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Evapotranspiration Partition and Dual Crop Coefficients in Apple Orchard with Dwarf Stocks and Dense Planting in Arid Region, Aksu Oasis, Southern Xinjiang

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Abstract: Crop coefficients are critical to developing irrigation scheduling and improving agricultural water management in farmland ecosystems. Interest in dwarf cultivation with high density (DCHD) for apple production increases in Aksu oasis, southern Xinjiang. The lack of micro-irrigation scheduling limits apple yield and water productivity of the DCHD-cultivated orchard. A two-year experiment with the DCHD-cultivated apple (Malus × domestica 'Royal Gala') orchard was conducted to determine crop coefficients and evapotranspiration (ET_a) with the SIMDualKc model, and to investigate apple yield and water productivity (WP) in response to different irrigation scheduling. The five levels of irrigation rate were designed as W1 of 13.5 mm, W2 of 18.0 mm, W3 of 22.5 mm, W4 of 27.0 mm, and W5 of 31.5 mm. The mean value of basal crop coefficient (K_{cb}) at the initial-, mid-, and late-season was 1.00, 1.30, and 0.89, respectively. The Kc-local (ET_a/ET_0) range for apple orchard with DCHD was 1.11–1.20, 1.33–1.43, and 1.09–1.22 at the initial, middle, and late season, respectively. ET_a of apple orchard in this study ranged between 415.55–989.71 mm, and soil evaporation accounted for 13.85–29.97% of ET_a. Relationships between total irrigation amount and apple yield and WP were developed, and W3 was suggested as an optimum irrigation schedule with an average apple yield of 30,540.8 kg/ha and WP of 4.45 kg/m^3 in 2019–2020. The results have implications in developing irrigation schedules and improving water management for apple production in arid regions.

Keywords: crop coefficients; SIMDualKc; evapotranspiration; dwarf cultivation with high density; Royal Gala; water productivity

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1. Introduction

Southern Xinjiang (Figure 1a), an extremely arid area, has abundant light and heat resources. The particular climatic conditions of oases in southern Xinjiang are favorable for producing high-quality fruits. Aksu oasis, one of the large oases in southern Xinjiang, has an apple cultivation area of 2.6 × 10^4 hm^2 [1]. Arborized apple trees accounted for about 80% of an apple orchard (Figure 1b), with a long growth period and late harvesting time. Moreover, the large canopy of arborized apple trees resulted in low light transmittance then reduced fruit quality. In recent years, the dwarf cultivation with high density (DCHD, Figure 1c) gradually increased up to 10% apple area in Aksu oasis [2], because of its incomparable advantages with the conventional cultivation at a high mechanization level, early harvesting time, high fruit yield, and quality [3].

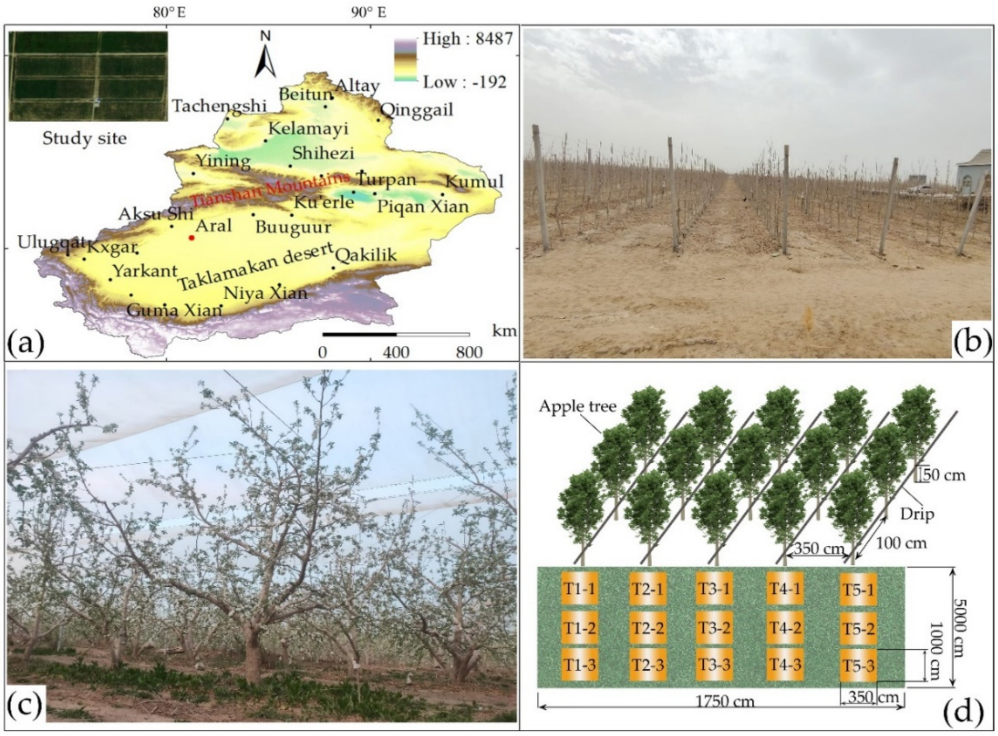

Figure 1. (**a**) Location of the experimental site; (**b**) an orchard of dwarf cultivation with high density of apple trees; (**c**) an orchard of arborized apple trees; (**d**) layout of experimental plots.

In the extremely arid oasis in southern Xinjiang, e.g., Aksu oasis with annual precipitation of 50 mm, agricultural production is seriously restricted by local water resources scarcity [4]. Irrigation for agricultural practices in this region utilizes more than 92% of the local freshwater, while the utilization efficiency of irrigation water is only approximately 0.43 [5]. Nowadays, most arborized orchards in Aksu oasis are still irrigated by flood irrigation or water storage pit irrigation [6], resulting in low irrigation water efficiency. Although the DCHD orchards with drip irrigation have a low proportion of regional apple orchards, their potential for increasing yield and water productivity has attracted more attention. Whereas, achieving the potential benefits of drip-irrigated DCHD orchards requires proper irrigation scheduling and good irrigation management. Determination of crop coefficients and actual crop evapotranspiration (ET_a) is the fundamental requirement of irrigation scheduling and irrigation efficiency [7,8].

Direct measurement methods in the field can obtain ET_a, such as water balance method [9,10], lysimeters [8], sap flow measurements [11–13] and eddy covariance [10,14–16], and by crop evapotranspiration modelling, e.g., SIMDualKc [7,14,15,17,18], HYDRUS [19], CropSyst [8], and remote sensing information [20,21]. The FAO crop coefficient procedure, classified as single coefficient and dual coefficients, is one of the most common methods for determining ET_a [22]. Soil evaporation and plant transpiration could be separately considered by using the soil evaporation coefficient (K_e) and the basal crop coefficient (K_{cb}) in the dual crop coefficient approach [22]. Under environmental stress conditions, K_s, a stress coefficient, should be considered, that is, the actual basal crop coefficient $K_{cb\ act} = K_s\ K_{cb}$.

