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How can drip irrigation save water and reduce evapotranspiration compared to border irrigation in arid regions in northwest China

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ABSTRACT

Drip irrigation has been widely used in arid regions in recent years. However, how the drip irrigation technology can affect soil evaporation and crop transpiration, and whether it can save water under the sufficient irrigation condition, are still of great controversy in the world.

In order to interpret the problem, we initially conducted the comparative experiments between the drip-irrigated maize field and the border-irrigated maize field in large areas during 2014 – 2018. Evapotranspiration (ET), soil evaporation (E) and crop transpiration (T) over the drip irrigation (**DI**) and border irrigation (**BI**) treatments were continuously measured by two eddy covariance systems, micro-lysimeters and the packaged stem sap flow gauges.

Results indicate that the total maize ET over the whole crop season under the **DI** treatment was lower than that under the **BI** treatment by 4%, 16 %, 2%, 16 %, -3% in 2014, 2015, 2016, 2017 and 2018, respectively. For the whole five years, **DI** averagely decreased ET by 7% and 40 mm per year against the traditional **BI**. Compared to **BI**, **DI** reduced E by 0.1 % in 2014, 50 % in 2015, 7% in 2016, 22 % in 2017, 17 % in 2018 and 23 % (30 mm) in 2019 averagely, and shortened the growth days by 15, 23, 10, 5, and 13 days, respectively, for the whole five years.

Our research uncovered the ET decrease of DI against BI was mainly due to the significant reduction in E and growth days. In addition, the acceleration of crop growth induced by DI is a new finding and will provide an important scientific basis for interpreting the magic power of the technology and extending it to more arid regions to solve the global water and food crisis.

1. Introduction

Water scarcity poses a severe global problem to agriculture in semi-arid and arid regions that are dominated by irrigated agriculture and restrict the development of economy and agriculture, especially to smallholder farmers who cannot afford sophisticated irrigation facilities. Most farmers on these marginal lands are smallholder farmers, with the average household size less than 0.6 hm^2. Whereas Gansu Province in NW China is a typical example and has most of such farms. It is urgent to develop water-saving agriculture technology. Drip irrigation under film mulch has been a successful water-saving irrigation technology in arid regions, owing to its two advantages: drip irrigation to increase water and fertilizer efficiency (Postel et al., 2001; Vázquez et al., 2006) and film mulching to reduce water and heat loss from soil (Ramakrishna et al., 2006; Zhou et al., 2009). DI has been widely used in various crop types, including food crops (Wang et al., 2000; Hou et al., 2010; He et al., 2018) and cash crops (fruits, trees, vegetables and flowers) (Tiwari et al., 2003; Costa et al., 2007; Ibarra et al., 2007; Coelho et al., 2019; Tunc et al., 2019). In China, the technology of drip irrigation under film mulch has been extended to approximately 4.7 million hm^2 in China (He et al., 2018).

Drip irrigation under mulch could change the water-energy-nexus and have further influence on the regional eco-hydrology process (Wang et al., 2000; Coelho et al., 2019; Qin et al., 2019). Many studies have investigated the influence on ET, an important process in water cycle that links soil water and atmospheric water, of drip irrigation compared with traditional irrigation under mulch. Tiwari et al. (2003) showed that the yield of cabbage increased under drip irrigation than that of conventional furrow irrigation, even with a 40 % reduction in water use. Vázquez et al. (2006) indicated that irrigation of 80 % of ET,

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Table 1
Length of maize growth period under film mulching border irrigation (BI) with these under film mulching drip irrigation (DI) over the whole growing stage during 2014-2018.

Treatment	Year	Period	Days	Date period (Days)			
				Early growth	Middle growth		Late growth
					Rapid growth	Stable growth	
BI	2014	4/25 – 9/20	149	4/25 – 5/21 (27)	5/22 – 7/02 (42)	7/03 – 8/27 (56)	8/28 – 9/20 (24)
DI	2014	4/27 – 9/07	134	4/27 – 5/23 (27)	5/24 – 7/03 (41)	7/04 – 8/18 (46)	8/19 – 9/07 (20)
BI	2015	4/15 – 9/16	155	4/15 – 5/18 (34)	5/19 – 7/01 (44)	7/02 – 8/14 (44)	8/15 – 9/16 (33)
DI	2015	4/26 – 9/04	132	4/26 – 5/10 (35)	5/11 – 6/22 (24)	6/23 – 8/04 (43)	8/05 – 9/04 (31)
BI	2016	4/20 – 9/20	154	4/20 – 6/03 (45)	6/04 – 7/19 (46)	7/20 – 9/02 (45)	9/03 – 9/20 (18)
DI	2016	4/20 – 9/10	144	4/20 – 5/28 (39)	5/29 – 7/17 (50)	7/18 – 8/25 (39)	8/27 – 9/10(16)
BI	2017	4/27 – 9/20	147	4/27 – 6/04 (39)	6/05 – 7/08 (34)	7/09 – 9/03 (57)	9/04 – 9/20 (17)
DI	2017	4/22 – 9/10	142	4/22 – 5/27 (36)	5/28 – 7/09 (43)	7/10 – 8/22 (44)	8/23 – 9/10 (19)
BI	2018	4/17 – 9/22	159	4/17 – 5/22 (36)	5/23 – 7/04 (43)	7/05 – 9/07 (65)	9/08 – 9/22 (15)
DI	2018	4/23 – 9/15	146	4/23 – 5/20 (28)	5/21 – 6/30 (41)	7/01 – 8/22 (53)	8/23 – 9/15 (24)

calculated by the crop coefficient method, showed no reduction in crop yield during the tomato growth period, but water stress produced by deficit irrigation may increase transpiration. Hou et al. (2010) found that the mulch reduced irrigation water required by 12 % and ET by 10 % based on the water balance method in a potato field. Bai et al. (2015) indicated that the daily ET rate of cotton under plastic mulch was lower than that under the non-mulched condition. Qin et al. (2016) found that the film mulching drip irrigation lowered about 10 % total maize ET than that of border irrigation mainly by shortening the length of crop growth. Nouri et al. (2018) investigated the water-saving effect of soil mulching and drip irrigation at the catchment scale and concluded that mulching reduced the blue water footprint by 3.6 %, but mulching combined with drip irrigation reduced it by 4.7 %. Valentín et al. (2020) studied that the surface drip systems caused the seasonal maize ET reduction of 25 % and corresponding T of 30 % against sprinkler irrigation.

