Evapotranspiration and crop coefficient of drip-irrigated winter wheat in China's Xinjiang Province

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ABSTRACT: Drip-irrigated winter wheat (*Triticum aestivum*) is grown on 5.07×10^5 ha in China's Xinjiang Uyghur Autonomous Region. Information about evapotranspiration (ET), evaporation, and crop coefficient (K_c) is important for maximizing water savings in drip-irrigated wheat. A field experiment was conducted during two winter wheat growing seasons at the Shihezi University Agricultural Experiment Station, Xinjiang Province. The study included three irrigation amounts (375, 600, and 750 mm, abbreviated D1, D2, and D3, respectively). The results showed that the ET of drip-irrigated winter wheat generally increased as irrigation increased. Averaged across both growing seasons, average daily ET rates decreased significantly in the order D3 (2.64 mm/d) > D2 (2.26 mm/d) > D1 (1.55 mm/d). Evaporation was greatest between 1 and 4 days after irrigation and accounted for 26–28% of ET during the entire growing season. The K_c values ranged between 0.45 and 1.35 across all growth stages, averaging 0.96. A fourth-order polynomial equation ($R^2 > 0.75$) describes the changes in K_c across the growing season. A logarithmic function ($R^2 > 0.96$) described the relationship between K_c and the leaf area index. The average yield was greater in D3 (10 520 kg/ha) than in D2 (10 060 kg/ha) and D1 (8000 kg/ha) in both years. The water use efficiency in D1 was 1.14–1.16 times that in D2, and 1.27–1.30 times that in D3. Thus considering the yield, the water use efficiency, and the harvest index, the optimum irrigation amount was 600 mm. These results are helpful for improving irrigation management and crop water use predictions in Xinjiang Province and elsewhere in the world with similar irrigation methods and climatic conditions.

KEYWORDS: yield, soil evaporation, leaf area index, soil water, water use efficiency

INTRODUCTION

Drip irrigation has been used around the world to increase crop production and water use efficiency (WUE). Drip irrigation consists of frequent application of small amounts of water to the soil. This reduces water loss due to percolation below the crop root zone. Drip irrigation also influences water loss by evapotranspiration (ET) through its effects on the root zone soil water status and the field microclimate[1].

ET is the main component of the soil-plant-atmosphere continuum, accounting for more than 90% of total agricultural water use[2, 3]. Because of its effects on both the water balance and the heat balance, ET is a key link in the hydrological cycle[4].

There is a close relationship between ET and crop physiological activity. Furthermore, ET influences on crop growth and yield[5, 6].

Accurate determination of ET is critical for improving WUE and for developing suitable irrigation schedules[7, 8]. Weighing lysimeters, which are the standard method for measuring crop ET, can capture information about ET over time periods as short as 30 min. Large weighing lysimeters have been used to study ET in flood-irrigated winter wheat (*Triticum aestivum*) fields on the North China Plain[9, 10]. The authors reported that the evaporation (E) to evapotranspiration ratio ($E/$ET) was 30% in northern China. Gao reported that the ET for subsurface drip-irrigated winter wheat with three irrigation treatments ranged from 393–449 mm on

Table 1 Monthly means for daily air temperature, daily solar radiation, relative humidity, rainfall, and evaporation during the winter wheat growing period in Shihezi.

	Mean temp. (°C)		Solar rad. (MJ m^{-2} d^{-1})		Relative humidity (%)		Rainfall (mm)		Evaporation (mm)	
	Y13–14	Y14–15	Y13–14	Y14–15	Y13–14	Y14–15	Y13–14	Y14–15	Y13–14	Y14–15
Oct	11.3	9.8	11.1	12.3	56	69	9.5	8.3	50.2	45.6
Nov	0.3	0.1	8.7	9.5	76	77	11.7	10.2	15.5	12.6
Dec	−6.3	−13.5	6.3	6.9	82	86	12.4	8.8	8.3	6.1
Jan	−14.2	−15.5	5.4	5.8	78	89	8.9	5.2	5.9	3.4
Feb	−15.6	−14.7	4.6	5.3	73	85	8.3	10.5	18.6	14.6
Mar	−0.6	2.7	12.3	11.5	69	71	7.6	8.4	65.2	60.3
Apr	12.5	14.0	17.8	18.9	47	49	5.5	7.5	160.6	162.5
May	20.8	22.1	22.4	23.7	33	29	5.2	6.2	208.5	194.2
Jun	24.8	26.7	24.6	24.9	41	38	7.9	7.2	223.2	220.8

Abbreviations: Y13–14, year 2013–2014; Y14–15, year 2014–2015.

the North China Plain[11]. Water use efficiency and yield are both greater under drip irrigation than under either furrow irrigation or sprinkler irrigation[12]. Irrigation efficiency (or water application efficiency) under drip irrigation systems ranges between 75–95% compared with 25–50% for surface irrigation (furrow or block), 70–80% for fixed set sprinklers, and 65–75% for portable sprinkler systems[13]. To our knowledge, E and ET in drip-irrigated winter wheat fields in China's Xinjiang Province have not been studied.

The crop coefficient (K_c) is often used to estimate cropland ET[14]. The K_c reflects the crop species, its biological characteristics, yield, soil conditions, and fertilizer management[15, 16]. Studying many crops, Pereira and Alves emphasized the necessity of calculating K_c under different climatic conditions[17]. Allen suggested that K_c can be calculated using large weighing lysimeters and local meteorological data[18]. Previous studies have been done about ET in flood-irrigated winter wheat. For example, Zhang estimated the K_c of flood-irrigated winter wheat on the North China Plain using the dual crop coefficient approach[19]. The authors reported that the K_c values were 0.12, 1.15, and 0.30 during the initial development, mid-season, and late-season stages, respectively. However, there are no reports about K_c in drip-irrigated winter wheat.

