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Research Article

Effects of Subsurface Drip Irrigation on Water Consumption and Yields of Alfalfa under Different Water and Fertilizer Conditions

Xuesong Cao[1] **Yayang Feng**[2] **Heping Li**[1] **Hexiang Zheng**[1] **Jun Wang**[1] **and Changfu Tong**[1]

[1]*Institute of Water Resources for Pastoral Area, China Institute of Water Resources and Hydropower Research, Huhhot 010020, China*
[2]*Water Conservancy and Civil Engineering, Inner Mongolia Agricultural University, Hohhot 010018, China*

Correspondence should be addressed to Xuesong Cao; cxsmks@126.com

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A field experiment was conducted for the purpose of examining the effects of different combinations of water and fertilizer applications on the water consumption and yields of alfalfa under subsurface drip irrigation (SDI). The results showed that the jointing and branching stages were the key stages for alfalfa water requirement. The water consumption had varied greatly (from 130 to 170 mm) during the growth period of each alfalfa crop. The water consumption during the whole growth period was approximately 500 mm, and the maximum water consumption intensity was $3.64\,\mathrm{mm\cdot d^{-1}}$. The overall changes in water consumption and yields during the growth period of the alfalfa displayed trends of first increasing and then decreasing. The sensitivities of the yields to water changes were much higher than that of fertilizer. The water use efficiency (WUE) of the alfalfa was determined to range from 1.68 to $3.20\,\mathrm{kg\cdot m^{-3}}$, and the rate of growth had ranged from 4.85% to 51.77%. The WUE and rate of growth of the alfalfa indicated the following trend: second crop > third crop > first crop. The results of frequency analysis based on the water-nitrogen-yield regression equation are the following: irrigation amounts of 142~165 mm and nitrogen application of $61\sim80\,\mathrm{kg\cdot hm^{-2}}$ have a 95% probability of obtaining a hay yield of alfalfa of more than $11903\,\mathrm{kg\cdot hm^{-2}}$. These results suggest that SDI is a promising irrigation method, which can increase the WUE and hay yield of alfalfa under the condition of SDI within an appropriate amount of water and nitrogen fertilizer, and too low or too high water and nitrogen fertilizer will adversely affect the WUE and hay yield of alfalfa.

1. Introduction

With the global economic development, population growth, and regional water shortages, agricultural production, as the world's primary consumer of water resources, is increasingly focused on agricultural water conservation, environmental protection, and improving crop quality and yield, which is also increasingly squeezed by the demands from other society sectors and threatened by potential climatic change [1]. SDI, as a new irrigation method in recent years, has attracted much attention in agricultural production in arid and semi-arid areas due to its improving WUE and ability to minimize the adverse effects of excessive irrigation on the environment [2, 3]. Studies have shown that SDI saves water resources and does not interfere with ground production of alfalfa and can improve crop water productivity and hay yield [4–7]. In modern precision agricultural activities, two of the three "precisions" (precision sowing, precision fertilization, and precision irrigation) are implemented through SDI. The technical characteristics of SDI include small flow, local moistening, and frequent irrigation. When compared with surface irrigation methods, SDI has been found to have outstanding advantages, such as water conservation, lower amounts of required fertilizer, reducing evaporation losses, increasing crop WUE, irrigation WUE and crop yield, good adaptability to various terrain, uniform irrigation, and ease of technology integration [8–15].

Alfalfa (*Medicago sativa L.*) is a type of high-quality perennial leguminous forage, with the characteristics of good palatability, high stress resistance, high yield, rich nutrition, and so on [16–22]. Throughout the world, alfalfa enjoys the reputation as the " Queen of Forage" [16] and is one of the main high-quality forage crops planted in pastoral areas and occupies a very important position in agricultural production. Alfalfa is not suitable for aboveground drip irrigation due to its mowing multiple times per year and its growth characteristics; therefore, alfalfa under SDI technology came into being. With the development of new water-saving irrigation technology, artificial grass SDI technologies with increased water-saving potential have become important directions for the current development projects in arid and semiarid pastoral regions. Studies have shown that alfalfa has better adaptability to SDI in arid and semiarid areas [23–25]. Furthermore, as a form of engineered water-saving irrigation, SDI has been widely applied in actual production processes. It has been found to have the ability to improve farmland production environments, along with regulating the physiological processes of crops, and also have certain positive effects, such as increasing hay yield [26, 27] and saving water [28]. In a previous study, Kou et al. [29] examined the effects of subsurface regulated deficit drip irrigation on the water consumption, yields, and quality of alfalfa and also pointed out that with increases in the water deficit and yields, the water consumption of the alfalfa had been reduced. Meanwhile, the water usage efficiency had been increased. However, some studies have shown that the fresh and dried yield of alfalfa decreases with the decrease of water supply, and the WUE increases instead [30, 31]. SDI can also greatly reduce surface evaporation and deep percolation; studies had shown that using SDI can save a quarter of total water transfers in the season [32, 33]. Similarly, alfalfa under SDI can increase crop yields by improving precise control of water and fertilizer. Compared with the conventional method of irrigation, the water-saving ratio due to SDI that precisely regulates water and fertilizer ranges from 30 to 70 per cent whereas gain in productivity for different crops ranges from 20 to 90 per cent as well as reduces the requirement of labors and fertilizers [34]. Stavarache et al. [35] determined that nitrogen applications had a significant promoting effect on the yields of alfalfa grown in the same year. In another related study, Liu et al. [36] proposed a precision regulation model of water and fertilizer for irrigation and fertilizer management in alfalfa. Therefore, a comprehensive understanding of crop water needs and water and fertilizer precise control ratio under SDI conditions is of great significance for vigorously developing efficient water-saving agricultural methods, alleviating water shortages, and improving crop water and fertilizer usage efficiency.

In the current experiment, the water and fertilizer were transported directly to the roots of the alfalfa plants using an SDI belt. The irrigation and fertilization processes for the alfalfa were strictly controlled in order to effectively analyze the water consumption rule of the alfalfa under SDI conditions. The effects of the different irrigation and fertilization treatments on the yields and water usage efficiency of the alfalfa were studied in order to obtain the best combination points for the water and fertilizer application amounts. The results of this study provided a theoretical basis for the development of irrigation in artificial forage land, improvements in the forage quality and efficiency; protection of grassland ecological environments, adjustments in the livestock industry structures, and promotion of the sustainable development of grassland animal husbandry in the arid and semiarid pastoral areas of western Inner Mongolia. This paper provides findings for the enrichment of the alfalfa SDI technology system and offers valuable data support and theoretical basis by field experiment data analysis for water saving, yield enhancement, and quality improvement of agricultural crops in this region.