The previous studies above indicate that the drip irrigation can reduce soil evaporation and save water. However, these researches paid little attention to the effect of drip irrigation on crop transpiration. Under adequate water supply, the crop under drip irrigation usually yielded higher biomass, leaf area index and yield than that under border irrigation, when the same or less amount of water is used. Therefore, the crop under drip irrigation may consume more water and generate higher transpiration. Whether the drip irrigation can reduce the total evapotranspiration and how much water can drip irrigation save on a regional scale, is still of great controversy. In addition, few studies paid attention to the effect of drip irrigation on crop growth days. To answer these questions, we conducted long-term continuous measurements during 2014 – 2018 in NW China, a region where a transformation from traditional border irrigation to drip irrigation has been undertaken as a national initiative to save irrigation water, under film-mulching border irrigation (**BI**) treatment and film-mulching drip irrigation (**DI**) treatment. The study employed eddy covariance systems, micro-lysimeters, and sap flow gauges to measure evapotranspiration, soil evaporation, and crop transpiration under the BI and DI treatments, to accurately evaluate the water-saving effect of drip irrigation.

2. Materials and methods

2.1. Experimental site

Field experiments were conducted from 2014 to 2018 at the Shiyanghe Experimental Station for Water-saving in Agriculture and Ecology of the China Agricultural University (N 37°52′, E 102°50′, elevation 1581 m), which is located in Wuwei City, Gansu Province, NW China. The region was characterized as a typical temperate continental arid climate, with an annual mean temperature of 8 °C, an annual accumulated temperature (> 0 °C) of approximately 3550 °C, a mean annual pan evaporation of approximately 2000 mm, an annual precipitation of 164 mm, and an average annual duration of sunshine of 3000 h. The groundwater table in the station is 40–50 m below the ground surface (Li et al., 2013a, b; Li et al., 2015, 2016; Li et al., 2018). The experimental soil was usually silty loam at 100 cm depth. The distribution of precipitation in the region is uneven during the year, with most of the precipitation happening from July to September in summer.

The experimental area is one of the areas with the most shortage of water resources in NW China due to insufficient precipitation, excessive evaporation, and uneven distribution of precipitation every year. Growing maize under plastic mulch is the most commonly practiced cropping system in the region. In recent years, due to the development of water-saving agriculture and deteriorative regional water shortage, film-mulching drip irrigation has attracted more attention. The irrigation practice is shifting from border irrigation to drip irrigation in the experimental areas, although border irrigation is still the most common irrigation method to date. To improve and analyze local field management, the irrigation frequency and amount in our study were consistent with the local standards. The growth period of maize under DI and BI were shown in Table 1.

2.2. Experimental design

This research monitored performance of maize growth with drip irrigation under mulch (DI) and border irrigation under mulch (BI) over five years. During the five-year study, the treatment followed the local farmers' traditional planting mode. The plastic mulches were 1.2 m wide, covering 4 seed rows. The distance between neighboring mulches was 0.4 m, and the distance between seed rows under the same mulch was 0.23 m. Seeds were sown 0.3 m apart within each row. The soil type in this region is silty loam. Male maize seeds and female maize seeds were one line for male plants and several lines for female plants.

The experimental sites were shown in Fig. 1. The BI treatment is the most common irrigation method, with an area of 400 m × 200 m during 2014–2015 (Site I) and an area of 500 m × 250 m during 2016–2018 (Site II). The soil at 100 cm depth had an average soil dry bulk density of 1.52 g cm^{-3} and a field capacity of 0.29 cm^3 cm^{-3} from 2014 to 2015. In addition, the average soil dry bulk density was 1.52 g cm^{-3} and soil field capacity 0.32 cm^3 cm^{-3} at 100 cm depth in 2016 and 2018.

The DI treatment covered an area of 2000 m × 1000 m during 2014–2015 (Site III), and 400 m × 200 m from 2016 to 2018 (Site I). The soil at 100 cm depth had an average soil dry bulk density of 1.52 g cm^{-3} and a field capacity of 0.30 cm^3 cm^{-3} from 2014 to 2015. In addition, the average soil dry bulk density was 1.52 g cm^{-3} and the soil

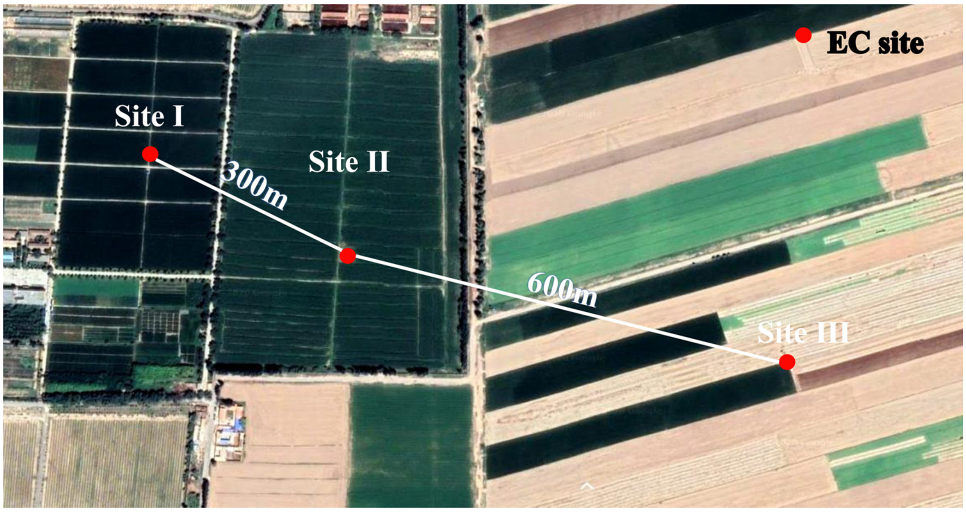


Fig. 1. Locations of the experimental sites under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment. Red dots represent the eddy covariance (EC) system.

field capacity was 0.29 $cm^3\ cm^{-3}$ at 100 cm depth during 2016 - 2018.

2.3. *Measurements in the maize field*

2.3.1. *Eddy covariance system*

The eddy covariance (EC) system has the advantages of high measurement precision and fast sampling frequency. Evapotranspiration was measured by an EC system in the central south of the maize field. Maize is the principal crop cultivated in the surrounding regions, and adequate fetch can be met for EC measurement during 2014 − 2018. The locations of EC system were shown in Fig. 1.

Site I: In 2014, there was an old EC system consisted of a 3-D sonic anemometer/thermometer (model CSAT3), a Krypton hygrometer (modelKH20), a temperature and humidity sensor (model HMP45C), a net radiometer (model NR-LITE) and two soil heat flux plates (model HFP01), as described by Li et al. (2013a, b), Li et al. (2015), 2016, and Li et al. (2018). During 2016–2018, a new eddy covariance (EC) system was installed in the site to replace the old one under the BI treatment. The new EC system consisted of a CO_2/H_2O open path gas analyzer (model EC150), two temperature and RH probes (model HMP155A), a Kipp & Zonen radiometer (model CNR4), two soil heat flux plates (model HFP01), a set of water content reflectometer (model CS616), a set of soil thermocouple probes (model TCAV), and an infrared radiometer (model SI-111). These instruments have been described by Qin et al. (2016) and Qin et al. (2019).