As crop coefficients change across places and seasons, the site-specific value of crop coefficients is required for local conditions. Measurements of soil evaporation and plant transpiration are essential to adjust crop coefficients, while it is more difficult for fruit trees than herbaceous crops [23]. Rainfall interception plays an important role in plant evapotranspiration, especially in arid regions. It refers to the process that the total rainfall falling on the plant surface is captured, retained, and finally evaporated from the leaves, stems, and branches of the plant. Studies have shown that the canopy interception of fruit trees was about 26 mm [24]. Meanwhile, the rainfall intercepted by plant canopy accounts for 20 ± 8% of the total global rainfall [25]. Crop coefficients of woody plants in different regions have been reported by researchers, such as olives in Portugal [12,15,18,20,23], apples in Spain [8], Italy [16], Chile [21], North China [6,24,26–28] and South Africa [13,29], pears in Portugal [14,17,30], citrus in India [10], and pecan in southwestern USA [31]. Although several apple crop coefficient results were reported, the dual crop coefficients and evapotranspiration components of the DCHD orchards are limited, especially for the DCHD apple orchards in extremely arid regions.

Compared with the traditional apple orchards in Aksu oasis, the DCHD apple trees have smaller canopy volumes, which changes crop coefficients pattern by impacting radiation interception and transpiration (Figure 1b,c). As the determination of crop coefficients and evapotranspiration components in the DCHD apple orchards are scare, objectives of this study were (i) to determine K_c for the DCHD apple trees in Aksu oasis with soil balance method, (ii) to calibrate and validate the SIMDualKc model, (iii) to develop the curve of K_{cb} and K_e from the calibrated SIMDualKc model, (iv) to estimate ET_a and its components using the dual crop coefficient approach.

2. Materials and Methods

2.1. Study Site

Field experiments were conducted at a 600-ha apple orchard (40°39′ N, 81°16′ E, altitude 1011 m.a.s.l) with dwarf stocks and dense planting, located in Alar City, 1st Division of the Xinjiang Production and Construction Corps (Figure 1a), from April to August in 2019 and 2020. The experimental site is situated in a warm temperature zone, characterized as an extreme continental arid desert climate. The study site has an annual average precipitation of 50 mm, annual average temperature of 11 °C, annual pan evaporation of 2100 mm, annual sunshine duration of 2900 h, and a frost-free period of over 200 days. The seasonal precipitation in the apple growing season of 2019 and 2020 was 56.2 and 17 mm, respectively (Figure 2). The soil type is sandy loam with an average bulk density of 1.51 g/cm^3 and field capacity of 0.185 cm^3/cm^3 at 0–120 cm soil depth. Table 1 shows the specific physical parameters of the soil. The bulk density was measured by the core method with a solid ring, the field capacity was obtained by the plot irrigation method, and the wilting point was obtained by measuring the soil moisture content under 15 bar by using the pressure membrane meter method. On average of the two growing seasons, soil available N, P, and K contents of the cultivated horizon (0–30 cm) were 10.0, 3.2, and 33 mg/kg, and soil organic matter content was 11.05 g/kg, pH was 8.71, and electrical conductivity was 154.6 µs/cm. Groundwater is located at >3.0 m below the soil surface.

2.2. Experimental Design

The experiment followed a one-factor completely random block design. The apple variety is Royal Gala (Malus × domestica 'Royal Gala'), planted in 2016 with a plant spacing of 1 m and row spacing of 3.5 m (Figure 1c). The average height, diameter at breast height, and crown diameter of apple trees were 3.3 m, 39.6 mm, and 1.75 m, respectively. During the apple growing season, the ground coverage and leaf area index ranged from 0.39–0.52, and from 1.17–2.93, respectively. There were five irrigation rates with three replicas, i.e., W1 of 13.5 mm, W2 of 18 mm, W3 of 22.5 mm, W4 of 27 mm, and W5 of 31.5 mm. In the arid oasis of Aksu, southern Xinjiang, the irrigation rate of 31.5 mm was primarily scheduled for apple trees. In order to optimize irrigation scheduling of apple orchards, the ±20% and ±40% changes in irrigation rate of 22.5 mm were designed in this study. Each plot has an area of 35 m^2. The apple trees were irrigated with drip irrigation, and the drip lines were fixed at the height of 50 cm (Figure 1d). The drip line diameter was 16 mm, and the emitters with a flow rate of 4 L/h were placed 30 cm apart in the line. Irrigation scheduling was on the difference between reference evapotranspiration (ET_0) and precipitation (P). Irrigation was carried out whenever $ET_0 - P$ reached 22.5 mm, and all treatments were irrigated on the same day. There were 28 irrigation events in each season;

the total irrigation amounts for W1, W2, W3, and W4 were 378, 504, 630, 756, and 882 mm, respectively (Table 2). The distinct difference in rainfall distribution (Figure 2) caused the two seasons to have the same irrigation events. The amount of N, P_2O_5, and K_2O was 75.90, 87.37, and 153.39 kg/ha, respectively (Table 2). Pests were controlled using standard management practices by application of and pesticides.