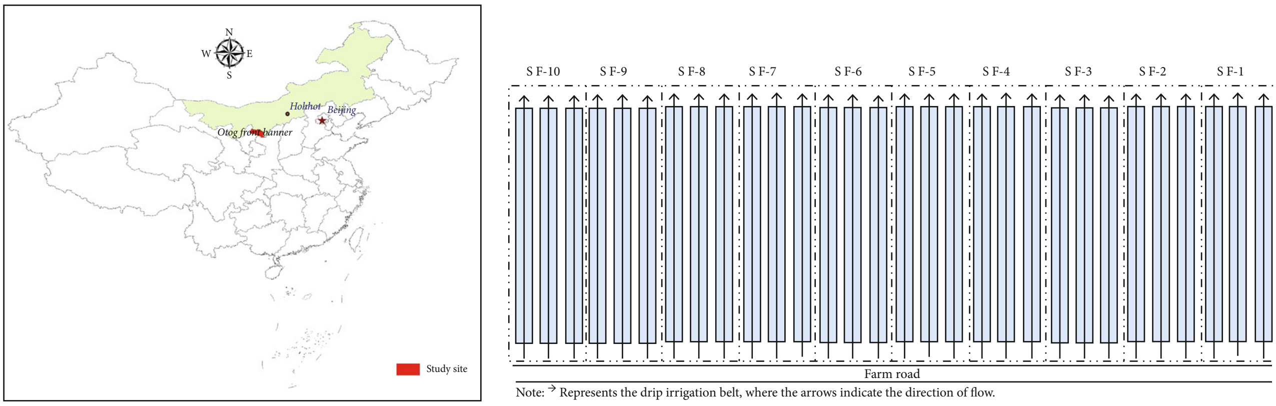
2. Materials and Methods

2.1. Experimental Site. This study's experiment was carried out at the Hengfeng water-saving irrigation experimental base in Otog Front Banner, Ordos City, Inner Mongolia (Figure 1(a)) from April to October 2019. The Otog Front Banner is located in the abdomen of Mu Us Sandland and at the junction of Inner Mongolia, Shaanxi, and Ningxia Provinces. Its geographic coordinates are eastern longitude $106°30' - 108°30'$ and northern latitude $37°38' - 38°45'$, with an altitude ranging between 1,300 and 1,400 m. The study area is characterized by the semiarid continental climate of a middle temperate zone, which includes hot summers, cold winters, dry conditions with little rainfall, strong evaporation conditions, and abundant sunlight. The annual average temperature is 7.9°C; annual average precipitation is 260.6 mm; annual average evaporation is 2,497.9 mm; and the annual prevailing wind direction is south, followed by west and east wind directions, with an average annual wind speed of 2.6 $m{\cdot}s^{-1}$. In the study area, the average number of sandstorm days is 16.9 days, and the average relative humidity is 49.8%. Also, the number of annual average sunshine hours ranges between 2,500 and 3,200 hours, with an average of 2,958 hours, and the frost-free period is 171 days. The maximum frozen soil depth is 1.54 m. The 40 cm deep soil type in the experimental area was determined to be sandy soil with a bulk density of 1.62 $g{\cdot}cm^{-3}$. The soil mechanical composition of 0~40 cm soil layer is shown in Table 1.

2.2. Test Material and Planting Method. SDI material: the SDI belts were embedded at a depth of 20 cm, as part of a patch-type SDI belt system. The wall thicknesses were 0.4 mm; drip discharge was 2.0 $L{\cdot}h^{-1}$; and the drip spacing was 0.3 m. Each SDI belt controlled four rows of alfalfa, and the spacing between the SDI belts was 60 cm.

Varieties of alfalfa: the alfalfa which was used in this study was in its third year of planting. The alfalfa variety was Grassland No. 2. The alfalfa was sown using drills, with the seeding amount set as 30 $kg{\cdot}hm^{-2}$ and the line spacing set at 15 cm.

Planting method: alfalfa was artificially sown using drills with line spacings of 15 cm. In order to ensure the nutritional value and palatability of the alfalfa, the alfalfa was harvested and stored at the initial flowering stage. The alfalfa was harvested in three crops a year. The alfalfa strikes rooted in early April of each year, and the third crop was harvested at the end of September.



(a) (b)

Figure 1: Study site on the map of China (a) and experimental plot layout of the studied field (b).

Table 1: Soil mechanical composition of 0~40 cm soil layer in the test area.

Bulk density ($g \cdot cm^{-3}$)	Proportion	Soil particle distribution (%)			Soil type
		0.05~2 mm	0.002~0.05 mm	<0.002 mm	
1.62	2.71	76.85	21.69	1.46	Sandy soil

Fertilizers used in the experiment: in this study, the nitrogen fertilizer was urea (N 46.4%).

2.3. Experimental Design. A 2-factor and 3-level orthogonal combination design was used in this study's experiment. The designs of the specific experimental factors and levels are shown in Table 2. Nine different orthogonal design treatments and one conventional field control treatment were set up in the experimental area, with a total of ten experimental treatments being conducted in this study. Each treatment was repeated three times, for a total of 30 experimental plots. Each experimental treatment had a length of 60 m, width of 8 m, and area of 480 m^2. The total area of the experimental plots was 4,800 m^2. In order to avoid the mutual impact of the treatments, a 2 m wide isolation belt was set up between every two treatments (Figure 1(b)). Each treatment was divided into three experimental plots during the experiment monitoring process. For example, each experimental plot had a length of 20 m, width of 8 m, and area of 160 m^2. When the soil moisture content of the SF-5 treatment was reduced to 65% of the field water holding capacity, each treatment was irrigated according to the irrigation quota (the amounts of irrigated water were recorded by a rotor digital water meter), and each experimental treatment had the same irrigation date and frequency.

2.4. Measurement Indexes and Method. Observations of the meteorological factors: a farmland meteorological station (HOBO U30 Onset, Onset Computer Corporation, Bourne, MA, USA) was set up in the experimental area for the purpose of observing the temperature, rainfall, wind speeds, relative humidity, air pressure, wind directions, and other factors occurring during the growing period of the alfalfa crops. The effective rainfall was determined to be 182.10 mm during the entire alfalfa growth period, and the details are shown in Figure 2 (the red line in Figure 2 represents the two-period moving average trend line).

Table 2: Designs of the experimental factors and levels for the fertilization of the alfalfa under SDI conditions.