Site II and Site III: In Site II, the EC system was the same as the new EC system of Site I during 2015–2018. Along with change in the experiment site, the EC system of Site II was moved to Site III for data collection during 2016–2018.

In 2014, the sensors were 1.0 m above the maize canopy. During 2015 − 2018, the EC150 and CNR4 sensors were 4.0 m above the ground surface, and the HMP155A sensors were 2 m, 4 m and 6 m above the ground surface, respectively. Additionally, two HFP01 plates were installed deeper than 5 cm below the mulched soil and bare soil respectively. Five water content sensors and five soil temperature probes were set at 20 cm, 40 cm, 60 cm, 80 cm and 100 cm, respectively. The system was manufactured by Campell Scientific in USA. The 30-min energy flux data, such as the latent, sensible, radiation and ground heat fluxes were obtained from the EC system with a sampling frequency of 20 Hz.

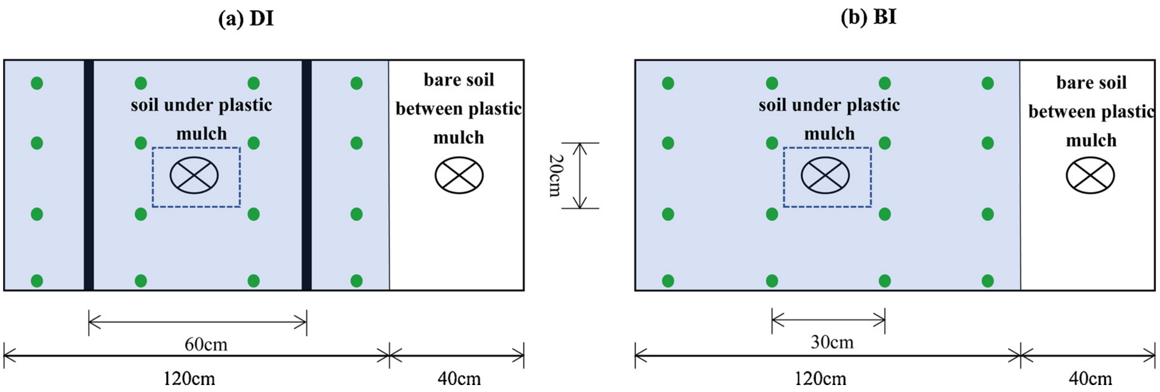
The EC flux data were collected by a CR3000 data logger, and then disposed and converted into available data (30-minute interval) with Eddy Pro 4.0 software. Due to the influences of weather and some other factors, Eddy pro software was used to assess and correct the data before further analysis. The basic procedures exercised are as follows: (1) the raw peaks detection and elimination, (2) double coordinate rotation method (Finnigan et al., 2003), (3) the correction of frequency loss, (4) the correction of air density (Webb et al., 1980). Then the software evaluated the data to remove the unreliable data. Additionally, the software estimated the footprint of EC measurement. Data taken out of the experimental area should be deleted (Qin et al., 2018). As for the missing data, the linear interpolation method was used for data gap filling when fewer than four observations were missing, and the MDV (mean diurnal variation) method was adopted when five or more observations were missing (Falge et al., 2001).

2.3.2. *Sap flow*

Stem-flow gauges (Flow32 − 1 K, Dynamax Co. USA) were used to measure maize transpiration. The probes were installed 20 cm above the ground on eight maize stems (five female plants and three male plants) and data were collected with the CR1000 data logger with a sampling frequency of 20 Hz. The sap flow and transcription rate were calculated using methods described previously by Jiang (2014). The monitored flux data ($L\ d^{-1}$) of the sap flow were firstly scaled to the specific maize transpiration ($mm\ d^{-1}$ per plant) by the mean surface area. Then the average monitored female/male maize transpiration per plant was obtained from the monitored eight plants and scaled to the field female/male maize transpiration ($mm\ d^{-1}$) using the average monitored female/male plant leaf area and the field female/male plant leaf area index, respectively (Jiang et al., 2014). The maize transpiration ($mm\ d^{-1}$) was calculated by summing the products of the female and male plant transpiration and ratios of female and male plants to the total number of plants.

2.3.3. *Soil evaporation*

The micro-lysimeter method was used to measured soil evaporation every day. The height and diameter of micro-lysimeter PVC tubes were 20 cm and 10 cm, respectively. Three micro-lysimeters were buried in the middle of mulch, and three others were set in the bare soil between mulch areas under both treatments during 2014 − 2018 (Fig. 2). All these micro-lysimeters were weighted by an electronic balance (Mettler Toledo, PL6001-L, USA) at 7:30 pm daily to get the amount of soil water evaporation per day. The average soil evaporation under mulch/ bare soil was obtained from the observed values and converted to soil evaporation under mulch/ bare soil per unit area. Then the field soil evaporation was calculated by summing the products of soil evaporation under mulch and bare soil and ratios of each part to the whole field. Previous studies considered soil water evaporation under plastic


(a) DI

(b) BI

Fig. 2. Locations of the micro-lysimeters in maize field under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment. Green dots represent the seeding holes and circular rings represents the micro-lysimeters.

mulch negligible, assuming that the plastic mulch can prevent water exchange between soil and atmosphere completely. The observations of Qin (2018) indicated that the soil water evaporation under plastic mulch (Ems) was about 4.04 – 7.07% of the total evapotranspiration, among which Ems in the daytime accounted for 3.58–5.37 % of the total evapotranspiration and 0.99–2.10 % of the total evapotranspiration in the nighttime. Thus, Ems was considered not to be negligible. These results provide support insight for our under-mulching setup of the micro-lysimeters.

2.3.4. Measurements of other experimental items

The irrigation amount was controlled by water meters. Soil water contents (SWC) were measured at 20-cm intervals along soil profiles in the range of 0–100 cm by the CS616 probes. Meanwhile, soil samples with five replications were collected at the same depths every 7–10 days to get calibration data of SWC by the oven drying method. The precipitation and wind speed at a height of 2 m were recorded by an automatic weather station (H21001, Onset Computer Crop., Cape Cod, MA, USA). The data were sampled every 5 s, and calculations were made every 15 min by a data logger. Field observation items and measurements are listed in Table 2.

2.3.5. Data interpolation

(1) Sap flow interpolation: The thermal balance system measurements have specific requirements on the thickness of the stem. Maize plants in the early stage with thinner stems are not suitable to observe the stem flow. Interpolation need to be done to obtain the variation of maize transpiration over the whole growth period. In the previous study by Li (2013) and Qin (2018), the adjusted Shuttleworth-Wallace model considering the mulching effect on evapotranspiration performed well on simulating evapotranspiration, transpiration and evaporation under the mulch condition in arid areas. This model was used to interpolate the missing transpiration data in our study. (2) Soil evaporation interpolation: When encountering continuous rainfall events and high amount irrigation events, the micro-lysimeters cannot get accurate data. By the interpolation of maize transpiration described above and EC system, we obtained evapotranspiration data and transpiration data during the whole growth period. The missing evaporation data can be obtained by subtracting transpiration from evapotranspiration on the same day.