Drip-irrigated winter wheat production occurs at 5.07×10^5 ha in China's Xinjiang Uyghur Autonomous Region[20]. This makes the region one of the major wheat producing areas in China. However, the Xinjiang Region is a typical arid/semiarid area with low rainfall and humidity, high temperatures and humidity, strong winds, and long days. This has restricted regional agricultural develop-

ment and grain output. Information about the ET and K_c of drip-irrigated winter wheat in Xinjiang Province is important for the sustainable use of water resources and economic development.

In this study, we used large weighing lysimeters to determine the effects of irrigation amount on the ET characteristics of drip-irrigated winter wheat. The specific objectives of this study were (1) to measure ET and K_c at different stages of the winter wheat growing season, (2) to investigate the factors affecting seasonal variation in K_c, and (3) to provide useful information for optimizing drip irrigation of winter wheat.

MATERIALS AND METHODS

Experimental site description

The field experiment was carried out during two winter wheat seasons (Sept 2013–June 2014 and Sept 2014–June 2015) at the Water-Saving Irrigation Research Institute of Shihezi University, Xinjiang Province, China (45° 19′ N, 86° 03′ E, 440 m above sea level). During the 2013–2014 winter wheat growing season, the mean temperature was 3.7 °C, total radiation was 3435 MJ/m^2, mean relative humidity was 62%, total rainfall was 77 mm, and total evaporation was 746 mm (Table 1). During the 2014–2015 winter wheat growing season, the mean temperature was 4.76 °C, total radiation was 3408 MJ/m^2, mean relative humidity was 66%, total rainfall was 72.3 mm, and total evaporation was 720 mm.

The soil is classified as a grey desert soil. The field capacity was 24% in 2013–2014 and 22% in 2014–2015. The wilting point was 8% in 2013–2014 and 8% in 2014–2015. The physico-

Table 2 Selected soil physical and chemical properties (0–60 cm depth) in the experiment plots.

Parameter	Value	
	2013–2014	2014–2015
Clay (%)	19.5 ± 1.8	20.5 ± 2.1
Silt (%)	36.8 ± 2.2	37.2 ± 2.0
Sand (%)	41 ± 2	43 ± 2
pH	7.72 ± 0.23	7.52 ± 0.34
Organic matter (mg/kg)	27.2 ± 1.4	25.2 ± 1.2
Alkaline-N (mg/kg)	62.5 ± 2.1	60.5 ± 1.9
Olsen-P (mg/kg)	27.2 ± 1.3	25.2 ± 1.1
Available K (mg/kg)	343 ± 11	339 ± 12
Field capacity (%)	23.6 ± 1.5	22.4 ± 1.2
Wilting water content (%)	8.2 ± 0.3	7.9 ± 0.2
Saturated volumetric water content (%)	33.9 ± 2.1	33.7 ± 1.6

Table 3 Irrigation rates in the field experiment.

Year	Date	Irrigation rate (mm)		
		D1[†]	D2	D3
2013–2014	28 Sep	60	60	60
	11 Nov	35	92	138
	28 Mar	35	56	69
	7 Apr	35	56	69
	17 Apr	35	56	69
	27 Apr	35	56	69
	7 May	35	56	69
	17 May	35	56	69
	27 May	35	56	69
	6 Jun	35	56	69
2014–2015	1 Oct	60	60	60
	4 Nov	35	92	138
	27 Mar	35	56	69
	6 Apr	35	56	69
	16 Apr	35	56	69
	26 Apr	35	56	69
	6 May	35	56	69
	16 May	35	56	69
	26 May	35	56	69
	5 Jun	35	56	69

[†] Treatments.

chemical properties of the soil at the experimental sites were similar in both years (Table 2).

Experiment materials and design

The experiment included three irrigation amounts: 375 mm (D1), 600 mm (D2), and 750 mm (D3) (Table 3). The plots were drip-irrigated ten times during both growing seasons. Sixty mm of water was applied to each treatment on the day after sowing to ensure germination. Additional 35, 92, and 138 mm of water were applied in D1, D2, and D3, respectively, in November. After regreening in spring, the plots were irrigated once every 10 d. On each day, the irrigation amounts in D1, D2, and D3 were 35, 56, and 69 mm, respectively.
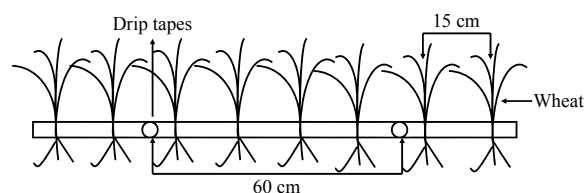
Winter wheat 'Xindong 43' (obtained from the Agricultural Reclamation Breeding Academy of Xinjiang Province) was sown on 25 Sept 2013 and on 30 Sept 2014. The wheat was harvested on 28 June 2014 and 27 June 2015. The row spacing (15 cm) and seeding rate (4.5 million seeds/ha) were the same in both cropping seasons. Fertilizer was applied at the following rates: 250 kg/ha N (urea), 250 kg/ha P_2O_5 (calcium superphosphate), 75 kg/ha K_2O (KCl), and 30 kg/ha $ZnSO_4$. The urea fertilizer was applied via drip irrigation in equal amounts (75 kg/ha N) in November and then at regreening, jointing, and heading. The other fertilizers were incorporated into the soil at sowing.