Treatment	Levels and factors for production target	
	Irrigation quota (mm)	N ($kg \cdot hm^{-2}$)
SF-1	20	0
SF-2	20	60
SF-3	20	120
SF-4	25	0
SF-5	25	60
SF-6	25	120
SF-7	30	0
SF-8	30	60
SF-9	30	120
SF-10	A local herdsman's traditional alfalfa planting field was taken as the control treatment	

Observations of the groundwater levels: the groundwater level changes in the experimental area were measured using a HOBO automatic groundwater level meter (HOBO U30 Onset, Onset Computer Corporation, Bourne, MA, USA). The groundwater burial depths in the experimental area were determined to be between 1.2 and 2.0 m.

Irrigation amounts: the soil moisture levels of each plot were automatically monitored by the HOBO soil moisture automatic measuring instrument (HOBO U30 Onset, Onset Computer Corporation, Bourne, MA, USA). When the soil moisture content had reached the lower water limit, irrigation was implemented in time for the treatment. The irrigation for the local control treatment (SF-10) was based on the irrigation experiences of the local herdsmen, and the amounts of the irrigation were measured using water meter

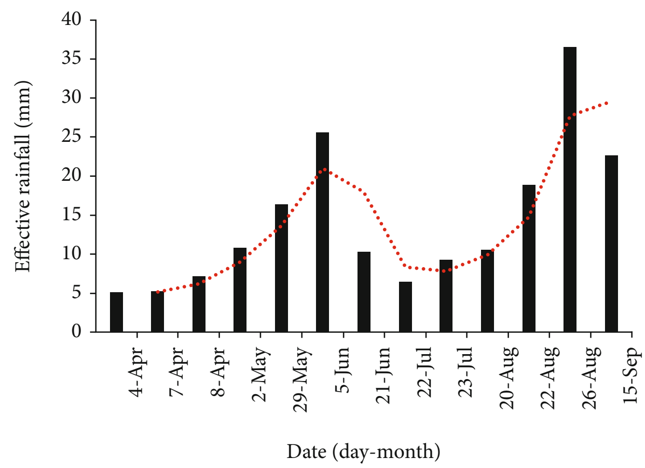


Figure 2: Effective rainfall during the entire growth period of the alfalfa.

Table 3: Irrigation amounts of each alfalfa crop during each growth period.

Treatment	Irrigation amounts (mm) (the first/second/third crop)				
	Seedling establishment stage	Jointing stage	Branching stage	Flowering stage	Total irrigation
SF-1	20/20/20	40/20/20	40/40/0	20/20/20	120/100/60
SF-2	20/20/20	40/20/20	40/40/0	20/20/20	120/100/60
SF-3	20/20/20	40/20/20	40/40/0	20/20/20	120/100/60
SF-4	25/25/25	50/25/25	50/50/0	25/25/25	150/125/75
SF-5	25/25/25	50/25/25	50/50/0	25/25/25	150/125/75
SF-6	25/25/25	50/25/25	50/50/0	25/25/25	150/125/75
SF-7	30/30/30	60/30/30	60/60/0	30/30/30	180/150/90
SF-8	30/30/30	60/30/30	60/60/0	30/30/30	180/150/90
SF-9	30/30/30	60/30/30	60/60/0	30/30/30	180/150/90
SF-10	0/0/0	80/80/80	80/80/80	0/0/0	160/160/160

readings. The irrigation amounts of each growth period of the experiment are detailed in Table 3.

Soil moisture content levels: the field water holding capacity of undisturbed soil samples which were taken using a cutting ring from the experimental area was measured in this study's laboratory facilities. Then, the results were compared with the field experiment results, and the field water holding capacity of the 0 to 40 cm soil layer in the experimental area was determined to be 22.86%. The soil moisture content of each experimental plot was measured by instrument measurement methods and checked by an oven-drying method. The instrument used in the measurement method was the HOBO soil moisture automatic measuring instrument, and the measured depth of the soil layer was 10, 20, 30, 40, 50, and 60 cm, respectively. The oven-drying method utilized a soil auger to extract the soil samples, and an oven was used for the drying process.

Hay yields of the alfalfa crops: the growth stage of the alfalfa was divided into the seedling establishment stage, branching stage, squaring stage, and flowering stage. The alfalfa hay was cut when it had entered the flowering stage, and three crops were harvested each year. A quadrat sampling method was used for measurements of the hay yields. The quadrat area was set as 1 m × 1 m. The fresh weight of the alfalfa after cutting was determined, and the fresh hay samples were placed into an oven. A water removal treatment was conducted for 30 minutes at a high temperature of 105°C, and then, the temperature was adjusted to 65°C in order to dry the samples for a period of 48 hours under constant temperature conditions. The samples were then taken out of the oven; the dry weights of the samples were calculated after the samples had cooled.

2.5. Calculation and Analysis of the Water Consumption of the Alfalfa. Water consumption: the water consumption of the alfalfa was calculated using a water balance equation as follows:

$$ET_a = P + I - \Delta W - Q, \quad (1)$$

where ET_a represents the water consumption (mm) during each period, P is the effective precipitation (mm) during the corresponding period, I denotes the irrigation amount during the corresponding period, ΔW represents the changes in the soil water storage (mm) during the corresponding period, and Q is the water flux (mm) of the lower boundary during the corresponding period.

Changes in the soil water storage levels: the changes in the soil water storage levels during each growth stage were calculated according to soil moisture content of each experimental treatment, and the formula was as follows:

$$\Delta W = \frac{\theta_{i+1} - \theta_i}{100} \times \gamma \times h, \tag{2}$$

where θ_i denotes the initial soil water content (%) during the corresponding period, θ_{i+1} is the final soil water content (%) during the corresponding period, γ represents the soil bulk density (cm^3/g), and h is the planned depth (mm) of the wetting layer.

Soil water fluxes of the lower boundary: the soil water fluxes at the lower boundary of the alfalfa were the deep soil leakage or recharge during each growth period which was calculated according to the soil's negative pressure measured during the experiment. The recharge and leakage of the soil moisture at the lower boundary of the planned wetting layer were calculated using an oriented flux method, and the measuring instrument was a negative pressure gauge. The calculation formula of the oriented flux method was as follows:

$$q(z_{1-2}) = -k(\bar{H}) \times \left(\frac{H_2 - H_1}{\Delta z} + 1\right), \tag{3}$$

where $k(\bar{H})$ represents the permeability coefficient of the soil at $\bar{H}$, $\Delta z = z_2 - z_1$, $\bar{H} = (H_1 + H_2)/2$, and H_1 and H_2 indicate the negative pressure values of the soil at the locations z_1 and z_2, respectively. Therefore, the soil water flow $q(z_{1-2})$ per unit area during the period from t_1 to t_2 could be obtained. Similarly, the flow $q(z)$ on each section could be calculated according to $q(z_{1-2})$ as follows:

$$q(z) = q(z_{1-2}) + \int_z^{z_{1-2}} [q(z, t_2) - q(z, t_1)]dz. \tag{4}$$

WUE: WUE refers to the output per unit of water consumption of crops, the value of which is equal to the ratio of the crop yields to the net water consumption of crops. In this study, the crop WUE was calculated using the following formula:

$$\mathrm{WUE} = \frac{Y}{ET_a}, \tag{5}$$

where WUE is the water use efficiency (kg·m^{-3}), Y represents the crop yields (kg·hm^{-2}), and the meanings of the other symbols are the same as previously mentioned.

