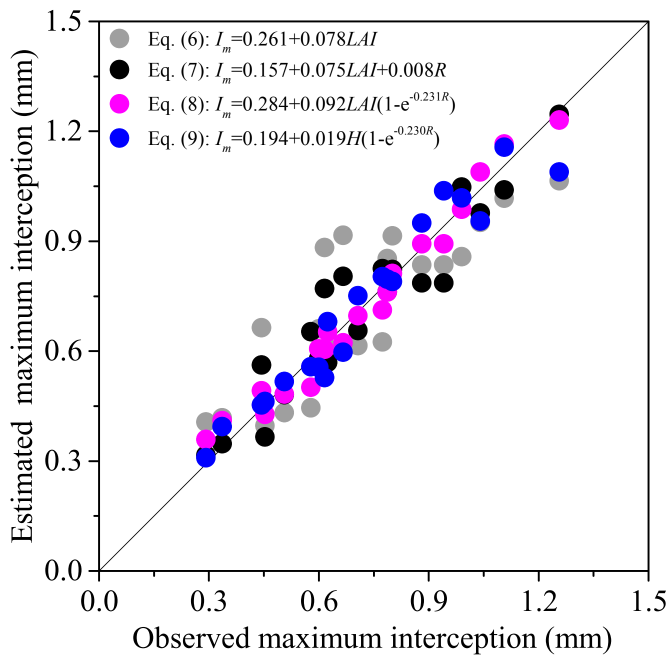

Figure 6. Observed and estimated maximum interception for four equations. I_m is the maximum interception, LAI is leaf area index, R is sprinkling intensity, and H is plant height. The diagonal line indicates the ratio of 1:1.

In previous studies, LAI, sprinkling intensity, and plant height were preferred variables for estimating maximum interception. Other research based on winter wheat canopy [28] and olive canopy [9] also proposed that LAI was an important explanatory variable for predicting canopy interception capacity. Zhang et al. [7] and Wang et al. [42] reported that rainfall intensity was another predictive variable for interception to some extent. The provided nonlinear equations in our experiments had higher values of adjusted coefficient of determination than reported linear equations [7,28,42]. Therefore, the nonlinear Equation (8) combined with sprinkling intensity and LAI

could better estimate the maximum interception. In addition, the nonlinear Equation (9) incorporating plant height and sprinkling intensity was also recommended. Since Equation (9) was more practical than Equation (8), using Equation (9) can achieve convenient and accurate estimation for interception capacity of the alfalfa canopy.

5. Conclusions

The dynamic model of rainfall interception for the plant of alfalfa derived in this paper was validated by experimental data, and the adjusted coefficients of determination of this model ranged from 0.977 to 0.999. Based on the model, the water intercepted by the canopy increased rapidly with time during the early phase of sprinkler irrigation, and then the increase of interception leveled off until the maximum retention capacity of the canopy was reached.

The experimental results showed that the maximum interception of the alfalfa canopy ranged from 0.29 to 1.26 mm. During early vegetative stages of alfalfa, the maximum interception was low and the rate of interception was high. Conversely, the maximum interception was high and the rate of interception was low during late vegetative stages. When the intensity of sprinkler irrigation was greater, both the maximum interception and the rate of interception of the alfalfa canopy tended to increase.

There were three main factors influencing the maximum interception of the canopy of alfalfa, including the leaf area index, the intensity of sprinkler irrigation, and plant height. In this paper, two linear and two nonlinear estimation equations for the maximum interception of alfalfa canopy were developed. The linear equations indicated that the *LAI* and the sprinkling intensity were the most influential variables. With a more ideal goodness of fit, a nonlinear equation also based on *LAI* and sprinkling intensity was then provided. Finally, a more practical nonlinear equation with plant height and sprinkling intensity as key variables was recommended, because the plant height variable is more conveniently available in practice.