The drip tapes were manufactured by the Lüyuan Company (Beijing, China). There was 60 cm spacing (i.e., four wheat rows) between each drip tape (Fig. 1). The emitter discharge rate was 3.2 l/h, the dripper spacing of 0.30 m was chosen in the actual production, the percentage of wetted

Fig. 1 Sketch map showing the spacing between wheat rows and between drip tapes.

area is 70% in drip irrigation. The amount of irrigation applied to each plot was controlled with a water meter. The plots were 5 m × 8 m. The plots were arranged in a randomized complete block design with three replicates. Impermeable plastic membrane was buried between the plots to prevent lateral water movement.

Measurements

Evapotranspiration: ET was measured using large weighing lysimeters (2 m long × 2 m wide × 2.3 m deep, Xi'an New Clear Water Environment Technology Co., LTD., Xi'an, China) that were installed in each plot. The upper edge of each lysimeter was 10 cm above the soil surface. The height of the soil surface was the same inside and outside the lysimeters. The weighing system consisted of

a high-precision, counter-weighted platform scale. The scale could detect moisture changes between 0 and 3000 kg with accuracy of ± 0.2 kg (0.05 mm). The abnormal values were automatically filtered by the software and then the data were converted to ET with a calibration coefficient. Lysimeter performance was checked once at each growth stage. Data collected during rainfall and irrigation events were eliminated. The measurements were made automatically each hour.

Reference evapotranspiration: ET_0 was determined with an ET_0 calculator which was based on the Penman-Monteith equation[21]. This equation, which is recommended by the FAO, is the most general and widely used method for calculating daily reference ET_0 [22]. The inputs for the calculator [maximum air temperature (T_{max}), minimum air temperature (T_{min}), maximum relative humidity (RH_{max}), minimum relative humidity (RH_{min}), sunshine hours (n/N) and wind speed at a height of 2 m (u_2)] were based on weather data collected between 2013 and 2015 at the Shihezi Meteorological Observatory station.

Soil evaporation: daily soil evaporation was measured with four micro-lysimeters that were placed between two wheat rows. The micro-lysimeters contained small isolated volumes of bare soil mounted flush with or slightly above the soil surface[9]. Specifically, the micro-lysimeters consisted of two polyvinyl chloride pipes (20 cm high). The larger external pipe (11 cm diam) was installed vertically in the soil profile (Fig. 1). The smaller internal pipe (9 cm diam) was filled with soil and then lowered into the larger pipe so that the soil surface inside the small pipe was level with that outside the large pipe. The small (i.e., inner) pipes were removed from the larger pipes daily (sometimes more frequently) and then weighed with an electronic balance (0.01 kg precision) to determine water loss. The small pipes were then placed back inside the large pipes. Evaporation was calculated using the formula $E = \Delta W / \pi r^2$ where ΔW is the change in weight of the micro-lysimeter per unit time and r is the inner diameter of the small pipe (i.e., micro-lysimeter barrel). Soil E in each plot was calculated as the average of the four micro-lysimeters.

Soil moisture: soil water content was measured using Decagon 5 TE soil moisture probes (Decagon Device Inc. Washington State, USA). The probes were installed in each plot at the 20, 40, 60, 100, and 150 cm depths. The soil water content was measured each day from sowing to maturity.

Leaf area, predicted yield, and aboveground biomass: Green leaf area was measured with an LI-3100 leaf area meter (LI COR Inc., Lincoln, NE, USA). The leaf area index (LAI) was calculated by multiplying the leaf area (m^2/plant) by the plant population (plant number/m^2). Samples were collected once every seven days. The samples were dried in an oven at 75 °C for at least 72 h and then the weights of the leaf blades, stems, and panicles were measured. At maturity, 1 m^2 areas from each plot were harvested to calculate the grain yield and harvest index (the ratio of the filled spikelet weight to the total aboveground biomass).

Water use efficiency: WUE was calculated by dividing grain yield by ET (i.e., WUE = Y/ET).

Meteorological data: the meteorological data (i.e., temperature, humidity, wind speed, relative humidity, and soil temperature) were downloaded from the website of the Shihezi Meteorological Observatory. The experiment site was located 100 m from the observatory.

Statistical analysis

The data were analysed using the generalized linear model procedure (SPSS version 16.0). Differences between means were compared using Fisher's least-significant-difference test at the 5% probability level.

RESULTS

Yield, WUE, and harvest index

The number of panicles per hectare, grain number per spike, 1000 grain weight, and yield increased as irrigation amount increased in both cropping seasons (Table 4). The differences between D2 and D3 were not significant in either growing season. In contrast, the means of both treatments were significantly greater than those of D1. The yields of D2 and D3 were 1.25–1.32 times those of D1. WUE decreased as the amount of irrigation water increased. Depending on the cropping season, WUE in D1 was 1.14–1.16 times that in D2, and 1.27–1.3 times that in D3. The harvest index increased as irrigation amount increased. Differences between D2 and D3 were not significant in either growing season. The harvest indexes of D2 and D3 were 1.26–1.42 times that of D1.

Soil water

The effect of irrigation on volumetric soil water content decreased as soil depth increased (Fig. 2). During winter, the volumetric soil water content did

Table 4 Winter wheat yield, water use efficiency (WUE), and harvest index as affected by drip irrigation amount.