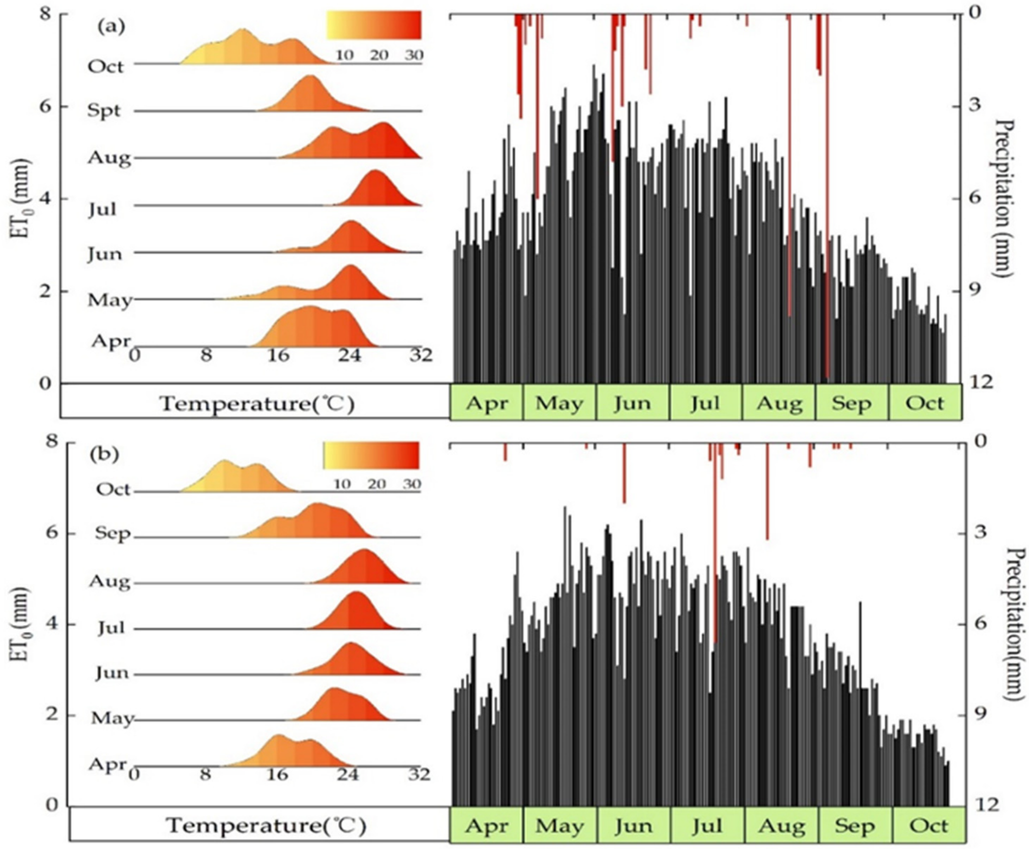

Figure 2. Meteorological data in (**a**) 2019 and (**b**) 2020.

Table 1. Soil physical parameters in experimental site.

Depth (cm)	Bulk Density (g/cm^3)	Filed Capacity (m^3/m^3)	Wilting Point (m^3/m^3)	Clay (%)	Silt (%)	Sand (%)
0–20	1.41	0.12	0.06	0.77	4.24	94.99
20–40	1.52	0.13	0.07	1.08	6.33	92.59
40–60	1.57	0.14	0.07	0.67	3.15	96.17
60–80	1.54	0.14	0.07	0.73	3.73	95.54
80–100	1.50	0.23	0.12	1.28	8.42	90.3
100–120	1.51	0.35	0.18	4.41	11.75	86.84

2.3. Measurement Set-Up

2.3.1. ET_{a-w} Calculated with Water Balance Model

ET_{a-w} is determined by the soil water balance equation as follows [32]:

$$ET_{a-w} = P + I + U - R - D_w - \Delta S \quad (1)$$

where P is precipitation (mm), I, irrigation (mm), U, the upward capillary flow into the root zone (mm), R, runoff (mm), D_w, the downward drainage out the root zone, ΔS, variation of soil water storage (mm). Darcy's law was used to estimate R and D_w, indicating that both R and D_w were negligible as low irrigation rate, the hydraulic properties of sandy loam soil, and groundwater table [7,32]. Under the condition of a low amount of irrigation water and rainfall as well as flat topography, R was negligible. In situ, soil water content was measured by the S-SMC-005 soil moisture sensors, which were buried at the depth of 20, 40, 60, 80, 100, and 120 cm, with a measurement range of 0–0.55 m^3 /m^3 and a measurement accuracy of ±0.031 m^3/m^3 (HOBO, Onset, MA, USA). Under the drip lines, auger a 7 cm hole to the depth at which the sensor was to be installed, insert the sensor into the undisturbed soil by a PCV pipe with a notch cut in the end, then remove the PVC pipe and backfill the hole. The soil moisture data were recorded with the HOBO-U30 data logger every 1 h. Soil water content at sowing and harvesting were measured gravimetrically at the interval of 20 cm from soil surface to 120 cm depth.

Table 2. Irrigation and fertilizer amount of five irrigation treatments in each month of apple trees in 2019 and 2020.

Year	Stage	Irrigation Amount (mm)					Fertilizer (kg/ha)		
		W1	W2	W3	W4	W5	Nitrogen	K_2O	P_2O_5
2019	4.23–5.5 (Flowering and fruit period)	27	36	45	54	63	13.75	9.86	15.13
	5.6–7.20 (Fruit expansion period)	216	288	360	432	504	45.11	40.89	77.06
	7.21–8.10 (Fruit maturity)	40.5	54	67.5	81	94.5	5.99	14.03	29.15
	8.11–10.26 (Deciduous period)	94.5	126	157.5	189	220.5	10.95	22.46	31.84
	Total	378.0	504.0	630.0	756.0	882.0	75.81	87.25	153.18
2020	4.22–5.7 (Flowering and fruit period)	27	36	45	54	63	13.75	9.86	15.13
	5.8–7.21 (Fruit expansion period)	216	288	360	432	504	45.11	40.89	77.06
	7.22–8.12 (Fruit maturity)	40.5	54	67.5	81	94.5	5.99	14.03	29.15
	8.13–10.26 (Deciduous period)	94.5	126	157.5	189	220.5	10.95	22.46	31.84
	Total	378.0	504.0	630.0	756.0	882.0	75.81	87.25	153.18

2.3.2. Evapotranspiration Simulation

The dual crop coefficient procedure [22] was used to estimate evapotranspiration:
(i) Under standard condition,

$$ET_C = (K_{cb} + K_e)ET_0 \quad (2)$$

(ii) Under stress condition,

$$ET_{a-F} = (K_sK_{cb} + K_e)ET_0 \quad (3)$$

where K_{cb} is the basal crop coefficient for transpiration, K_e is the evaporation coefficient, K_s is the stress coefficient, ET_0 is the reference evapotranspiration (mm/d). The development stages for DCHD-cultivated apple trees are shown in Table 2. ET_0 is calculated with the Penman–Monteith Equation as described in [22]:

$$ET_0 = \frac{0.408\Delta(R_n - G)\gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (4)$$

where Δ is the slope of the saturation vapor pressure curve (kPa/°C), R_n the net radiation (MJ/(m^2d), G the soil heat flux density (MJ/(m^2d), γ the psychrometric constant (kPa/°C), T the mean daily air temperature at 2 m height (°C), u_2 the wind speed at 2 m height (m/s), e_s the saturation vapor pressure (kPa), e_a the actual vapor pressure (kPa). Daily weather data used for estimating ET_0 were measured with a HOBO weather station (U30-NRC), which has a HOBO U30 USB data collector, an air pressure sensor of S-BPB-CM50, a rain sensor of S-RGB-M002, an air temperature/relative humidity sensor of S-THB-M002, a wind speed sensor of S-WSB-M003, and a pyranometer of S-LIB-M003. The automatic weather station was installed in an open field inside the orchard, about 100 m to the experimental plots.