3. Results

3.1. Comparison of evapotranspiration (ET_{BI}) under the border irrigation (BI) treatment and evapotranspiration (ET_{DI}) under the drip irrigation (DI) treatment

The daily variation of ET_{BI} and ET_{DI} during 2014 – 2018 are shown in Fig. 3. In the early growth period, the maize plant was small with extremely low degree of canopy coverage and the evapotranspiration process was dominated by evaporation. Therefore, both ET_{BI} and ET_{DI} increased as the soil evaporation increased after the rainfall or irrigation. Due to the similar meteorological conditions and growth conditions, both of ET_{BI} and ET_{DI} were close, with a relatively gentle daily fluctuation during 2014 – 2018. In the middle growth period, the maize grew rapidly. The LAI increased rapidly and then kept at a higher and more stable value for about 40 days after the rapid growth stage. Soil evaporation was gradually limited while plant transpiration gradually increased. Both ET_{BI} and ET_{DI} were gradually increased compared to the previous stage. Due to more frequent rainfall and irrigation, both ET_{BI} and ET_{DI} fluctuated greatly. There were some differences in crop growth and surface water content between BI treatment and DI treatment, which ended up with obviously higher ET_{DI} than ET_{BI} in the rapid growth stage, but the duration varied from 2014 to 2018. In the late growth period, ET_{BI} and ET_{DI} were both reduced due to senescence of crop, less radiation at the soil surface, decreased temperature, irrigation and rainfall.

For the whole growth period, we find that the total ET_{BI} was higher than total ET_{DI} during 2014–2017, and the total ET_{BI} was very close to total ET_{DI} in 2018 (Fig. 4 **(a)-(e)**). The daily ET_{DI} was equal to 0.96 ET_{BI}

Table 2
Field observation items in film-mulching border irrigation (BI) and film-mulching drip irrigation (DI).

Observation Data	Instrument	Sampling interval	Unit	Sensors	Period	Treatments
Evapotranspiration (ET)	Eddy covariance system	30 min	$mm\ d^{-1}$	KH20, USA	2014	BI
Evapotranspiration (ET)	Eddy covariance system	30 min	$mm\ d^{-1}$	EC150, USA	2015 – 2018	BI
Evapotranspiration (ET)	Eddy covariance system	30 min	$mm\ d^{-1}$	EC150, USA	2014 – 2018	DI
Meteorological Data	Meteorological Station	5 s	d^{-1}	H21001, USA	2014 – 2018	BI and DI
Leaf area index	LAI-2200			LAI-2250, USA	2014 – 2018	BI and DI
Irrigation	water meter	m^3		Rotating vane	2014 – 2018	BI and DI
Soil water content (SWC)	CS616 probes	30 min	$cm^3\ cm^{-3}$	CS616, USA	2014 – 2018	BI and DI
Soil evaporation (E)	Micro-Lysimeters	1d	$mm\ d^{-1}$	Micro-Lysimeter	2014 – 2018	BI and DI
Maize transpiration (T)	Sap-flow gauges	30 min	$mm\ d^{-1}$	Dynamax, USA	2014 – 2018	BI and DI

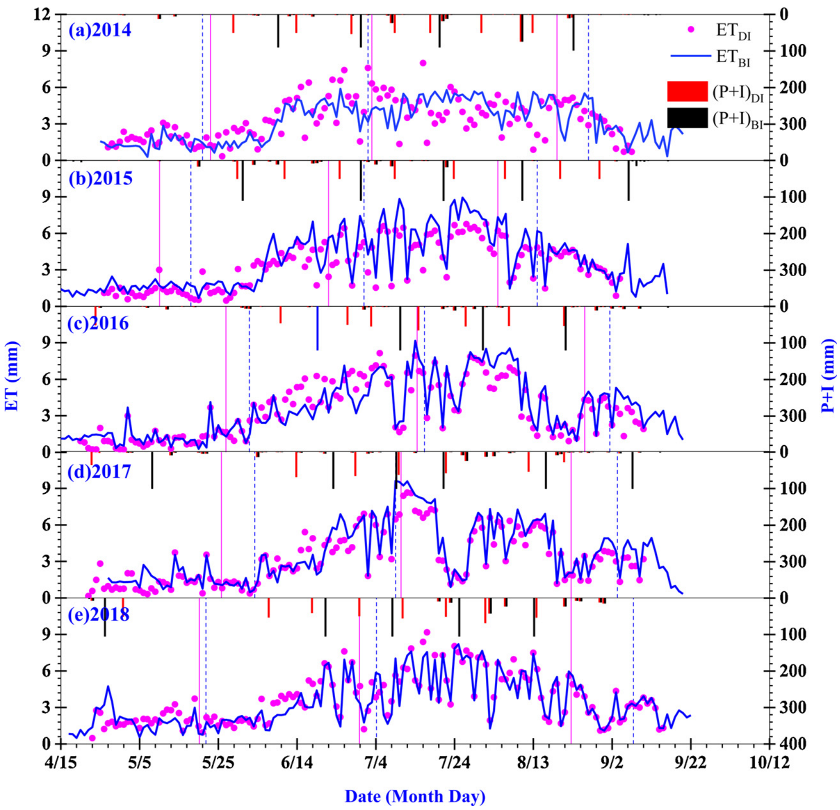


Fig. 3. Seasonal variations of evapotranspiration (ET) measured by eddy covariance system during the maize growing season from 2014 to 2018 under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment. As a reference, the precipitation and irrigation events during 2014-2018 are also presented, respectively. The vertical line in the figure is the division line of crop growth period. The full line represents DI and the dotted line represents BI.

of the five years (Fig. 4 **(f)**). Table 3 showed the total ET, average ET and daily ET rate under two treatments, respectively, during 2014−2018. With the change of the irrigation mode from film-mulching border irrigation to film-mulching drip irrigation, the annual mean ET during the whole growth stage decreased 40 mm (about 7%) and the annual mean daily ET rate decreased 0.05 mm d^{-1} during 2014−2018.