Acknowledgments: This work was supported by the National Natural Science Foundation of China (No. 51379011). The authors would like to thank the support provided by the staff and technicians associated with Clover Group Shuangqiao Experimental Base: Yishan Liu, Jianming Sun and Pai Hou. The authors would like to express their gratitude to anonymous reviewers for their constructive comments in improving the manuscript.

Author Contributions: Jian Jiao and Derong Su conceived and designed the experiments; Jian Jiao, Liliang Han and Yadong Wang performed the experiments; Jian Jiao analyzed the data and wrote the paper. Both authors read and approved the manuscript.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

References

1. Sun, Q.Z.; Yu, Z.; Ma, C.H.; Xu, C.C. Achievements of the alfalfa industry in last decade and priorities in next decade in China. *Pratacultural Sci.* **2013**, *30*, 471–477.
2. Li, L.; Li, N.; Sheng, J.D.; Wang, H. Effects of nitrogen fertilizer and planting density on alfalfa growth and seed yield. *Acta Agrestia Sin.* **2012**, *20*, 54–57.
3. Ouazaa, S.; Latorre, B.; Burguete, J.; Serreta, A.; Playán, E.; Salvador, R.; Paniagua, P.; Zapata, N. Effect of the start–stop cycle of center-pivot towers on irrigation performance: Experiments and simulations. *Agric. Water Manag.* **2015**, *147*, 163–174. [CrossRef]
4. Urrego-Pereira, Y.; Cavero, J.; Medina, E.; Martínez-Cob, A. Role of transpiration reduction during center-pivot sprinkler irrigation in application efficiency. *J. Irrig. Drain. Eng.* **2013**, *139*, 221–232. [CrossRef]
5. Stambouli, T.; Martinez-Cob, A.; Faci, J.M.; Howell, T.; Zapata, N. Sprinkler evaporation losses in alfalfa during solid-set sprinkler irrigation in semiarid areas. *Irrig. Sci.* **2013**, *31*, 1075–1089. [CrossRef]
6. Urrego-Pereira, Y.F.; Martínez-Cob, A.; Fernández, V.; Cavero, J. Daytime sprinkler irrigation effects on net photosynthesis of maize and alfalfa. *Agron. J.* **2013**, *105*, 1515–1528. [CrossRef]