2.3.3. Calibration and Validation of SIMDualKc Model

In this study, the dual crop coefficient approach was performed using the SIMDualKc model [33]. Adopting the trial-and-error procedure, the SIMDualKc model was calibrated by adjusting parameters of crop (Kcb; p, the depletion fraction) and soil (TEW, the total evaporable water; REW, the readily evaporable water; Ze, the depth of soil surface layer). Calibration was performed with the data in the treatment of W5 in the two seasons, and the calibrated parameters of the SIMDualKc model are shown in Table 3. Validation was carried out using independent data over the two seasons.

Table 3. Initial and calibrated values of crop and soil parameters in SIMDualKc.

Parameter	Initial Values	Calibrated Values
Crop coefficients		
$K_{cb\text{-}ini}$	1.10	1.00
$K_{cb\text{-}mid}$	1.33	1.30
$K_{cb\text{-}end}$	1.09	0.89
p	0.55	0.50
Soil evaporation		
Depth of the surface soil layer, Ze (m)	0.15	0.10
Total evaporable water, TEW (mm)	30	21
Readily evaporable water, REW (mm)	10	8

Plant height was measured with a steel ruler once every 2 months. The ground coverage was calculated by using UAV aerial photos and Photoshop2018 (Adobe, CA, USA) [34]. Soil evaporation was measured with microlysimeters, which were installed between apple trees (Figure 3a). The microlysimeter was made of stainless steel and consisted of an inner and outer tank. The diameter of the inner and outer tank was 10.0 and 12.0 cm, respectively (Figure 3b). The outer tank was fixed in the soil with its top edge leveling with the soil surface. To fill soil into each inner tank with an intact soil core, the inner tank was forced into the soil under drip line with the top leveling with the soil surface, then pull out and sealed the base with a plastic film. The microlysimeters were weighted at 10:00 a.m. The procedure of soil evaporation measurement by using microlysimeters was similar to the experiment of Gao et al. [35].

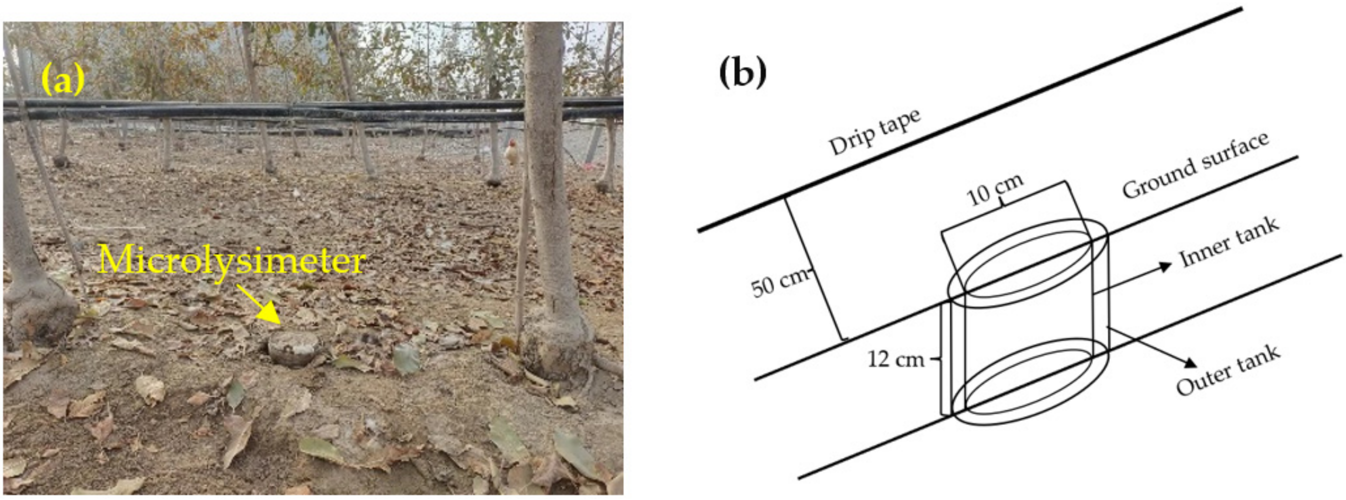

Figure 3. Microlysimeter used for soil evaporation measurement. (**a**) Location of microlysimeter; (**b**) diagram of microlysimeter.

2.3.4. Evaluation of Evapotranspiration Simulation

Model performance was evaluated by the root mean square error (RMSE), the average absolute error (AAE), and the Nash–Sutcliffe efficiency index (NSE).

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(S_i - O_i)^2} \tag{5}$$

$$\text{AAE} = \frac{1}{n}\sum_{i=1}^{n}|S_i - O_i| \tag{6}$$

$$\text{NSE} = 1 - \frac{\sum_1^i (O_i - S_i)^2}{\sum_1^i \left(O_i - \overline{O}\right)^2} \tag{7}$$

where S_i and O_i are the simulated and observed values, respectively; n the number of the paired set data; $S_i' = S_i - \overline{O}$, $O_i' = O_i - \overline{O}$, $\overline{O}$ is the measured mean [36]. The perfect model has NSE = 1.0 and AAE = RMSE = 0.

2.3.5. Yield and Water Productivity

Apple was harvested on 10 August 2019, and 12 August 2020, respectively. Yield (Y, kg/ha) was determined with nine replicas in each treatment. Water productivity (WP, kg/m^3) is calculated as follows:

$$\text{WP} = \frac{\text{Y}}{10\text{ET}_\text{a}} \tag{8}$$

2.4. Statistical Analyses

ETa, Y, and WP were subjected to an ANOVA using DPS 16.05 [37], and the Duncan test was applied at α = 0.05.

3. Results and Discussion

3.1. SIMDualKc Model Parameterization and Calibration

The initial value for Kc-ini, Kc-mid, and Kc-end in W5 was 1.00, 1.33, and 1.09, and the calibrated value was correspondingly 1.00, 1.30, and 0.89, respectively (Table 3). The initial Ze, TEW, and REW was 0.15 m, 30 mm, and 10 mm, respectively, and the calibrated value was 0.10 m, 21 mm, and 8 mm (Table 3), which is similar to the results of Paço et al. [15] and Santos [38]. For the soil of sandy loam in the south in the Mediterranean region, Paço et al. [15] showed the value of Ze, TEW, and REW was 0.10 m, 18 mm, and 9 mm, respectively. Santos [38] reported that the value of Ze, TEW, and REW in sandy loam was 0.10 m, 22 mm, and 8 mm, respectively.

The calibrated SIMDualKc model accurately predicted evapotranspiration in the apple orchard, with R^2 of 0.97–0.99, NSE of 0.97, RMSE of 0.34–0.35 mm day-1, and AAE of 0.27–0.28 mm day^{-1} over the two seasons (Table 4). Comparison between simulated and measured ET_a is shown in Figure 4. The calibrated model slightly underestimated ET_a with R^2 of 0.99, RMSE of 21.65 mm, and d of 0.99. The differences in simulated and measured ET_a may be a result of the uncertainty of soil moisture measurements due to spatial variability of soil [7].