Growing season	Treatment	Panicles ($\times 10^4$ ha^{-1})	Grain number per spike	1000-grain weight (g)	Yield (kg/ha)	WUE (kg/m^3)	Harvest index
2013–2014	D1	515 ± 13^b	39.2 ± 1.8^b	43.7 ± 1.1^b	7820 ± 260^b	1.84 ± 0.06^a	0.33 ± 0.03^b
	D2	585 ± 10^a	47.6 ± 1.5^a	50.4 ± 0.9^a	9880 ± 380^a	1.59 ± 0.06^b	0.43 ± 0.02^a
	D3	598 ± 6^a	49.6 ± 1.2^a	52.4 ± 1.9^a	$10\,360 \pm 390^a$	1.41 ± 0.05^b	0.47 ± 0.03^a
2014–2015	D1	561 ± 13^b	38.2 ± 1.1^b	40.1 ± 1.6^b	8180 ± 380^b	1.91 ± 0.09^a	0.35 ± 0.02^b
	D2	612 ± 12^a	44.8 ± 1.4^a	49.8 ± 1.7^a	$10\,240 \pm 770^a$	1.67 ± 0.13^{ab}	0.44 ± 0.02^a
	D3	621 ± 8^a	46.4 ± 1.2^a	51.2 ± 1.9^a	$10\,680 \pm 640^a$	1.50 ± 0.09^b	0.46 ± 0.01^a

Values are means $\pm$ SD. Means within a column followed by different lowercase letters are significantly different at $p < 0.05$. Abbreviations: D1, 375 mm; D2, 600 mm; D3, 750 mm.
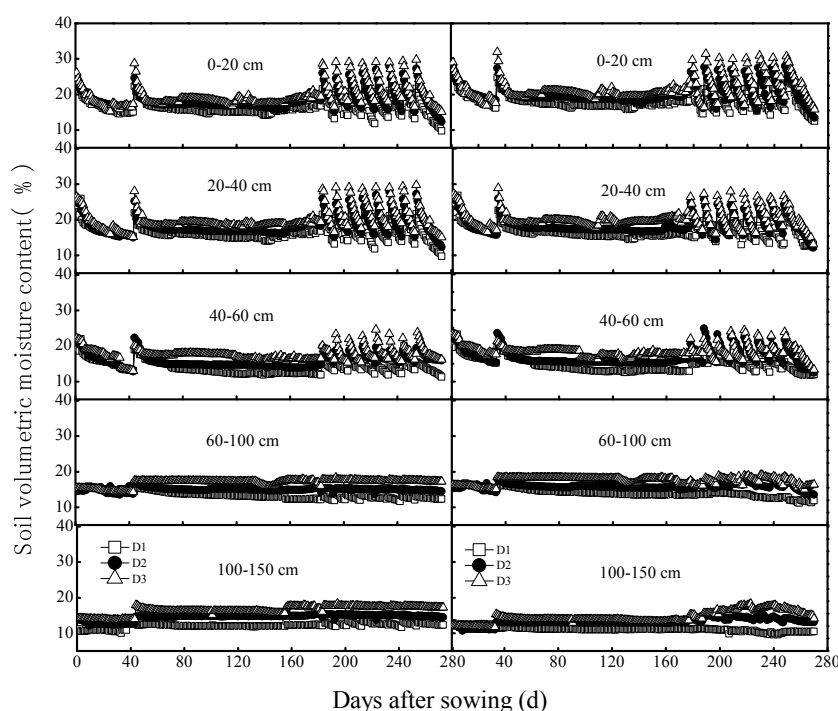

Fig. 2 Temporal changes in volumetric water content at different soil depths as affected by drip irrigation amount. Measurements were made during the 2013–2014 and 2014–2015 winter wheat growing seasons. Abbreviations: D1, 375 mm; D2, 600 mm; D3, 750 mm.

not differ significantly among the three treatments. After regreening, the volumetric water content in the 0–20 cm depth of D1 increased from 15% before irrigation to 24% after irrigation. An increase of similar magnitude was observed in the 20–40 cm depth. Smaller increases were observed in the 40–60 cm depth (from 11% before irrigation to 14% after irrigation) and the 60–100 cm depth (from 11% before irrigation to 12% after irrigation). Irrigation had almost no effect on volumetric water content in the 100–150 cm depth. This pattern was also observed in D2 and D3; however the difference in soil water content before and after irrigation

increased as irrigation amount increased. From regreening to maturity, the average soil volumetric water in the 0–20 cm depth was 27% in D3, 23% in D2, and 18% in D1. In the 20–40 cm depth, the average volumetric content was 24% in D3, 19% in D2, and 14% in D1.