2.6. Statistical Analysis. Analysis of variance was performed using the SPSS22.0 (IBM Corp., Armonk, New York, NY, USA) to determine the least significant difference (LSD) among treatments at $P < 0.05$, and Duncan's multiple range test was applied for comparing the means. OriginPro2019 (Origin Lab Corporation, Northampton, MA, USA) was used to draw the picture.

3. Results

3.1. Changes in the Soil Water Storage and Soil Water Fluxes. The changes in the soil water storage and water flux levels at the lower boundaries of the three alfalfa crops during each growth period are detailed in Tables 4 and 5, respectively. Results indicated that some treatments had a positive soil water storage capacity, which indicated a soil water surplus during growing seasons, whereas some treatments had a negative soil water storage capacity, which indicated a soil water deficit during growing seasons. According to the current irrigation system, in the SF-1~SF-9 treatments, the largest soil water surplus and soil water deficit during growing seasons occurred in the jointing stage of the first crop of SF-7 treatment and that of the third crop of SF-5 treatment, and the values were 19.25 and -10.67 mm, respectively. For the control treatment (SF-10), soil water surplus during growing seasons occurred in the jointing stage and branching stage, due to the irrigation during the two periods, whereas soil water deficit occurred in the seedling establishment stage and flowering stage, as there was no irrigation during this time. The changes in the soil water fluxes at the lower boundaries of each crop of alfalfa displayed similar laws and changes.

3.2. Water Consumption. The results of the calculated water consumption of the three crops of alfalfa during each growth stage are shown in Figure 3. Results indicated that the level of water consumption of the first crop of alfalfa during each growth stage under low, medium, and high water treatment conditions showed a trend of first increasing and then decreasing, and the relationship pattern of the water consumption during each growth stage was as follows: branching stage > jointing stage > seedling establishment stage > flowering stage. Furthermore, in accordance with the results of this study's comparison of total water consumption of the first crop of alfalfa (upper layer of Figure 3), the water consumption of the high water treatment (SF-7, SF-8, and SF-9) was greater than the water consumption of the medium water treatment (SF-4, SF-5, and SF-6), which was greater than the water consumption of the low water treatment (SF-1, SF-2, and SF-3). Furthermore, the water consumption during each growth period was observed to have increased with the increases in the irrigation amounts. The water consumption levels of the alfalfa during each growth period under the low, medium, and high water treatments were found to be lower than those of the local control treatment (SF-10). The control treatment (SF-10) was a one-time irrigation of alfalfa without applied fertilization treatments by the local herdsman for the purpose of pursuing a low input and high output scenario. In this study, by utilizing the results of this study's analyses of the water consumption levels of the alfalfa at different growth stages under the same water treatments and different fertilizer application rates, and according to the results of the comparison of a, b, and c detailed in the upper layer of Figure 3, it could be seen that under the same water treatment conditions, the water consumption levels of the alfalfa during the different growth stages were greatly affected by the amounts of the fertilizer applications.

Table 4: Changes in the soil water storage levels of each crop of alfalfa during each growth stage.

Treatment	Soil water storage (mm) (the first/second/third crop)				
	Seedling establishment stage	Jointing stage	Branching stage	Flowering stage	Total
SF-1	1.54/9.59/3.36	9.97/-3.27/-6.18	1.35/-3.95/13.35	3.83/-6.17/6.79	16.69/-3.80/17.32
SF-2	0.54/7.53/1.64	8.97/-5.97/-9.73	0.35/-3.61/12.46	2.83/-5.37/2.49	12.69/-7.42/6.86
SF-3	0.55/8.46/1.87	7.36/-5.48/-10.13	0.93/-2.92/14.61	2.63/-4.67/3.01	11.47/-4.61/9.36
SF-4	3.63/6.58/3.99	14.27/-3.37/-5.63	6.61/0.72/14.76	6.48/-4.38/5.47	30.99/-0.45/18.59
SF-5	3.36/5.69/3.01	12.23/-4.92/-10.67	3.85/-0.18/11.85	4.65/-4.55/3.13	24.09/-3.96/7.32
SF-6	3.68/5.99/3.05	12.87/-4.46/-8.81	6.37/0.25/13.16	4.49/-4.27/3.61	27.41/-2.49/11.01
SF-7	5.18/10.87/8.25	19.25/-1.14/-4.73	11.27/5.88/15.83	7.84/-1.62/8.36	43.54/13.99/27.71
SF-8	3.94/9.76/6.45	15.34/-2.07/-5.68	7.27/4.87/11.79	6.59/-1.86/5.16	33.14/10.70/17.72
SF-9	3.68/10.37/5.74	17.35/-1.48/-4.57	10.54/5.17/12.66	7.59/-1.25/5.63	39.16/12.81/19.46
SF-10	-9.68/-7.46/-8.89	23.35/23.75/17.65	19.56/13.69/56.08	-8.59/-15.18/-5.67	24.64/14.80/59.17

Table 5: Changes in the soil water fluxes of each crop of alfalfa during each growth stage.

Treatment	Water flux at the lower boundaries (mm) (the first/second/third crop)				
	Seedling establishment stage	Jointing stage	Branching stage	Flowering stage	Total
SF-1	1.29/8.06/2.89	8.76/-4.54/-7.23	1.19/-2.67/15.01	3.55/-4.34/3.58	14.79/-3.49/14.25
SF-2	0.29/6.72/0.83	6.76/-4.71/-11.29	0.19/-3.49/11.35	1.55/-5.88/2.08	8.79/-7.36/2.97
SF-3	0.76/7.09/1.16	8.64/-5.03/-9.78	0.17/-3.64/11.07	4.15/-5.18/2.16	13.72/-6.76/4.61
SF-4	3.78/7.24/4.87	14.34/-4.65/-7.88	6.31/0.83/12.27	6.19/-3.95/5.36	30.62/-0.53/14.62
SF-5	1.95/6.78/3.47	13.91/-4.74/-8.13	5.62/-0.35/9.39	3.97/-4.16/2.86	25.45/-2.47/7.59
SF-6	3.03/6.82/3.36	13.52/-4.81/-7.86	4.16/0.55/10.15	5.54/-3.99/3.37	26.25/-1.43/9.02
SF-7	5.61/11.36/6.42	18.18/-0.96/-3.06	10.48/6.43/12.14	8.85/-1.15/8.15	43.12/15.68/23.65
SF-8	5.82/10.85/5.18	19.61/-1.39/-7.67	9.69/5.52/10.18	7.86/-1.72/6.29	42.98/13.26/13.98
SF-9	6.27/10.89/5.99	18.26/-1.17/-6.76	8.91/5.58/11.19	8.17/-1.69/6.98	41.61/13.61/17.40
SF-10	-10.27/-6.19/-8.62	25.68/22.46/15.28	16.91/15.73/51.16	-8.17/-14.85/-6.42	24.15/17.15/51.40