Table 4. Performance of the SIMDualKc model for predicting evapotranspiration in the DCHD-cultivated apple orchard in 2019 and 2020.

Year	b	R^2	AAE (mm/day)	RMSE (mm/day)	NSE	Performance Rating
2019	0.97	0.97	0.28	0.34	0.97	Pretty good
2020	1.1	0.99	0.27	0.35	0.97	Pretty good

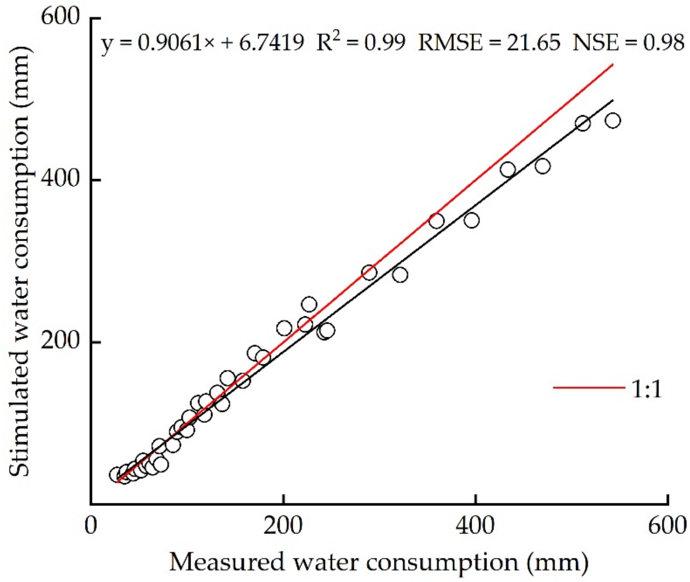

Figure 4. Comparison between measured and simulated values of water consumption during apple growing season in 2019 and 2020.

For the DCHD-cultivated apple orchard with drip irrigation, the values of K_{cb} in the initial period, midseason period, and the end of the season were calibrated as 1.00, 1.30, and 0.89, which were correspondingly greater than the tabulated values in FAO-56, i.e., $K_{cb\text{-}ini}$ = 0.3, $K_{cb\text{-}mid}$ = 1.15, $K_{cb\text{-}end}$ = 0.8 [22]. The difference was mainly from the distinct cultivation patterns, growing environments, and apple tree varieties. The apple orchard with DCHD has a lower value of canopy cover in comparison with the orchard with arborized trees, and the orchards with sandy loam soil in the Alar region usually suffered wind with a rate of 0.74–1.40 m/s in April and May, which resulted in a high value of ET_a and $K_{cb\text{-}ini}$. However, for the apple trees in California, Mhawej reported that K_{cb} in April and May was 1.18 and 1.11 [39], which was similar to the K_{cb} value of the present study in the same period. After harvesting of Royal Gala in mid-August, the orchard still has a high value of canopy cover and high ambient temperature, resulting in high ET_a (Figure 2) and relatively high $K_{cb\text{-}end}$ [40].

3.2. *Crop Coefficient-Kc-Local*

The seasonal variation of ET_a/ET_0, namely $K_{c\text{-}local}$, with Julian day and growing degree days are shown in Figure 5. For the DCHD-cultivated apple orchard in this study, the $K_{c\text{-}local}$ range was 1.11–1.20, 1.33–1.43, and 1.09–1.22 at the initial, middle, and late season, respectively. Marsal suggested that it is complicated to determine site-specific values concerning plant characteristics and management as many factors can influence crop coefficients in different ways across a season [8]. $K_{c\text{-}local}$ of DCHD-cultivated apple trees increased first and then decreased with the time course (Figure 5a) and GDD (Figure 5b). The relationship between $K_{c\text{-}local}$ and Julian day and GDD could be fitted with the quadratic function, the determination coefficients (R^2) were greater than 0.63 for each season, while R^2 was just higher than 0.53 over the two seasons (Figure 5). Munitz et al. also indicated a quadratic function between $K_{c\text{-}local}$ and Julian day and GDD for a vineyard [41]. In addition, Martínez-Cruz et al. [42] and Marcial-Pablo et al. [43] also suggested similar results for sorghum and maize.