Evapotranspiration

Temporal changes in actual daily ET showed similar patterns in all three treatments in both cropping seasons (Fig. 3). Daily ET rates decreased slowly between 0 and 160 days after sowing (DAS) and then more rapidly as air temperature decreased in
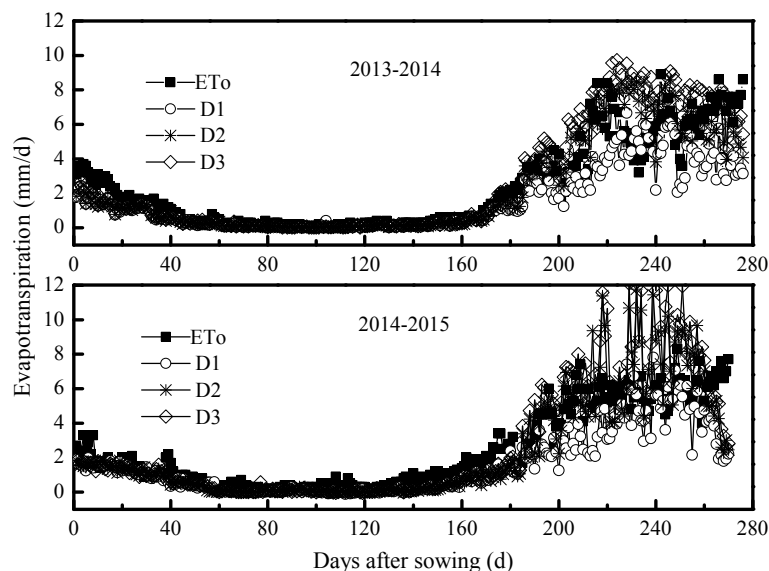
Fig. 3 Daily evapotranspiration rates as affected by drip irrigation amount in the 2013–2014 and 2014–2015 winter wheat growing seasons. Abbreviations: ET_0, reference evapotranspiration; D1, 375 mm; D2, 600 mm; D3, 750 mm.
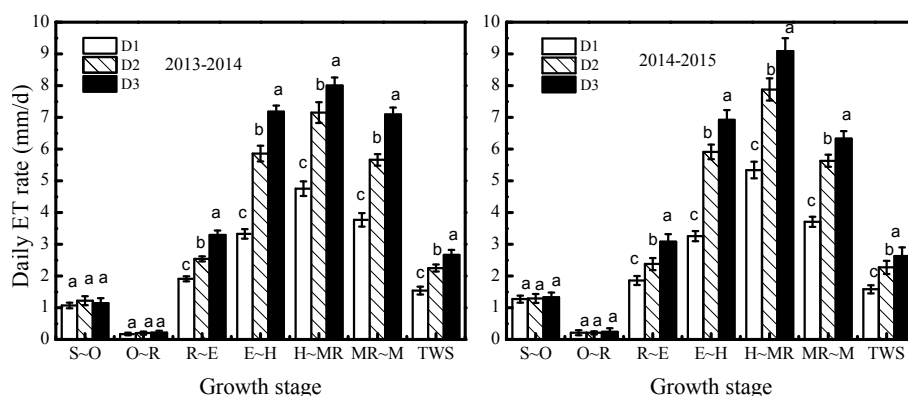

Fig. 4 Average daily evapotranspiration rates at different winter wheat growth stages as affected by drip irrigation amount. Measurements were made during the 2013–2014 and 2014–2015 growing seasons. Error bars represent standard deviation ($n = 3$). Bars with different lowercase letters are significantly different at $p < 0.05$. Abbreviations: D1, 375 mm; D2, 600 mm; D3, 750 mm; S∼O, sowing-overwinter; O∼R, overwinter-regreening; R∼E, regreening-elongation; E∼H, elongation-heading; H∼MR, heading-milk ripening; MR∼M, milk ripening-maturity; TWS, the entire winter wheat growing season.

late fall and early winter. Daily ET rates were lowest during the overwinter period. Daily ET rates rapidly increased from regreening to milk ripening and then gradually declined during late grain filling. Daily ET rates decreased in the order D3 > D2 > D1. The ET and ET_0 showed the same pattern with time.

Average daily ET rates during different growth stages were calculated by dividing total ET during the growth stage by the number of days. Similar patterns were observed during both growing seasons (Fig. 4). Average daily ET rates were lowest during

sowing-overwinter and overwinter-regreening. Furthermore, there was no significant difference among the treatments during those two periods. Average daily ET rates decreased significantly in the order D3 > D2 > D1 after regreening. Average daily ET rates were greatest during heading-milk ripening, averaging 8.53 mm/d in D3, 7.52 mm/d in D2, and 5.05 mm/d in D1. The second highest rates were during elongation-heading, averaging 7.05 mm/d in D3, 5.89 mm/d in D2, and 3.30 mm/d in D1. The milk ripening-maturity and regreening-elongation
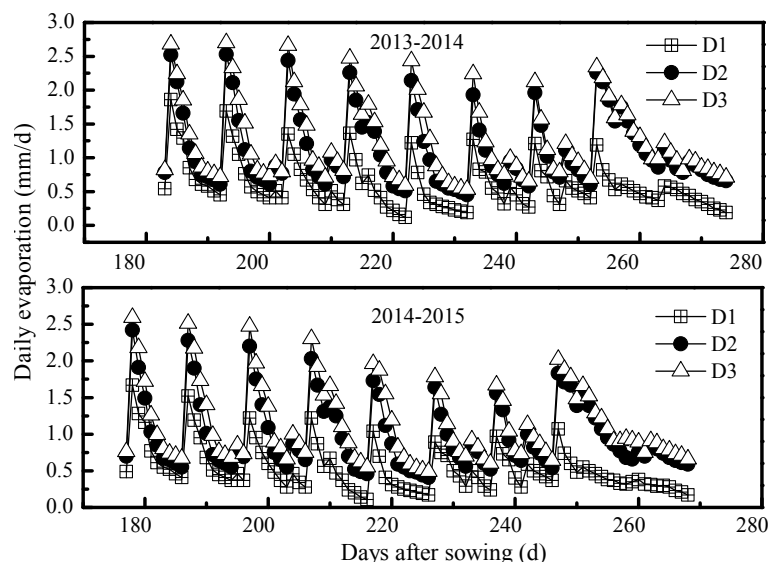
Fig. 5 Daily soil evaporation rates as affected by drip irrigation amount in the 2013–2014 and 2014–2015 winter wheat growing seasons. Abbreviations: D1, 375 mm; D2, 600 mm; D3, 750 mm.

stages had the third and fourth highest rates, respectively. Averaged across both growing seasons, average daily ET rates decreased significantly in the order D3 (2.64 mm/d) > D2 (2.26 mm/d) > D1 (1.55 mm/d).