The water consumption intensity of three alfalfa crops during each growth stage under different water and fertilizer combination applications was detailed in Table 6. Results showed that the value of water consumption intensity of alfalfa ranged from 1.84 to 3.27 mm/d at the seedling establishment stage, from 1.97 to 3.75 mm/d at the jointing stage, from 2.21 to 3.89 mm/d at the branching stage, and from 1.90 to 3.75 mm/d at the flowering stage, respectively. The value of average water consumption intensity of alfalfa throughout its growth period ranged from 1.98 to 3.64 mm/d. Secondly, the average water consumption intensity of the alfalfa had first increased and then decreased with the increases in the irrigation quota. The average water consumption intensity of the second alfalfa crop treatment was observed to be the lowest at 3.12 mm d^{-1}. The average water consumption intensity of the SF-8 treatment was observed to be the largest at 3.64 mm d^{-1}, which was 16.67% higher than that of the SF-1 treatment. The water consumption intensity pattern of the three crops of alfalfa during each growth stage was as follows: branching stage > jointing stage > flowering stage > - seedling establishment stage. Thirdly, it was determined that the water consumption of the second crop was greater than that of the first crop, which was higher than that of the third crop (second crop > first crop > third crop). The alfalfa had tended to grow vigorously due to the high temperatures during the second crop period and was observed to grow more slowly during the third crop period due to the lower temperatures. Finally, it was found that under the same water treatment conditions, with the increases in the fertilizer applications, the average water consumption intensity of the alfalfa had first increased and then decreased, and the water consumption intensity pattern of the alfalfa was as follows: medium fertilization > high fertilization > low fertilization.

Note: different letters within the same column indicate significant differences in 0.05 level, the same as below.

3.3. Hay Yield and WUE. In this research, in order to make the test results more obvious, the WUE and growth rates of the three alfalfa crops during each treatment period were calculated based on the control treatment (SF-10). The calculation results are shown in Tables 7 and 8. Results showed that the hay yield of the first alfalfa crop ranged from 2576.29 to 3326.66 kg·hm^{-2}, of the second alfalfa crop ranged from 3526.76 to 5352.68 kg·hm^{-2}, and of the third alfalfa crop ranged from 3051.53 to 4352.18 kg·hm^{-2}, respectively. Similarly, the WUE of the first alfalfa crop ranged from 1.68 to 2.34 kg·m^{-3}, of the second alfalfa crop ranged from 2.15 to 3.20 kg·m^{-3}, and of the third alfalfa crop ranged from 1.98 to 2.65 kg·m^{-3} (Table 7), respectively. Obviously, the WUE of the alfalfa ranged between 1.68 and 3.20 kg·m^{-3}, and the

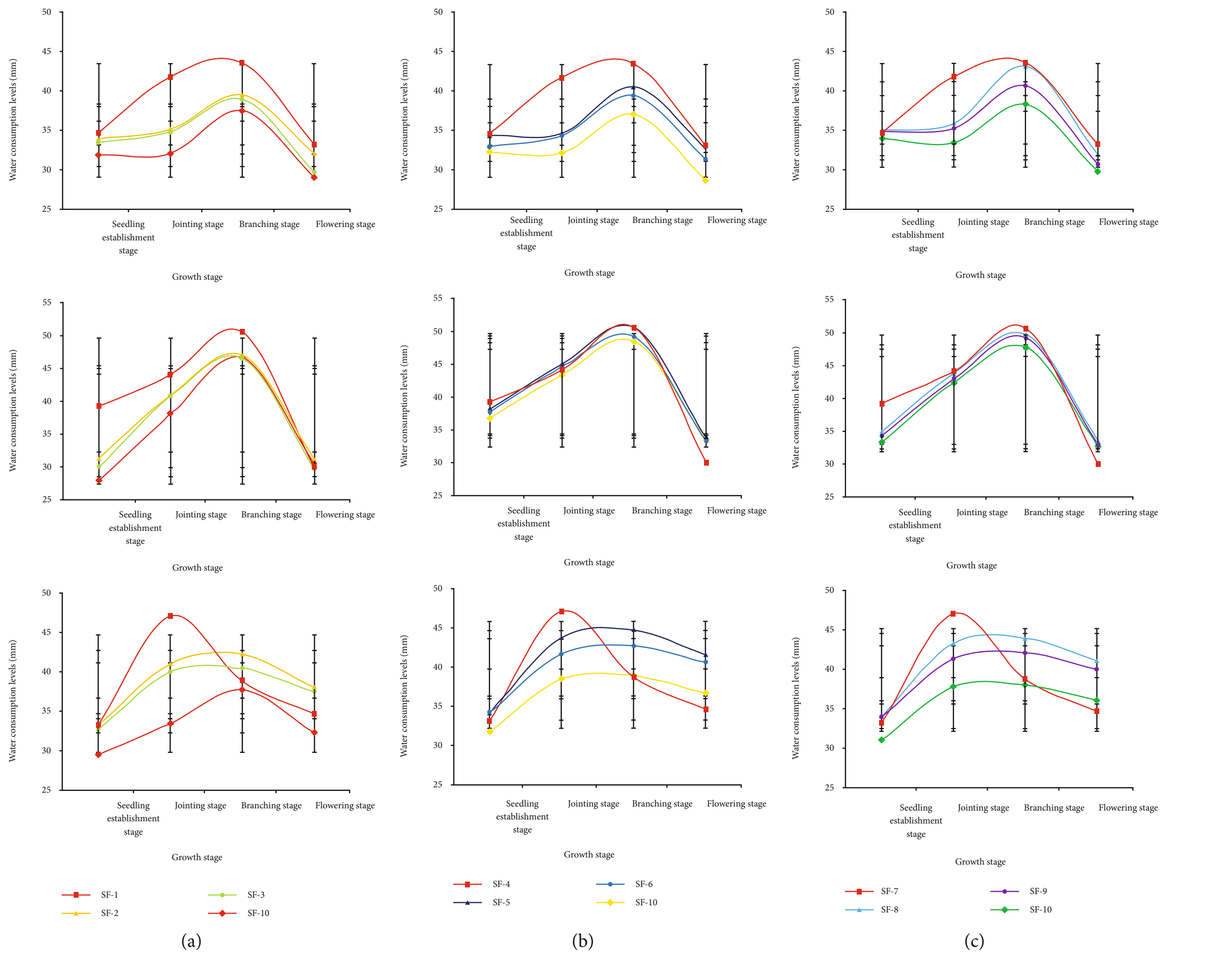


Figure 3: Water consumption levels of alfalfa during each growth stage. Note: the water consumption of the first, second, and third crops of alfalfa is plotted in the upper, middle, and lower layers in order, and (a–c) represent the low, medium, and high water level treatments in turn.