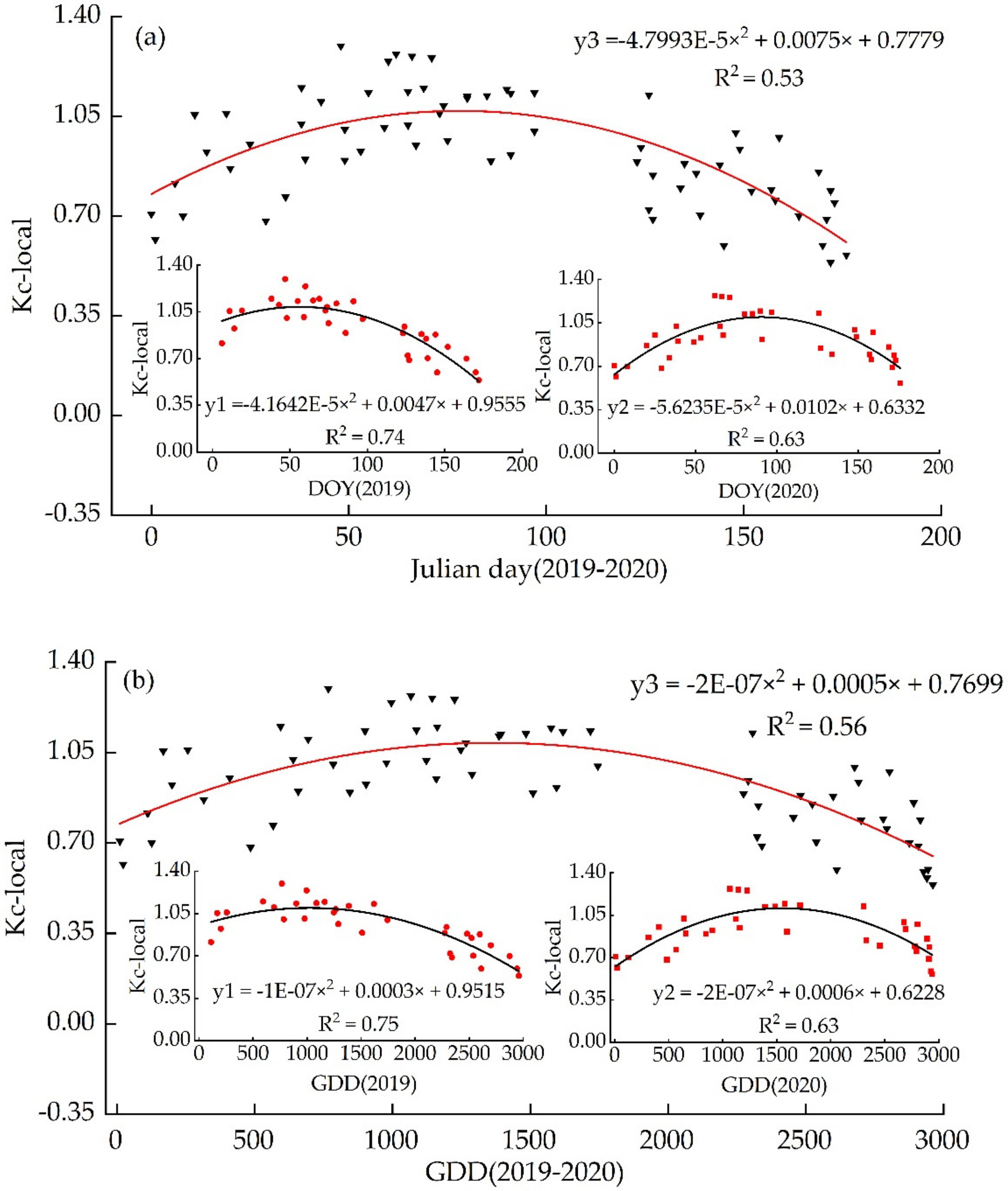

Figure 5. Variation of crop coefficient, $K_{c\text{-}local}$, with (**a**) Julian day and (**b**) GDD (growing degree days) in 2019 and 2020.

3.3. Dual Crop Coefficients

The dynamics of Ks in the treatments of W1–W5 during the two seasons are shown in Figure 6. The apple trees in different treatments experienced different levels of water stress during the two seasons. The Aksu oasis belongs to an extremely arid region, with severe water scarcity in spring [44]. Therefore, apple trees in all treatments suffered water stress in the early growing stage as restricted by irrigation water supply. From the development stage to harvesting, irrigations did not compensate for soil water loss and caused water stress of apple trees, K_s was negatively associated with irrigation rate. After harvesting, soil water stress increased (low value of K_s) as low irrigation frequency.

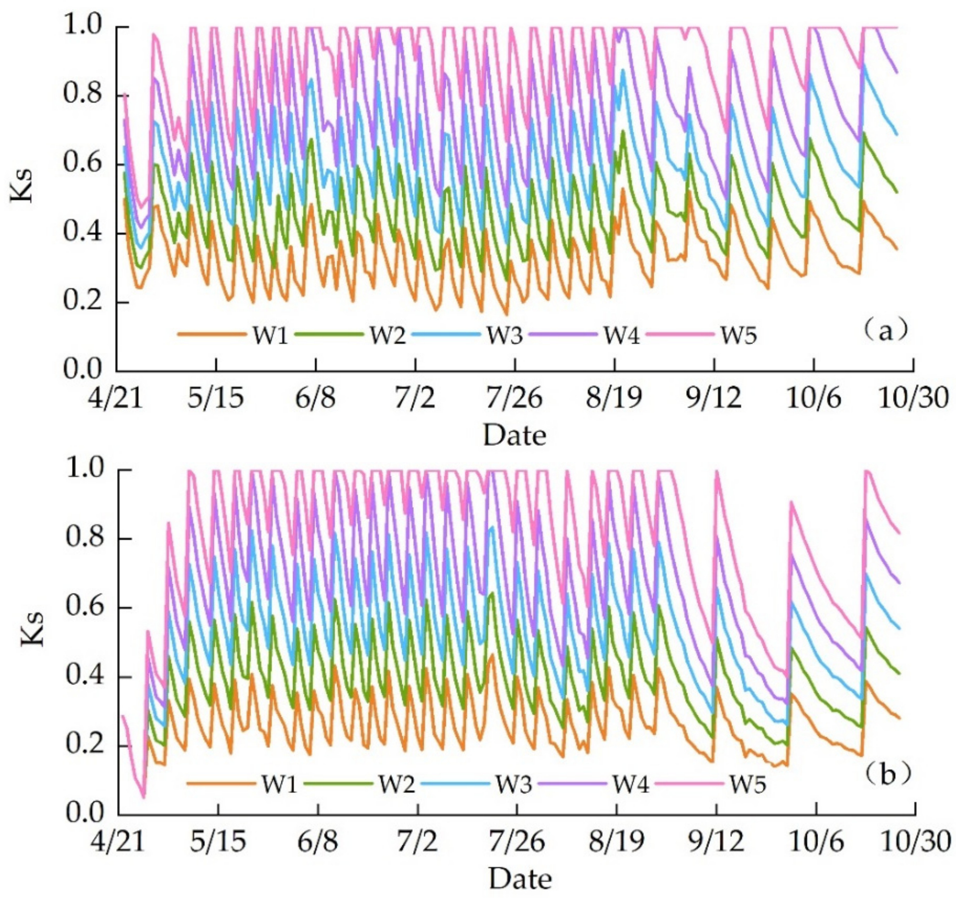

Figure 6. Seasonal changes in soil water stress coefficient (Ks) in the DCHD-cultivated apple orchard with drip irrigation in (**a**) 2019 and (**b**) 2020.

With the calibrated parameters of the SIMDual_Kc model as shown in Table 3, the time course of K_{cb}, $K_sK_{cb} + K_e$, and $K_{c\text{-local}}$ in the treatments of W1-W4 were determined with the SIMDual_Kc model (Figure 7). Seasonal variation of K_e in the treatments was similar and was negatively related to irrigation rate. During the two seasons, the maximum K_e in all treatments was measured at the initial growing period of apple trees, as the early growing stage had low canopy cover and high soil evaporation [45]. Fruit tree canopies are not uniform, and their shape depends on how they are trained [8]. When entering the rapid growth period of fruit trees, the ground coverage increased due to the complete expansion of leaves, which induced the decrease in K_e. While K_e increased during the late season of apple trees, mainly resulting from a low value of irrigation frequency and canopy cover [46]. The orchards in an arid region, e.g., Alar, received a high frequency of irrigation during the growing season, which markedly increased soil evaporation and K_e [47].

$K_sK_{cb} + K_e$, which could be denoted as $K_{c\text{-adj}}$, significantly increased after irrigation and rainfall (Figure 7). Crop coefficients reflect the effects of biological characteristics of plants, soil water and nutrients status, and agronomic measures [48]. The curves of $K_{c\text{-adj}}$ fluctuated markedly during the apple tree growing seasons and differed among the five treatments (Table 5). The differences in apple tree growth and irrigation rate were attributed to the variations of $K_{c\text{-adj}}$ among treatments.