Soil evaporation under the drip irrigation

Daily soil E rates in the drip-irrigated winter wheat are shown in Fig. 5. Daily soil E rates decreased in the order D3 > D2 > D1. However, the temporal changes in daily soil E were generally the same, regardless of water amount. Specifically, daily soil E rates increased to 0.5 and 3.0 mm/d immediately after irrigation. The E rates decreased rapidly to < 1.0 mm/d within four days after irrigation and then levelled off.

Evaporation accounted for 75% of ET during sowing-overwinter and 70% of ET during overwinter-regreening (Table 5). This is because (i) transpiration rates and groundcover were both low, and (ii) the water content of the surface soil was great enough to respond to the evaporative demand. During regreening-elongation, E/ET decreased to an average of 29% in D1, 40% in D2, and 42% in D3. During elongation-heading, E/ET was 16% in D1, 20% in D2, and 20% in D3. Transpiration reached a maximum during heading-milk ripening, with E/ET decreasing to 8% in D1, 11% in D2, and 12% in D3. The wheat leaves began to senesce after milk ripening and groundcover declined. This caused E/ET to increase. Averaging both growing seasons,
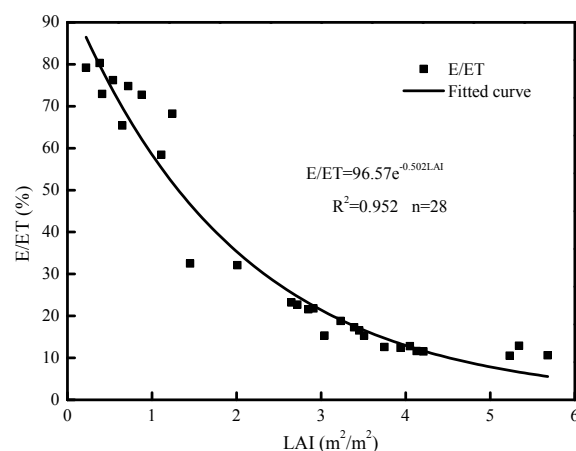

Fig. 6 Relationship between the evaporation/evapotranspiration ratio (E/ET) and the leaf area index (LAI) during two winter wheat growing seasons.

ET was 427 mm in D1, 617 mm in D2, and 722 mm in D3. The E/ET values averaged 26% in D1, 27% in D2, and 28% in D3.

Fig. 6 shows that E/ET decreased rapidly as LAI increased while the canopy was still developing (i.e., LAI < 3). This is because transpiration rates and groundcover both increased as the canopy grew. The decrease in E/ET was not as rapid when LAI > 3. The leaf area became stable resulting in a relatively stable E and transpiration; hence E/ET decreased slowly as LAI increased. The relationship

Table 5 Evaporation (E), evapotranspiration (ET) and the E/ET ratio as affected by irrigation amount in the 2013–2014 and 2014–2015 winter wheat growing seasons.

Year	Treatment	Variate	S~O[‡]	O~R	R~E	E~H	H~MR	MR~M	TWS
2013–2014	D1[†]	E (mm)	39.6	15.5	15.6	13.5	10.8	12.5	107.5
		ET (mm)	52.4	21.3	53.5	86.6	132.9	79.1	425.9
		E/ET (%)	75.6	72.8	29.2	15.6	8.1	14.5	25.2
	D2	E (mm)	42.1	18.8	28.1	31.5	19.6	23.8	163.9
		ET (mm)	55	24.7	71	152.5	200.2	118.9	620.4
		E/ET (%)	76.5	76.1	39.6	20.7	9.8	20	26.4
	D3	E (mm)	44.5	20.4	38.5	36.7	25.9	39.9	201.9
		ET (mm)	56	25.6	92	186.6	224.1	148.8	733.2
		E/ET (%)	79.5	79.7	41.8	19.7	11.6	24.1	27.5
2014–2015	D1	E (mm)	40.8	18.2	16.1	13.8	11.9	12.5	113.3
		ET (mm)	54.6	26.2	55.8	81.6	138.8	70.4	427.4
		E/ET (%)	74.7	69.5	28.9	16.9	8.6	17.8	26.5
	D2	E (mm)	42.3	19.3	29.4	27.8	23.6	28.4	170.8
		ET (mm)	55.6	26.7	71.4	147.6	205	106.9	613.1
		E/ET (%)	76.1	72.2	41.1	18.8	11.5	26.6	27.8
	D3	E (mm)	43.5	20.6	39.8	36.1	28.4	32.8	201.2
		ET (mm)	57	30.2	92.4	173.1	236.4	120.2	711.3
		E/ET (%)	76.3	68.2	43.1	20.9	12	27.3	28.3

[†] D1, 375 mm; D2, 600 mm; D3, 750 mm.

[‡] S~O, sowing-overwinter; O~R, overwinter-regreening; R~E, regreening-elongation; E~H, elongation-heading; H~MR, heading-milk ripening; MR~M, milk ripening-maturity; TWS, the entire winter wheat growing season.

Table 6 Crop coefficient (K_c) in the D2 treatment (600 mm irrigation water) during the 2013–2014 and 2014–2015 winter wheat growing seasons.