Table 6: Water consumption intensity levels of each crop of alfalfa during each growth stage.

Treatment	Water consumption intensity levels (mm/d) (the first/second/third crop)				
	Seedling establishment stage	Jointing stage	Branching stage	Flowering stage	Average value
SF-1	$1.99^{b}/2.33^{e}/1.84^{c}$	$2.29^{c}/3.18^{c}/1.97^{e}$	$2.34^{c}/3.59^{b}/2.21^{c}$	$2.23^{c}/3.39^{b}/1.90^{d}$	$2.21^{c}/3.12^{c}/1.98^{d}$
SF-2	$2.12^{a}/2.61^{d}/2.08^{a}$	$2.51^{b}/3.42^{b}/2.41^{c}$	$2.47^{b}/3.62^{b}/2.48^{b}$	$2.46^{a}/3.47^{b}/2.24^{b}$	$2.39^{b}/3.28^{b}/2.30^{b}$
SF-3	$2.09^{a}/2.50^{d}/2.04^{a}$	$2.49^{b}/3.40^{b}/2.35^{c}$	$2.43^{b}/3.58^{b}/2.37^{b}$	$2.28^{c}/3.32^{b}/2.20^{b}$	$2.32^{c}/3.20^{c}/2.24^{b}$
SF-4	$2.02^{b}/3.07^{b}/1.99^{b}$	$2.30^{c}/3.61^{a}/2.27^{d}$	$2.32^{c}/3.73^{a}/2.29^{c}$	$2.21^{c}/3.70^{a}/2.16^{b}$	$2.21^{c}/3.53^{a}/2.18^{c}$
SF-5	$2.15^{a}/3.18^{a}/2.14^{a}$	$2.48^{b}/3.75^{a}/2.58^{b}$	$2.53^{b}/3.89^{a}/2.63^{a}$	$2.52^{a}/3.75^{a}/2.45^{a}$	$2.42^{b}/3.64^{a}/2.45^{a}$
SF-6	$2.06^{b}/3.15^{a}/2.14^{a}$	$2.46^{b}/3.71^{a}/2.45^{c}$	$2.47^{b}/3.78^{a}/2.51^{a}$	$2.41^{b}/3.70^{a}/2.39^{a}$	$2.35^{b}/3.59^{a}/2.37^{a}$
SF-7	$2.12^{a}/2.78^{c}/1.94^{b}$	$2.38^{c}/3.53^{b}/2.22^{d}$	$2.39^{c}/3.67^{b}/2.24^{c}$	$2.29^{b}/3.64^{a}/2.12^{c}$	$2.29^{c}/3.41^{b}/2.13^{c}$
SF-8	$2.18^{a}/2.92^{b}/2.13^{a}$	$2.56^{b}/3.65^{a}/2.55^{b}$	$2.69^{a}/3.82^{a}/2.59^{a}$	$2.46^{a}/3.73^{a}/2.42^{a}$	$2.47^{b}/3.53^{a}/2.42^{a}$
SF-9	$2.17^{a}/2.86^{c}/2.12^{a}$	$2.51^{b}/3.58^{a}/2.43^{c}$	$2.53^{b}/3.79^{a}/2.48^{b}$	$2.36^{b}/3.66^{a}/2.35^{a}$	$2.39^{b}/3.47^{a}/2.35^{a}$
SF-10	$2.17^{a}/3.27^{a}/2.08^{a}$	$2.98^{a}/3.67^{a}/2.77^{a}$	$2.72^{a}/3.89^{a}/2.28^{c}$	$2.55^{a}/3.34^{b}/2.04^{c}$	$2.61^{a}/3.54^{a}/2.29^{b}$

growth rate was between 4.85 and 51.77%. It was found that the second crop of the SF-5 treatment had the highest WUE and growth rate, which were 3.20 kg·m^{-3} and 51.77%, respectively. It was determined that both the WUE and growth rates showed the following trend: second crop > third crop > first crop. The second crop of the SF-5 treatment was found

Table 7: Yields, WUE, and growth rates of each crop of alfalfa (the first/second/third crop).

Treatment	Total water consumption (mm)	Yield ($kg \cdot hm^{-2}$)	WUE ($kg \cdot m^{-3}$)	Yield increasing rate (%)
SF-1	$130.42^c/143.19^c/132.73^d$	$2701.35^c/4077.04^d/3351.68^d$	$2.07^b/2.85^b/2.52^b$	4.85/15.60/9.84
SF-2	$140.42^b/150.68^b/154.47^b$	$3201.60^a/4752.38^c/4127.06^b$	$2.28^a/3.15^a/2.67^a$	24.27/34.75/35.25
SF-3	$136.71^b/147.27^c/150.33^b$	$3076.54^b/4627.31^c/3951.98^b$	$2.25^a/3.14^a/2.63^a$	19.42/31.21/29.51
SF-4	$130.29^c/161.88^a/146.09^c$	$3026.51^b/5152.58^a/3801.90^c$	$2.32^a/3.18^a/2.60^a$	17.48/46.10/24.59
SF-5	$142.36^b/167.33^a/164.39^a$	$3326.66^a/5352.68^a/4352.18^a$	$2.34^a/3.20^a/2.65^a$	29.13/51.77/42.62
SF-6	$138.24^b/164.82^a/159.27^a$	$3226.61^a/5252.63^a/4177.09^a$	$2.33^a/3.19^a/2.62^a$	25.24/48.94/36.89
SF-7	$135.24^c/156.23^b/142.94^c$	$2801.40^c/4802.40^b/3676.84^c$	$2.07^b/3.07^a/2.57^a$	8.74/36.17/20.49
SF-8	$145.78^a/161.94^a/162.60^a$	$3076.54^b/5027.51^b/4227.11^a$	$2.11^b/3.10^a/2.60^a$	19.42/42.55/38.52
SF-9	$141.13^b/159.48^a/157.44^a$	$2976.49^b/4927.46^b/4077.04^b$	$2.11^b/3.09^a/2.59^a$	15.53/39.72/33.61
SF-10	$153.11^a/163.95^a/153.73^b$	$2576.29^d/3526.76^e/3051.53^e$	$1.68^c/2.15^c/1.98^c$	0/0/0

Table 8: Total yield, average WUE, and growth rates of the three alfalfa crops.