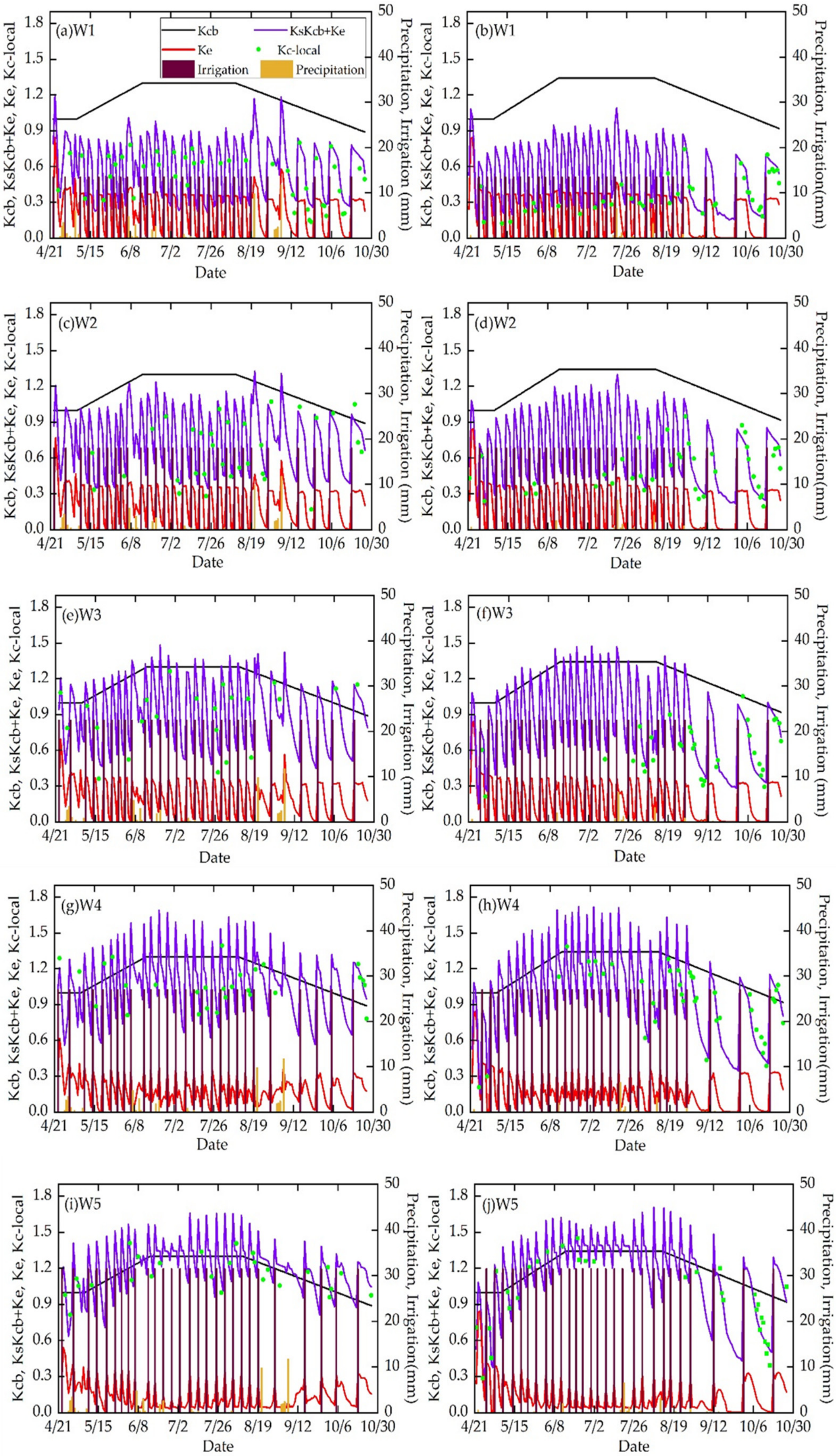

Figure 7. Variation of K_{cb}, $K_sK_{cb} + K_e$, K_e, and $K_{c\text{-}local}$ of different treatments in 2019 (left column) and 2020 (right column).

Table 5. $K_{c\text{-adj}}$ at different growing stages of apple orchard in different treatments in 2019 and 2020.

Year	Treatment	Ini-$K_{c\text{-adj}}$	Mid-$K_{c\text{-adj}}$	Late-$K_{c\text{-adj}}$	Average
2019	W1	0.71	0.55	0.60	0.62
	W2	0.79	0.73	0.75	0.76
	W3	0.86	0.91	0.89	0.90
	W4	0.93	1.09	1.03	1.04
	W5	1.00	1.29	1.17	1.18
2020	W1	0.53	0.53	0.45	0.53
	W2	0.59	0.69	0.58	0.66
	W3	0.64	0.86	0.71	0.80
	W4	0.70	1.03	0.85	0.93
	W5	0.75	1.27	0.99	1.08

3.4. ET_a and WP

Apple yield, ET_a, and WP in the five irrigation treatments over the two consecutive seasons are shown in Table 6. Apple yield increased first and then decreased with the increase in irrigation rate. In the two seasons, the maximum yield was obtained in W4, 26,960 kg/ha in 2019, and 35,328 kg/ha in 2020, respectively, while there was no significant difference in yield between W4 and W3 ($p < 0.05$). Apple yield in W4 and W3 was significantly greater than that in other treatments. The W3 and W4 treatments provided a suitable water supply for apple trees, limiting vegetative growth, improving fruit enlargement, and reducing fruit drop [49]. The highest yield in the present experiment was lower than the apple yield of Red Fuji in southern Xinjiang [50] and the results of Küçükyumu et al. [51], which may be related to the different types of fruit trees and rootstocks.

Table 6. Apple yield, crop evapotranspiration (ET_a) and water productivity (WP) of the five irrigation treatments in 2019 and 2020.

Year	Treatment	Yield (kg/ha)	ET_a (mm)	WP (kg/m^3)
2019	W1	16,480.00 d	415.55 e	3.97 a
	W2	18,384.00 c	539.69 d	3.41 a
	W3	26,377.60 a	665.21 c	3.97 a
	W4	26,960.00 a	794.76 b	3.39 a
	W5	24,659.20 b	919.12 a	2.68 b
2020	W1	20,856.00 c	443.04 e	4.71 b
	W2	22,152.00 c	587.34 d	3.77 d
	W3	34,704.00 a	706.03 c	4.92 a
	W4	35,328.00 a	831.06 b	4.25 c
	W5	28,272.00 b	989.71 a	2.86 e

Note: Different letters in the same column indicate that means are significantly different at $p < 0.05$.