Year	Variable	S~O[†]	O~R	R~E	E~H	H~MR	MR~M	TWS
2013–2014	Days	49	124	28	26	28	21	276
	ET (mm)	55	22.7	71	157.4	195.5	118.9	620.4
	ET_0 (mm)	87.5	40.6	78.7	137.2	151.8	145.2	642.1
	K_c	0.63	0.56	0.9	1.08	1.34	0.82	0.97
2014–2015	Days	43	127	30	25	26	19	270
	ET (mm)	55.6	26.7	71.39	147.6	204.95	106.9	613.1
	ET_0 (mm)	75.9	78.1	96.5	133.7	151.8	114.1	650.1
	K_c	0.77	0.34	0.74	1.1	1.35	0.94	0.94

[†] S~O, sowing-overwinter; O~R, overwinter-regreening; R~E, regreening-elongation; E~H, elongation-heading; H~MR, heading-milk ripening; MR~M, milk ripening-maturity; TWS, the entire winter wheat growing season.

between E/ET and LAI was best described with an exponential function (i.e., $E/\text{ET} = 96.57\,e^{-0.502\,\text{LAI}}$, $R^2 = 0.952$). The R^2 values were > 0.95.

Crop coefficient of the drip-irrigated winter wheat

The K_c is mainly affected by the characteristics of the specific crop. Climate, growing conditions, and growth stage also influence K_c. When yield, WUE, and harvest index were considered, D2 was best among the treatments in this study. Hence the K_c of

drip-irrigated winter wheat was calculated using the actual ET and the ET_0 of D2. The K_c was least during the sowing-overwinter and the overwinter-regreening stages. The K_c was greatest during heading-milk ripening. Averaged across both growing seasons, K_c was 0.70 during sowing-overwinter, 0.45 during overwinter-regreening, 0.82 during regreening-elongation, 1.09 during elongation-heading, 1.35 during heading-milk ripening, and 0.88 during milk ripening-maturity (Table 6). Averaged across all stages, the K_c was 0.96 for drip-irrigated winter
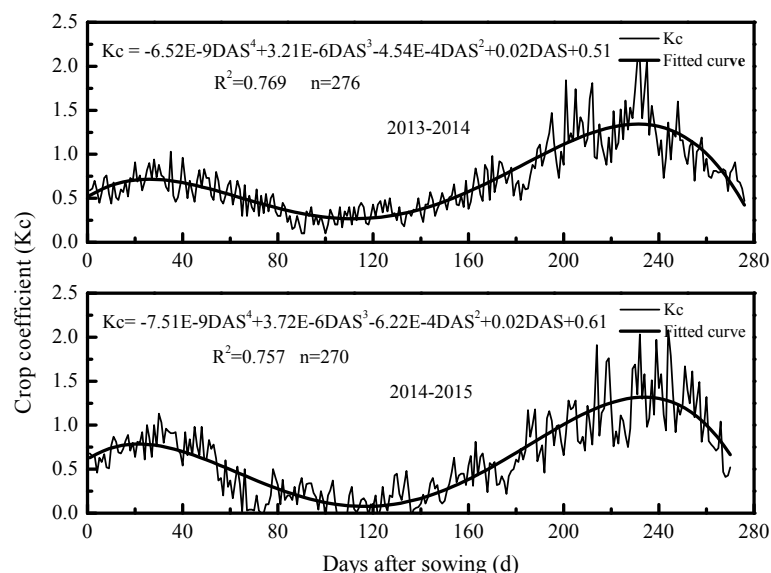
Fig. 7 Temporal changes in the crop coefficient (K_c) during the 2013–2014 and 2014–2015 winter wheat growing seasons.

wheat in Xinjiang Province.

A fourth-order regression curve ($K_c = a_4 \, \mathrm{DAS}^4 + a_3 \, \mathrm{DAS}^3 + a_2 \, \mathrm{DAS}^2 + a_1 \, \mathrm{DAS} + a_0$) was fitted to the daily K_c values across each growing season (Fig. 7). The K_c values increased to a maximum 35 DAS (tillering) and then decreased during overwintering. The K_c values increased again in the spring and reached a maximum 230 DAS (grain filling).

The relationship between K_c and LAI is shown in Fig. 8. The K_c values increased as LAI increased. The increases in K_c were the largest when LAI was < 1.5. The increases were smaller when LAI was > 3. Regression analysis showed that the relationship between K_c and LAI was best described by a logarithmic function, i.e. $K_c = b \ln(\mathrm{LAI}) + c$.

DISCUSSION

The availability of water for irrigation is limited in many arid and semiarid areas. Because of this, the goal of irrigation management should not be to maximize yield. Instead, the purpose should be to find the optimum benefit when considering yield, WUE, and harvest index.

In a previous survey, we observed large differences in irrigation rate among different locations in northern Xinjiang Province. The irrigation rates generally ranged between 400 and 750 mm. There were also large differences in the amount of irrigation water applied during the sowing-overwinter period. In some locations, farmers applied 35 mm irrigation water whereas in other areas farmers ap-

plied 92 or 138 mm. Overall, there was no standard. The irrigation rates in this study were chosen to represent the variation in field practices in northern Xinjiang Province.

Averaged across both growing seasons, ET was 427 mm in D1, 617 mm in D2, and 722 mm in D3. Total ET varied significantly among treatments and generally increased as irrigation amount increased. These results were consistent with studies involving sprinkler irrigation and flood irrigation[23, 24]. Rainfall and irrigation significantly influence daily ET[25]. The temporal changes in ET and ET_0 were the same in this region (Fig. 3), which is consistent with the results of the FAO. In addition, WUE declined as drip irrigation amount increased (Table 4). The harvest index and yield increased as irrigation amount increased; however, the differences between D2 and D3 were not significant. Based on these results, we conclude that D2 was the best irrigation amount for this region.