3.2. *Comparison of evaporation (E_{BI}) under the border irrigation treatment (BI) and evaporation (E_{DI}) under the drip irrigation treatment (DI)*

The daily variation of E_{BI} and E_{DI} during 2014−2018 are shown in Fig. 5. In the early growth period, the surface canopy coverage, radiation, rainfall and mulching ratio were similar under both treatments. Therefore, the evaporation of this stage was mainly affected by the irrigation events and the moisture condition of surface soil. E_{DI} of this stage was sufficiently higher than that of later stages, but E_{BI} were slightly higher than that of later stages during 2014−2018. In the

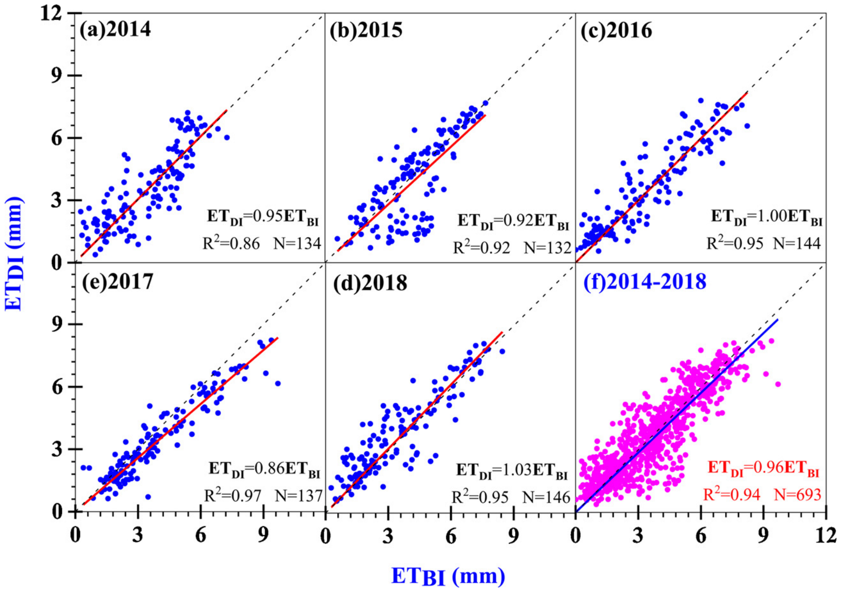


Fig. 4. Comparison of daily evapotranspiration (ET_{BI}) measured by eddy covariance system under film-mulching border irrigation (BI) treatment with daily evapotranspiration (ET_{DI}) measured by eddy covariance system under film-mulching drip irrigation (DI) treatment during 2014-2018.

Table 3
Comparison of maize evapotranspiration (ET), evaporation (E), transpiration (T), daily evapotranspiration rate, daily evaporation rate and daily transpiration rate under film mulching border irrigation (BI) with these under film mulching drip irrigation (DI) over the whole growing stage during 2014-2018.

Treatment	Year	Period	Days	ET (mm)	E (mm)	T (mm)	E/ET	Daily Rate (mm d^{-1})		
								ET	E	T
BI	2014	4/25 – 9/20	149	497	108	389	22 %	3.33	0.73	2.61
DI	2014	4/27 – 9/07	134	479	108	371	23 %	3.57	0.81	2.77
BI	2015	4/15 – 9/16	155	616	190	426	31 %	3.97	1.23	2.75
DI	2015	4/26 – 9/04	132	517	95	421	18 %	3.92	0.72	3.19
BI	2016	4/20 – 9/20	154	521	106	415	20 %	3.38	0.69	2.69
DI	2016	4/20 – 9/10	144	511	99	412	19 %	3.55	0.68	2.86
BI	2017	4/27 – 9/20	147	581	122	459	21 %	3.95	0.83	3.12
DI	2017	4/22 – 9/10	142	490	95	394	19 %	3.45	0.67	2.78
BI	2018	4/17 – 9/22	159	525	117	408	22 %	3.30	0.74	2.56
DI	2018	4/23 – 9/15	146	543	97	446	18 %	3.72	0.67	3.05
BI	Average	2014 – 2018	153	548	129	419	23 %	3.59	0.84	2.74
DI	Average	2014 – 2018	140	508	99	409	19 %	3.64	0.71	2.93

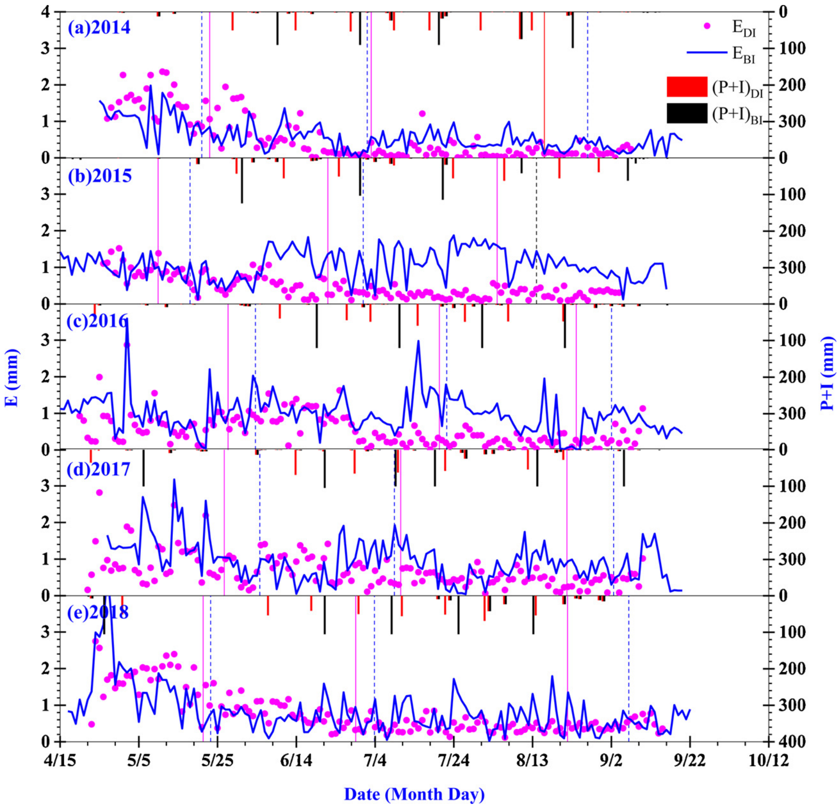


Fig. 5. Seasonal variations of evaporation (E) measured by micro-lysimeter during the maize growing season from 2014 to 2018 under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment. As a reference, the precipitation and irrigation events during 2014-2018 are also presented, respectively. The vertical line in the figure is the division line of crop growth period. The full line represents DI and the dotted line represents BI.

middle growth period, the maize grew rapidly, LAI increased rapidly, radiation enhanced, the irrigation and rainfall increased gradually. E$_{BI}$ was obviously higher than E$_{DI}$ during 2014 – 2018 due to the less frequency and more quantity irrigation traits under the BI treatment. The same observation could also be found in later growth periods due to the early end of harvest time under the DI treatment during the five years. In the late growth period, E$_{BI}$ was higher than E$_{DI}$ during 2014 – 2018 due to the lower canopy coverage at the soil surface during 2014–2016, higher soil surface water content in 2017 and longer duration under the DI treatment from 2014 to 2018.