7. Zhang, Y.F.; Wang, X.P.; Hu, R.; Pan, Y.X.; Paradeloc, M. Rainfall partitioning into throughfall, stemflow and interception loss by two xerophytic shrubs within a rain-fed re-vegetated desert ecosystem, northwestern China. *J. Hydrol.* **2015**, *527*, 1084–1095. [CrossRef]
8. Muzylo, A.; Llorens, P.; Domingo, F. Rainfall partitioning in a deciduous forest plot in leafed and leafless periods. *Ecohydrology* **2012**, *5*, 759–767. [CrossRef]
9. Gómez, J.A.; Giráldez, J.V.; Fereres, E. Rainfall interception by olive trees in relation to leaf area. *Agric. Water Manag.* **2001**, *49*, 65–76. [CrossRef]
10. David, J.S.; Valente, F.; Gash, J.H.C. Evaporation of intercepted rainfall. In *Encyclopedia of Hydrological Sciences*; John Wiley & Sons, Ltd: Chichester, UK, 2005.
11. Liu, H.J.; Kang, Y.H.; Wang, Q.G. Effect of crop canopy on soil water redistribution under sprinkler irrigation: A review. *Agric. Res. Arid Areas* **2007**, *25*, 137–142.
12. Liang, X.; Su, D.R.; Yin, S.X.; Wang, Z. Leaf water absorption and desorption functions for three turfgrasses. *J. Hydrol.* **2009**, *376*, 243–248. [CrossRef]
13. McNaughton, K. Net interception losses during sprinkler irrigation. *Agric. Meteorol.* **1981**, *24*, 11–27. [CrossRef]
14. ElMuzylo, A.; Llorens, P.; Valente, F.; Keizer, J.J.; Domingo, F.; Gash, J.H.C. A review of rainfall interception modelling. *J. Hydrol.* **2009**, *370*, 191–206.
15. Kozak, J.A.; Ahuja, L.R.; Green, T.R.; Ma, L. Modelling crop canopy and residue rainfall interception effects on soil hydrological components for semi-arid agriculture. *Hydrol. Process.* **2007**, *21*, 229–241. [CrossRef]
16. Llorens, P.; Domingo, F. Rainfall partitioning by vegetation under mediterranean conditions. A review of studies in Europe. *J. Hydrol.* **2007**, *335*, 37–54. [CrossRef]
17. Návar, J.; Bryan, R. Interception loss and rainfall redistribution by semi-arid growing shrubs in northeastern Mexico. *J. Hydrol.* **1990**, *115*, 51–63. [CrossRef]
18. Nulsen, R.A.; Bligh, K.J.; Baxter, I.N.; Solin, E.J.; Imrie, D.H. The fate of rainfall in a mallee and heath vegetated catchment in southern western Australia. *Austral Ecol.* **1986**, *11*, 361–371. [CrossRef]
19. Domingo, F.; Puigdefabregas, J.; Moro, M.J.; Bellot, J. Role of vegetation cover in the biogeochemical balances of a small afforested catchment in southeastern Spain. *J. Hydrol.* **1994**, *159*, 275–289. [CrossRef]
20. Jetten, V.G. Interception of tropical rain forest: Performance of a canopy water balance model. *Hydrol. Process.* **1996**, *10*, 671–685. [CrossRef]
21. Van Dijk, A.I.J.M.; Bruijnzeel, L.A. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 1. Model description. *J. Hydrol.* **2001**, *247*, 230–238. [CrossRef]
22. Pike, R.; Scherer, R. Overview of the potential effects of forest management on low flows in snowmelt-dominated hydrologic regimes. *J. Ecosyst. Manag.* **2003**, *3*, 44–60.
23. Howell, T.A. Enhancing water use efficiency in irrigated agriculture. *Agron. J.* **2001**, *93*, 281–289. [CrossRef]
24. Lamm, F.R.; Manges, H.L. Partitioning of sprinkler irrigation water by a corn canopy. *Trans. ASAE* **2000**, *43*, 909–918. [CrossRef]
25. Wang, D.; Li, J.; Rao, M. Sprinkler water distributions as affected by corn canopy. *Trans. Chin. Soc. Agric. Eng.* **2006**, *22*, 43–47.
26. Mauch, K.; Delgado, J.; Bausch, W.; Barbarick, K.; McMaster, G. New weighing method to measure shoot water interception. *J. Irrig. Drain. Eng.* **2008**, *134*, 349–355. [CrossRef]
27. van Dijk, A.I.J.M.; Bruijnzeel, L.A. Modelling rainfall interception by vegetation of variable density using an adapted analytical model. Part 2. Model validation for a tropical upland mixed cropping system. *J. Hydrol.* **2001**, *247*, 239–262. [CrossRef]
28. Kang, Y.H.; Wang, Q.G.; Liu, H.J. Winter wheat canopy interception and its influence factors under sprinkler irrigation. *Agric. Water Manag.* **2005**, *74*, 189–199. [CrossRef]
29. Pypker, T.G.; Bond, B.J.; Link, T.E.; Marks, D.; Unsworth, M.H. The importance of canopy structure in controlling the interception loss of rainfall: Examples from a young and an old-growth douglas-fir forest. *Agric. For. Meteorol.* **2005**, *130*, 113–129. [CrossRef]
30. Fan, J.; Oestergaard, K.T.; Guyot, A.; Lockington, D.A. Measuring and modeling rainfall interception losses by a native banksia woodland and an exotic pine plantation in subtropical coastal Australia. *J. Hydrol.* **2014**, *515*, 156–165. [CrossRef]
31. Rutter, A.J.; Kershaw, K.A.; Robins, P.C.; Morton, A.J. A predictive model of rainfall interception in forests, 1. Derivation of the model from observations in a plantation of corsican pine. *Agric. Meteorol.* **1971**, *9*, 367–384. [CrossRef]