When yield, WUE, and harvest index were considered, the optimum ET was 613–620 mm (Table 5). This value was slightly greater than the values reported by Wohlfahrt and Lei[26, 27]. The differences in optimum ET can be attributed to differences in climate among experiment sites. In Xinjiang Province, average temperatures are high, relative humidity is low, winds are strong, and days are long. As a result E and ET rates are greater here than in other, less arid regions. The maximum daily ET rates were observed during heading-milk
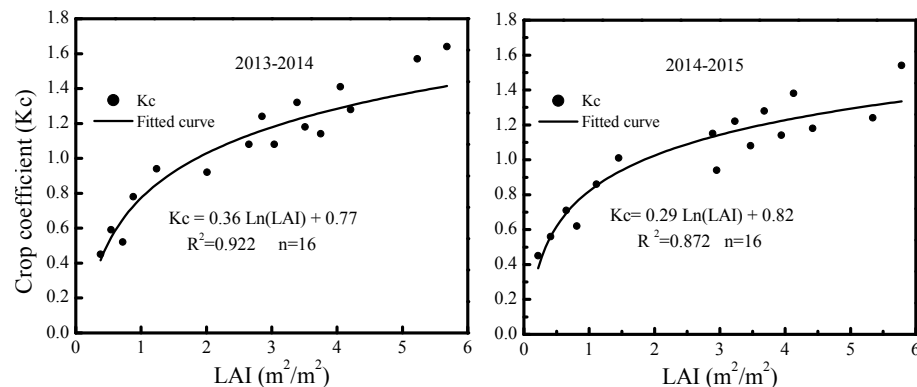
Fig. 8 Relationship between crop coefficient (K_c) and leaf area index (LAI) in the 2013–2014 and 2014–2015 winter wheat growing seasons.

ripening (Fig. 4., 5.05 mm/d in D1, 7.52 mm/d in D2, and 8.53 mm/d in D3). The results indicate this is a water sensitive period. Wei observed that maximum daily ET (9.35 mm/d) occurred 228–238 DAS for winter wheat in Daxing, Beijing[28]. Research indicates that 80–90% of winter wheat roots are in the 0–60 cm depth[29]. The soil water content in the 0–40 cm depth varied significantly in all three treatments (Fig. 2). This indicates that drip irrigation was able to prevent water loss from soil evaporation when evaporative demand was high.

Unlike transpiration, *E* does not directly affect crop yield. Controlling *E* is important for increasing WUE and for conserving irrigation water. Many scholars have studied evaporation. Sun reported that *E*/ET ranged from 31.3–37% in conventionally irrigated winter wheat in the North China Plain[30]. Similarly, Sadras and Rodriguez observed that *E*/ET ranged from 30–35% in a flood irrigated wheat field in eastern Australia[31]. Our results showed that when averaged across the entire growing season, *E* accounted for 26–28% of ET under drip irrigation (Table 5). These values were less than those reported in previous studies. Higher *E* rates may occur under traditional irrigation practices because the entire soil surface is wet. In contrast, only part of the soil surface is wet under drip irrigation. Soil *E* rates increased to 0.5 and 3.0 mm/d immediately after drip irrigation. Evaporation rates decreased during the next four days and then levelled out at about 0.5 mm/d (Fig. 5). When the soil water supply can meet the transpiration needs of crops, the *E*/ET ratio is mainly affected by LAI. An exponential equation ($R^2 > 0.95$) expressed the relation between *E*/ET and LAI. The *E*/ET values decreased rapidly until LAI reached 3.0 and then less rapidly after that. Hence applying larger amounts of wa-

ter less frequently could reduce evaporation and increase irrigation WUE in drip-irrigated systems in arid areas.

The K_c is an important parameter for irrigation management. In this study, the K_c values were 0.7 shortly after sowing (Table 6). The K_c values declined to a minimum (0.45) during the overwinter period. The K_c values increased to a maximum (1.35) at heading-milk ripening, before decreasing again as the wheat ripened. The K_c averaged 0.96 across the entire growing season. In the FAO Irrigation and Drainage Paper 56, the K_c value was a minimum (0.4–0.6) at both the beginning and ending of the winter wheat growing season[22]. The maximum value of K_c (1.15–1.2) was observed during the middle of the growing season, when LAI was greatest. The maximum K_c values in our study were greater than those in the FAO Paper. The K_c is determined by both ET and ET_0. The LAI of the winter wheat is maximum at the heading-milk ripening stage; hence *E* may have little influence on potential ET. High evaporative demand affects not only ET_0 but also ET. Also, the characteristics of crop variety and the form of irrigation can also have greatly influence K_c. The variation in K_c values can be shown as a function of days after sowing[32]. The relationship between K_c and days after sowing was fitted to a fourth-order polynomial equation ($R^2 > 0.75$). This equation will be useful for estimating crop water use by drip-irrigated winter wheat in arid regions. Daily K_c values exhibited a bimodal pattern with peaks about 35 and 230 days after sowing (Fig. 7).

CONCLUSIONS

Our results indicate that 600 mm irrigation was optimum for drip-irrigated winter wheat production

in Xinjiang. The K_c value was 0.96 across the entire growing season. E was about 26–28% of the winter wheat ET during the entire season. A relatively large irrigation quota and low irrigation frequency may be considered for reducing E. Similar management practices should be applicable in other arid or semi-arid areas.

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