For the whole growth period, the total E$_{BI}$ was distinctly higher than the total E$_{DI}$ during 2015 – 2018, and slightly higher than the total E$_{DI}$ in 2014 (Fig. 6 **(a)-(e)**). The daily E$_{DI}$ was equal to 0.71 E$_{BI}$ of the five years (Fig. 4 **(f)**). Table 3 has shown the total E, average E and daily E rate under the two treatments, respectively, during 2014 – 2018. With the change of the irrigation mode from film-mulching border irrigation to film-mulching drip irrigation, the annual mean E during the whole growth stage decreased by 30 mm (about 23 %) and the annual mean daily E rate decreased by 0.13 mm d^{-1} during 2014 – 2018.

3.3. Comparison of transpiration (T$_{BI}$) under the border irrigation treatment (BI) and transpiration (T$_{DI}$) under the drip irrigation treatment (DI)

The daily variations of T$_{BI}$ and T$_{DI}$ during 2014 – 2018 are shown in Fig. 7. In the early growth period, the maize began to enter the growth stage, when the LAI was very small and both T$_{BI}$ and T$_{DI}$ have small values. The diurnal variation curve of T$_{BI}$ and T$_{DI}$ fluctuated slowly upward during 2014 – 2018. In the middle growth period, with the increase of crop growth and surface canopy coverage, soil evaporation was gradually restricted and plant transpiration gradually increased. T$_{BI}$ and T$_{DI}$ were gradually increased during 2014 – 2018. At the early time, the LAI$_{DI}$ was greater than LAI$_{BI}$, but the duration varied from 2014 to 2018. The relative relationship between T$_{BI}$ and T$_{DI}$ was often corresponded to that between LAI$_{BI}$ and LAI$_{DI}$. In the late growth

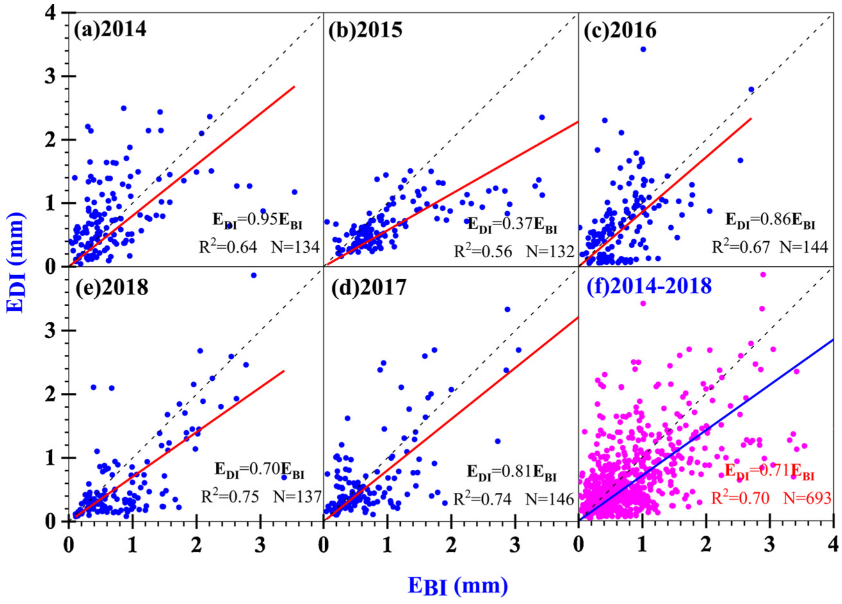


Fig. 6. Comparison of daily evaporation (E_{BI}) measured by micro-lysimeter under film-mulching border irrigation (BI) treatment with evaporation (E_{DI}) measured by eddy covariance system under film-mulching drip irrigation (DI) treatment during 2014-2018.

period, the relative relationship between T_{BI} and T_{DI} was also corresponded to that between LAI_{BI} and LAI_{DI}. T_{BI} and T_{DI} were similar and gradually decreased.

For the whole growth period, the total T_{BI} was close to the total T_{DI} during 2014 – 2018 (Fig. 8 **(a)-(e)**). The daily T_{DI} was equal to 1.00 T_{BI} of five years (Fig. 8 **(f)**). Table 3 has shown the total T, average T and daily T rate under the two treatments, respectively, during 2014 – 2018. With the change of irrigation mode from film-mulching border irrigation to film-mulching drip irrigation, the annual mean T during the whole growth stage decreased by 10 mm (about 2%) and the annual mean daily T rate increased by 0.19 mm d^{-1} during 2014 – 2018.

3.4. Comparison of the ratios of evaporation to evapotranspiration (E_{BI}/ET_{BI}) under the BI treatment and evaporation to evapotranspiration (E_{DI}/ET_{DI}) under the DI treatment, transpiration to evapotranspiration (T_{BI}/ET_{BI}) under the BI treatment and transpiration to evapotranspiration (T_{DI}/ET_{DI}) under the DI treatment

The daily variations of E_{BI}/ET_{BI} and E_{DI}/ET_{DI}, T_{BI}/ET_{BI} and T_{DI}/ET_{DI}

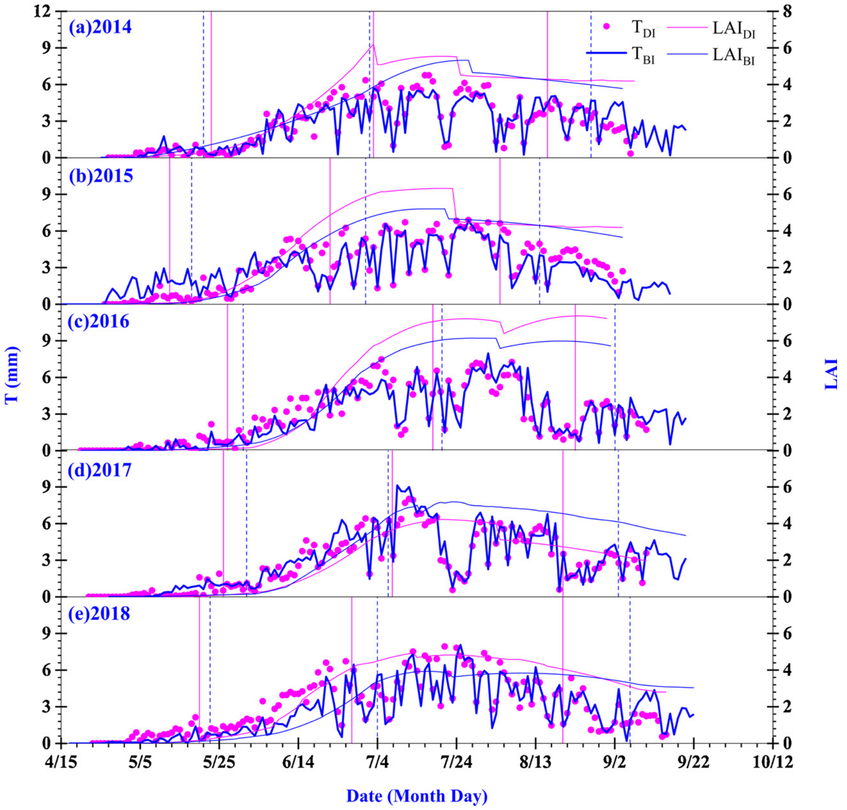


Fig. 7. Seasonal variations of transpiration (T) measured by sap flow during the maize growing season from 2014 to 2018 under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment. The leaf area index during 2014-2018 is also presented for reference, respectively. The vertical line in the figure is the division line of crop growth period. The full line represents DI and the dotted line represents BI.