ET_a of the apple orchard in this study ranged between 415.55–989.71 mm, and increased with the increase of irrigation rate, which was similar to the results of Hou et al. [52]. The maximum and minimum value of ET_a was measured in W5 and W1, respectively. Moreover, there was a significant difference in ET_a among treatments ($p < 0.05$). The water consumption in this experiment is higher than the results of Zeng [53] and Zhong et al. [54]. Both natural environments (high temperature and solar radiation) and dwarf cultivation with high density were attributed to high ET_a in southern Xinjiang.

Soil evaporation (E) and plant transpiration (T) in the apple orchard simulated with SIMDualKc in the two years are shown in Table 7. It could be found that in each growth stage, E decreased with the increase of irrigation rate, and decreased with the advance of the growth period, which was similar to the results of Wu et al. [55]. At the flowering and fruit setting stage, soil evaporation was high as the low value of canopy cover, accounting for 32.74–45.61% of ET_a. With increased canopy cover, soil evaporation reduced [56], while plant transpiration increased. In the 2019 and 2020 seasons, soil evaporation accounted for 13.85–29.97% of ET_a.

Table 7. Soil evaporation and crop transpiration in different growing periods in 2019 and 2020.

Growing Stage		2019					2020				
		W1	W2	W3	W4	W5	W1	W2	W3	W4	W5
Flowering and fruit period	E/%	44.00	41.12	38.57	35.64	32.74	45.61	43.88	42.43	41.20	39.64
	T/%	56.00	58.88	61.43	64.36	67.26	54.39	56.12	57.57	58.80	60.36
	ET_c/mm	36.05	39.89	43.65	47.30	50.79	34.44	38.05	41.75	45.46	49.05
Fruit expansion period	E/%	29.74	27.53	25.03	20.45	13.41	31.16	28.66	25.39	20.20	11.93
	T/%	70.26	72.47	74.97	79.55	86.59	68.84	71.34	74.61	79.80	88.07
	ET_c/mm	221.73	285.81	349.81	412.90	470.12	214.17	283.04	350.45	417.27	473.53
Fruit maturity	E/%	27.50	25.90	23.40	19.82	13.87	25.33	23.27	22.04	19.47	11.39
	T/%	72.50	74.10	76.60	80.18	12.20	74.67	76.73	77.96	80.53	88.61
	ET_c/mm	53.65	71.42	89.13	107.05	126.75	55.57	72.85	91.45	110.55	137.28
Deciduous period	E/%	27.37	25.47	22.86	18.57	12.20	24.31	22.90	21.20	18.24	13.76
	T/%	72.63	74.53	77.14	81.43	87.80	75.69	77.10	78.80	81.76	86.24
	ET_c/mm	124.57	155.37	186.25	217.20	246.48	94.84	123.50	152.20	180.94	211.98
Whole growth period	E/%	29.97	27.72	25.09	20.76	14.24	29.97	27.65	25.03	20.89	13.85
	T/%	70.03	72.28	74.91	79.24	85.76	70.03	72.35	74.97	79.11	86.15
	ET_c/mm	436.00	552.49	668.83	784.45	894.13	399.02	517.44	635.85	754.22	871.84

Over the two seasons, the minimum WP (2.68–2.86 kg/m^3) was measured in W5, which was significantly lower than that in other treatments ($p < 0.05$). In the 2019 season, there was no significant difference in WP among W1–W4, the maximum of 3.97 kg/m^3 was obtained in W3 and W1. However, there was a significant difference in WP among W1–W4 in 2020, the maximum of 4.92 kg/m^3 was measured in W3. The results indicated that an appropriate irrigation schedule was a benefit to improve water productivity. It may be that under appropriate irrigation scheduling, the vegetative growth of fruit trees was limited, more assimilates were distributed to fruits, and then yield and water productivity were improved. In general, WP increased and then decreased with the increase in irrigation rate, which was different from the results of Liao et al. [57]. The reason may be the differences in apple tree variety, natural environments, and irrigation and fertilization management.

Relationships between apple yield and ET_a and WP are shown in Figure 8. For the maximum value of apple yield and WP, the corresponding value of the total irrigation amount was 7351.89 m^3/ha and 5152.25 m^3/ha, respectively. In addition, the irrigation amount corresponding to the intersection of the two curves was approximately 6870 m^3/ha, which was within the range between W3 (6300 m^3/ha) and W4 (7560 m^3/ha). For the purpose of high yield and WP, it could be suggested that W3 was an optimum irrigation management for DCHD-cultivated apple orchard in southern Xinjiang.

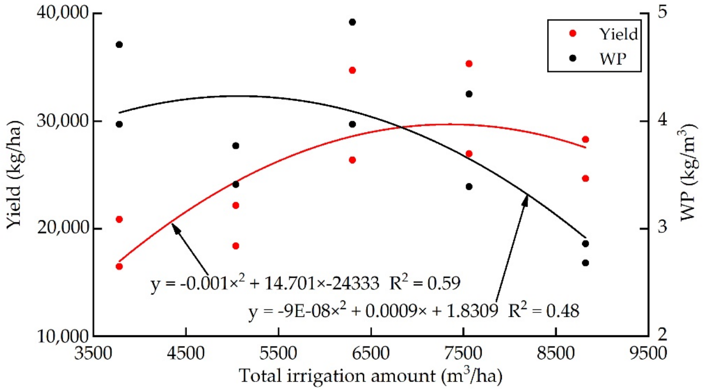

Figure 8. Relationships between total irrigation amount and apple yield and water productivity (WP) in 2019 and 2020.

4. Conclusions

Crop coefficients, evapotranspiration (ET_a), yield, and water productivity (WP) of the DCHD-cultivated apple orchard were investigated with a two-year field experiment. The dual crop coefficient curve of the DCHD-cultivated apple orchard was determined with the SIMDualKc model. The mean value of K_{cb} at the initial-, mid- and late-season over the two seasons was 1.0, 1.3, and 0.89, respectively. Soil evaporation and plant transpiration were contributed 13.85–29.97% and 70.03–86.15% to ET_a, respectively. Based on the relationship between irrigation amount and yield and WP, the irrigation scheduling with optimum yield and WP was developed, i.e., irrigation rate of 22.5 mm and irrigation amount of 630 mm. The optimal yield and WP were 30,540.8 kg/ha and 4.45 kg/m^3 over the two seasons, respectively. In this study, irrigation was controlled with the difference between ET_0 and P, which could be used as a threshold for the automatic irrigation system. The results could provide irrigation guidance for large-scale orchards with DCHD in arid regions in southern Xinjiang. Moreover, the method for determining crop coefficients and optimizing irrigation scheduling could be adopted to develop irrigation management for orchards in arid and semi-arid regions. To improve fruit yields and WP of orchards, knowledge of plant healthy growing water demand needs to be revealed to improve irrigation management in the future.

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