Treatment	Total water consumption (mm)	Yield ($kg \cdot hm^{-2}$)	WUE ($kg \cdot m^{-3}$)	Yield increasing rate (%)
SF-1	406.34^c	10130.06^d	2.49^b	10.66
SF-2	445.57^b	12081.04^b	2.71^a	31.97
SF-3	434.31^b	11655.83^c	2.68^a	27.32
SF-4	438.26^b	11980.99^b	2.73^a	30.87
SF-5	474.08^a	13031.51^a	2.75^a	42.35
SF-6	462.33^a	12656.33^a	2.74^a	38.25
SF-7	434.41^b	11280.64^c	2.60^b	23.22
SF-8	470.32^a	12331.16^b	2.62^a	34.70
SF-9	458.05^a	11980.69^b	2.61^b	30.87
SF-10	470.79^a	9154.58^e	1.94^c	0.00

to have the highest WUE and growth rate, at 3.20 $kg \cdot m^{-3}$ and 51.77%, respectively. It was observed that both the WUE and growth rates displayed the trend pattern of second crop > third crop > first crop. Tables 7 and 8 also showed that the yield and WUE level of the first crop of alfalfa control treatment (SF-10) were the lowest, at 2576.29 $kg \cdot hm^{-2}$ and 1.68 $kg \cdot m^{-3}$, respectively. The yield and WUE level of the SF-5 treatment were found to be the highest, at 3326.66 $kg \cdot hm^{-2}$ and 2.34 $kg \cdot m^{-3}$, respectively, which indicated that the yield and WUE had increased by 29.13% and 38.88%, respectively. When compared with the control treatment (SF-10), the growth rates of the alfalfa crops were 4.85% to 29.13% higher under the different water and fertilizer application treatments, which indicated obvious yield increase effects. The second and third crops of the alfalfa displayed similar results. It was found that under the same water treatment conditions, the hay yields and WUE levels of the alfalfa undergoing the medium fertilization treatment were the largest. Also, under the same fertilization treatment conditions, the hay yields and WUE levels of the alfalfa undergoing the medium fertilization treatment were the largest. Therefore, it was determined that with the increases in the water or fertilization treatments, both the crop yields and WUE levels had shown the phenomenon of "diminishing returns."

The frequency statistical analysis on the different levels of irrigation and nitrogen application (Figure 4) showed that there was a 95% probability that an irrigation water of 141.11~165.75 mm and a nitrogen application of 60.52~80.70 $kg \cdot hm^{-2}$ could obtain a hay yield of alfalfa of more than 11903.17 $kg \cdot hm^{-2}$.

4. Discussion

4.1. Effects of Subsurface Drip Irrigation on Water Consumption of Alfalfa. Water is one of the most important factors which affect alfalfa growth in arid and semiarid areas, where irrigation is required for crop production, and growers are seeking methods to save water by increasing irrigation efficiency. Water consumption, water consumption intensity, and WUE are important criteria for determining whether the irrigation application amounts are reasonable, especially WUE, which is considered to describe the physiological indicators of alfalfa growth, especially the relationship between harvest yield and crop water consumption [30]. In this study, the water consumption of alfalfa showed an increasing trend with the increase of irrigation. Most importantly, it could be seen that under the same water treatment conditions, the water consumption levels of the alfalfa during the different growth stages were greatly affected by the amounts of the fertilizer applications (Figure 3). This result indicated that fertilization was a sensitive factor, which had obvious water regulating effect, and proper fertilization could improve water consumption and WUE. Our findings were comparable to those obtained by Thompson et al. [37] and Agami et al. [38], who suggested that exogenous N-supply was effective in mitigating the adverse effects of drought stress, and understanding the water consumption rule of crops is significant for the prevention of unnecessary water losses. Similarly, al-Naeem [39] also reported that alfalfa dry yield could be severely affected under water stress irrigation management.

In this study, we also found that the water consumption of alfalfa during each growth stage under low, medium, and high water treatment conditions showed a trend of first increasing and then decreasing. This was because the coverage of the alfalfa plants was low during the seedling establishment stage, and the water consumption of the alfalfa during

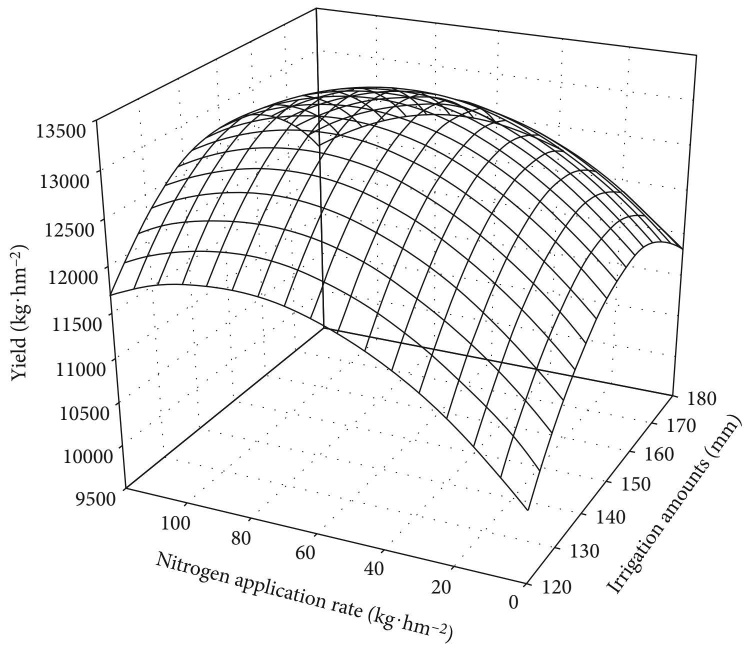


Figure 4: Relationship curve between the hay yield and the total irrigation amounts and fertilizer amount.