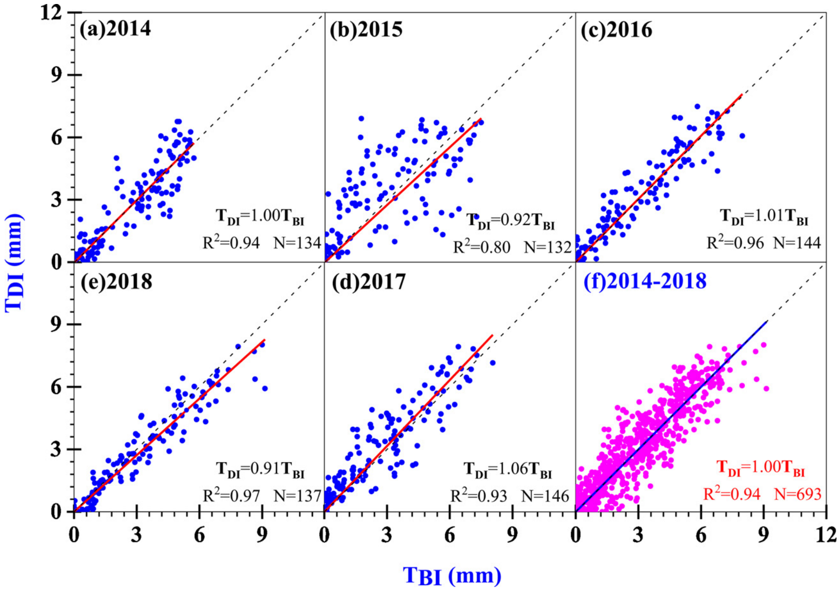


Fig. 8. Comparison of daily transpiration (T_{BI}) measured by sap flow under film-mulching border irrigation (BI) treatment with transpiration (T_{DI}) measured by eddy covariance system under film-mulching drip irrigation (DI) treatment during 2014-2018.

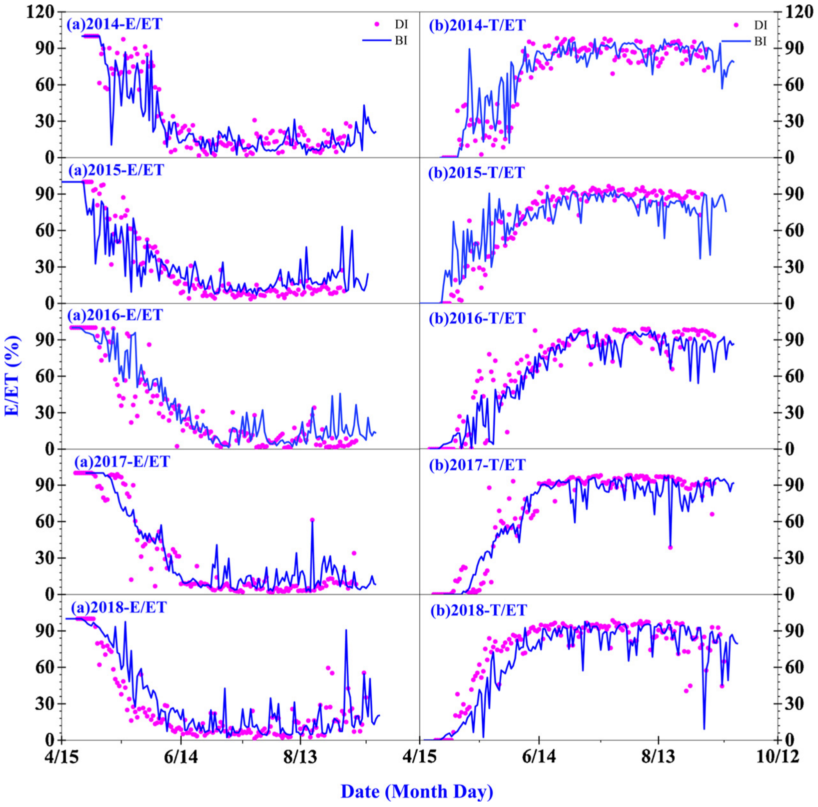


Fig. 9. Relative contribution of the evapotranspiration components to evapotranspiration under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment during 2014-2018. (a) Relative contribution of evaporation (E) to evapotranspiration (ET) and (b) Relative contribution of transpiration (T) to evapotranspiration (ET), obtained using the eddy covariance system, mico-lysimeter and sap flow method.

during 2014 – 2018 are shown in Fig. 9. Due to the relatively low coverage of the surface canopy, evaporation made the majority of evapotranspiration during the early period. The percentage of evaporation decreased as the crop was growing. The E_{BI}/ET_{BI} and E_{DI}/ET_{DI} shared a similar proportion in 2014 – 2018; T/ET under both treatments had the opposite pattern. With crop growth and increase of vegetation coverage, E/ET and T/ET gradually increased under both treatments. Then E_{BI}/ET_{BI} was distinctly larger during 2015–2017 and slightly larger in 2014 and 2018 than E_{DI}/ET_{DI} owing to the less difference in the irrigation volume under both treatments during 2014 and 2018. Finally, E_{BI}/ET_{BI} shared a larger value than E_{DI}/ET_{DI} at the end of crop growth stage during 2014 – 2018.

For the whole growth period, the daily E_{BI} /ET_{BI} was higher than the daily E_{DI} /ET_{DI} during 2014 – 2018 (Fig. 10 **(a)**). The daily E_{DI} /ET_{DI} was equal to 0.93 E_{BI} /ET_{BI} of the five years (Fig. 10 **(a)**). Inversely, the daily T_{BI} /ET_{BI} was lower than the daily T_{DI} /ET_{DI} during 2014 – 2018 (Fig. 10 **(b)**). The daily T_{DI} /ET_{DI} was equal to 1.02 T_{BI} /ET_{BI} of the five years (Fig. 10 **(b)**). Table 3 has shown E/ET under both treatments, respectively, during 2014 – 2018. With the change of the irrigation mode from film-mulching border irrigation to film-mulching drip