32. Rutter, A.; Morton, A.; Robins, P. A predictive model of rainfall interception in forests. Ii. Generalization of the model and comparison with observations in some coniferous and hardwood stands. *J. Appl. Ecol.* **1975**, *12*, 367–380. [CrossRef]
33. Horton, R.E. Rainfall interception. *Mon. Weather Rev.* **1919**, *47*, 603–623. [CrossRef]
34. Anzhi, W.; Jinzhong, L.; Jianmei, L.; Tiefan, P.; Changjie, J. A semi-theoretical model of canopy rainfall interception for pinus koraiensis nakai. *Ecol. Model.* **2005**, *184*, 355–361. [CrossRef]
35. Xiao, Q.; McPherson, E.G.; Ustin, S.L.; Grismer, M.E. A new approach to modeling tree rainfall interception. *J. Geophys. Res. Atmos.* **2000**, *105*, 173–188. [CrossRef]
36. Sayyadi, H.; Nazemi, A.H.; Sadraddini, A.A.; Delirhasannia, R. Characterising droplets and precipitation profiles of a fixed spray-plate sprinkler. *Biosyst. Eng.* **2014**, *119*, 13–24. [CrossRef]
37. Price, A.G.; Carlyle-Moses, D.E. Measurement and modelling of growing-season canopy water fluxes in a mature mixed deciduous forest stand, Southern Ontario, Canada. *Agric. For. Meteorol.* **2003**, *119*, 69–85. [CrossRef]
38. Staelens, J.; De Schrijver, A.; Verheyen, K.; Verhoest, N.E.C. Rainfall partitioning into throughfall, stemflow, and interception within a single beech (*Fagus sylvatica* L.) canopy: Influence of foliation, rain event characteristics, and meteorology. *Hydrol. Process.* **2008**, *22*, 33–45. [CrossRef]
39. Llorens, P.; Poch, R.; Latron, J.; Gallart, F. Rainfall interception by a Pinus sylvestris forest patch overgrown in a Mediterranean mountainous abandoned area I. Monitoring design and results down to the event scale. *J. Hydrol.* **1997**, *199*, 331–345. [CrossRef]
40. Chen, S.; Chen, C.; Cao, T.; Zhao, X.; Hao, H.; Pang, J.; Zhang, S. Effects of rainfall size class and intensity on canopy interception of Pinus tabulaeformis forest in the Qinling mountains, China. *J. Basic Sci. Eng.* **2015**, *23*, 41–55.
41. Holder, C.D. Effects of leaf hydrophobicity and water droplet retention on canopy storage capacity. *Ecohydrology* **2013**, *6*, 483–490. [CrossRef]
42. Wang, X.P.; Zhang, Y.F.; Hu, R.; Pan, Y.X.; Berndtsson, R. Canopy storage capacity of xerophytic shrubs in northwestern China. *J. Hydrol.* **2012**, *454–455*, 152–159. [CrossRef]
43. Mair, A.; Fares, A. Throughfall characteristics in three non-native hawaiian forest stands. *Agric. For. Meteorol.* **2010**, *150*, 1453–1466. [CrossRef]
44. Calder, I.R. A stochastic model of rainfall interception. *J. Hydrol.* **1986**, *89*, 65–71. [CrossRef]
45. Peng, H.; Zhao, C.; Feng, Z.; Xu, Z.; Wang, C.; Zhao, Y. Canopy interception by a spruce forest in the upper reach of heihe river basin, northwestern China. *Hydrol. Process.* **2014**, *28*, 1734–1741. [CrossRef]
46. Klamerus-Iwan, A. Different views on tree interception process and its determinants. *For. Res. Pap.* **2014**, *75*, 291–300. [CrossRef]
47. Carlyle-Moses, D.E.; Price, A.G. An evaluation of the gash interception model in a northern hardwood stand. *J. Hydrol.* **1999**, *214*, 103–110. [CrossRef]