that stage was mainly soil evaporation. With the growth and development of the crops, the alfalfa entered a vigorous growth stage and rapid plant growth had occurred. As the plant coverage began to reach the maximum, the bare field surfaces gradually decreased, and crop transpiration was the main form of crop evapotranspiration. At this time, the water consumption reached a maximum. Since the alfalfa was cut at the beginning of the flowering stage and quickly entered the seedling establishment stage of the next crop, this led to the water consumption being the lowest during the flowering stage. Our findings were in consensus with that of Li et al. [40], who suggested that the increased vegetation coverage induced a decrease in surface albedo and resulted in an increase in temperature, and this positive effect could be counteracted by higher evapotranspiration, and the net effect was a decrease in daytime land surface temperature. It should be noted that the water consumption of each experiment plot of the third crop of alfalfa during the branching and flowering stages was observed to be higher than that of the control treatment (SF-10). The reasons for these results were determined to be that the temperature was relatively low and nitrogen application caused alfalfa to still grow vigorously, which consumed more water under relatively low temperature conditions. These findings indicated that the fertilization treatments had potentially promoted the growth and development of alfalfa under low temperature conditions, which is consistent with Hannaway and Shuler [41], who suggested that a yield increase due to fertilizer N is even more likely when alfalfa is established in low N soils and relatively cool less than 60°F for several weeks after planting.

Water consumption intensity is defined as the water consumption per unit area of plant population per unit time. Under the current study, the supplied water was based on the actual water consumption in the root zone, where irrigation water was automatically supplied when needed. The results (Table 6) showed that the value of average water consumption intensity of alfalfa throughout its growth period ranged from 1.98 to 3.64 mm/d. These findings were comparable to those obtained by Jackson [42], Stanberry et al. [43], Daigger et al. [44], Krogman and Hobbs [45], and Wang et al. [25], who suggested that the water consumption intensity of alfalfa throughout the growing season ranged from 2.00 to 7.00 mm/d. Furthermore, the maximum water consumption intensity of alfalfa appeared at the branching stage and then decreased at the flowering stage. Our findings were in consensus with Wang et al. [25], who suggested that the water consumption intensity was also high for reproductive growth and nutrition growth at the bud stage and then decreased at the flowering stage when alfalfa grew slowly due to reproductive growth. Generally, the trend of water consumption of alfalfa during the fertility period in an arid and semiarid desert region was similar compared to other regions in which water consumption has been studied [46, 47].

4.2. Effects of Subsurface Drip Irrigation on Hay Yield and WUE of Alfalfa. WUE refers to the output per unit of water consumption of crops. Previous studies had shown that drought was an important environmental factor that influences growth and physiological processes in plants [48], there were a positive link between WUE and hay yield [49] and synergistic effects between water and fertilizer, and an appropriate N-supply had an obvious water regulating effect [50, 51], which could stimulate plant growth, improve WUE, and alleviate the effects of drought stress [52, 53]. The irrigation amount and nitrogen application rate had significant effects on the total hay yield of alfalfa. In the case of water deficit, crop root development is hindered, nutrient absorption capacity is reduced, and fertilizer efficiency is limited. When water is excessive, soil nutrient leaching occurs, soil permeability is reduced, and root respiration and nutrient uptake by crops are hindered [54], thereby reducing the hay yield of alfalfa. Therefore, it should be irrigated in small increments and frequently in order to attain high yields when an alfalfa crop is grown under arid and semiarid conditions [55]. In this study, we found that additional applications of fertilizer under the same water treatment conditions had an obvious effect of increasing hay yields of the alfalfa, which was in consensus with Wang et al. [56] and Liu et al. [57], who observed higher WUE under moderate water stress and a decrease of WUE under severe water stress conditions. Abd el–Mageed et al. [58] conducted field experiments for two years at the experimental farm of the Faculty of Agriculture, in EI Fayoum Province of Egypt, and found that application of higher levels of potassium fertilizer in an arid environment improves plant water status as well as growth and yield of soybean under water stress. In this study, we found that an appropriate amount of water and nitrogen fertilizer can increase the WUE of alfalfa under the condition of SDI and increase the hay yield, and too low or too high water and nitrogen fertilizer will adversely affect the WUE and hay yield of alfalfa. These were in consensus with Wang et al. [59], who suggested that partial root-zone drying could be a promising technique for alfalfa production in the arid area of Northwest China, with improved crop water productivity and positive effect on quality characteristics.

In the research, we also found that the second crop of alfalfa had the largest hay yield and WUE, and both appeared in the SF-5 treatment (Table 7). The reason for this phenomenon was that the second crop of alfalfa was in the season from late June to early August each year, when the temperature was higher, the metabolism of alfalfa was faster, and the growth was vigorous. Our findings were in consensus with Karimzadeh Soureshjani et al. [60], who suggested that cool weather during the emergence of first flower buds and first flowering stages led to forage yield loss of alfalfa. In this experiment, hay yield and WUE of alfalfa both increased first and then decreased with the increase of irrigation amount and increased first and then decreased with increasing nitrogen application (Table 8). This result indicated that fertilization had obvious water regulating effect, and proper fertilization could improve WUE [37]. Furthermore, fertilization can increase the soil water holding capacity [61], and successfully matching fertilizer availability with crop absorption improves water-use efficiency and increases yield [38]. Thus, SF-5 treatment is recommended for subsurface drip irrigation of alfalfa in Mu Us Sandland of Northwest China.

5. Conclusions

Overall, the larger the irrigation quota, the greater the water consumption of the alfalfa during each growth stage. The overall changes in the water consumption levels displayed a trend of first increasing and then decreasing. The water consumption during each growth period of each crop of alfalfa had changed within a range of 130 to 170 mm and had displayed a large amplitude of change, with the water consumption during the entire growth period measuring approximately 500 mm. The water consumption intensity of the alfalfa had first increased and then decreased with the increases in the irrigation quota. The average water consumption intensity of alfalfa ranged from 1.98 to 3.64 mm d^{-1}. The WUE of alfalfa ranged between 1.68 and 3.20 $kg \cdot m^{-3}$, and the growth rates were between 4.85% and 51.77%. The results indicated that there was a 95% probability of obtaining a hay yield of alfalfa of more than 11903 $kg \cdot hm^{-2}$ under SDI with the irrigation amounts of 142~165 mm and nitrogen application of 61~80 $kg \cdot hm^{-2}$. Our results demonstrated that SDI was a promising irrigation method, which can increase the WUE and hay yield of alfalfa under the condition of SDI within an appropriate amount of water and nitrogen fertilizer, and too low or too high water and nitrogen fertilizer will adversely affect the WUE and hay yield of alfalfa.

Data Availability

The raw/processed data required to reproduce the results obtained in this study cannot be shared at this time because they are used in an ongoing study.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Xuesong Cao and Yayang Feng contributed equally to this work.

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