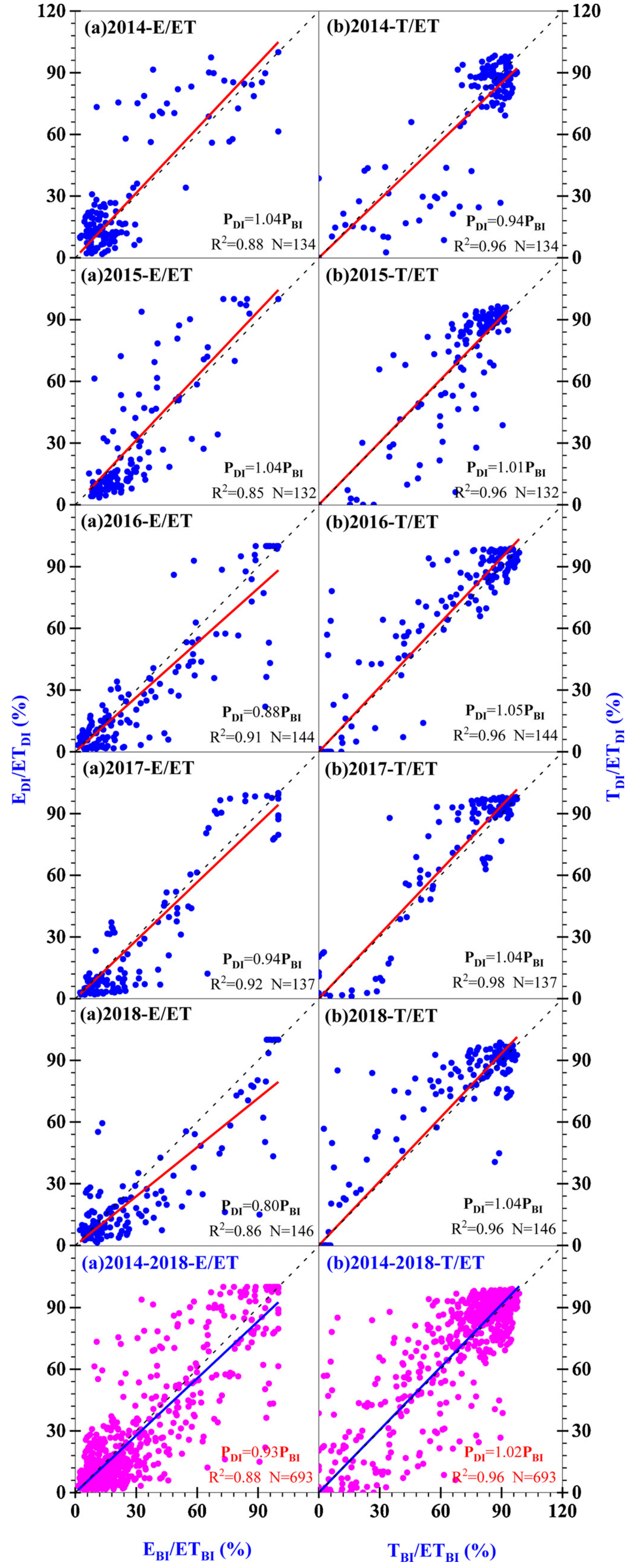


Fig. 10. Comparison relative contribution of the evapotranspiration components to evapotranspiration under film-mulching border irrigation (BI) treatment and film-mulching drip irrigation (DI) treatment during 2014-2018. (a) Comparison of relative contribution of evaporation (E) to evapotranspiration (ET) measured by eddy covariance system and mico-lysimeters. (b) Comparison of relative contribution of transpiration (T) to evapotranspiration (ET) measured by eddy covariance system and sap flow.

irrigation, the annual E/ET during the whole growth stage decreased by -0.8 % in 2014, 12.4 % in 2015, 1.1 % in 2016, 1.5 % in 2017 and 4.4 % in 2018, respectively.

4. Discussion

4.1. Why did drip irrigation reduce ET compared with the traditional border irrigation?

Results indicate that the annual mean ET_{DI} decreased by 40 mm (about 7%), where T_{DI} decreased by 10 mm (about 2%) and E_{DT} decreased by 30 mm (about 23 %) compared with those under the BI treatment over the five years (Fig. 9, Table 2). Our results confirmed that drip irrigation can averagely reduce ET by 7% on a long-term time scale and the regional spatial scale.

This can be primarily attributed to the significant reduction in soil evaporation induced by drip irrigation. This advantage was mentioned by the previous studies (Costa et al., 2007; Valentín et al., 2020). Compared with the BI treatment, the DI treatment induced a lower irrigation amount and a smaller wetting area, and the irrigation occurred under the mulching film. The plastic mulch significantly increased the water transfer resistance and severely limited the water vapor exchange between the mulched soil and atmosphere (Qin et al., 2016; Jin et al., 2018). The irrigation water in the DI treatment was more difficult permeating to the bare soil surface, which was an important place for soil evaporation.

The second reason is the significant acceleration of crop growth induced by drip irrigation. Different from the traditional BI treatment, the multi-frequency irrigation and sub-mulch fertilization under the DI treatment provided a better water and nutrition environment for plant growth (Jones, 2004; Hou et al., 2010; Bai et al., 2015; Qin et al., 2016). Zhang et al. (2020) concluded that lower water stress of DI against BI resulted in better developed crop canopy, which in turn intercepted more energy and thus increased ET. The growth days were shortened by 15 days in 2014, 23 days in 2015, 10 days in 2016, 5 days in 2017, 13 days in 2018 and average 13 days during 2014 − 2018 against the BI treatment (Fig. 11). This is caused by the higher daily temperature and less water stress under the DI treatment compared to the BI treatment (Yuan et al., 2003; Mendelsohn and Dinar., 2003; Hou et al., 2010; Qin et al., 2016).

Thus, the DI treatment decreased evaporation, accelerated crop growth and shortened the crop growth period. Though the daily average transpiration under the DI treatment may enhance, ET during the whole crop growth period can reduce, compared with that under the BI treatment.

4.2. Why was E_{DI}/ET_{DI} lower than E_{BI}/ET_{BI} during the whole growth stage

Previous studies find that different irrigation methods significantly influenced the ratio of soil evaporation to evapotranspiration (Zegada and Berliner., 2011; Zhang et al., 2013; Martins et al., 2013). Many researchers investigated E/ET under traditional irrigation and reported that E/ET might vary from 30 %-60 % (Yunusa et al., 1997; Sánchez et al., 2015; Trout and DeJonge, 2017; Valentín et al., 2020). Our results find that E/ET under the DI treatment varied from 18 % to 23 % and under the BI treatment was 20 %–31 %. This is similar with the study of Li and Ma (2019) and Rodrigues et al. (2013), who reported E accounted for 15 %–24 % of the maize ET under DI. The DI treatment reduced by -0.8 % in 2014, 12.4 % in 2015, 1.1 % in 2016, 1.5 % in 2017, 4.4 % in 2018 and average 4% during the five years. The results showed the DI treatment can improve the components ratio of ET.

Previous studies show that the rate of water loss (water leaching and E) under BI can exceed 40 % (Liu et al., 2017a; Zheng et al., 2017) compared to about 13 % under DI (Liu et al., 2017b; Umair et al., 2019). Meanwhile our study suggested that the DI treatment reduced E during the whole crop growth period compared with BI. Though ET

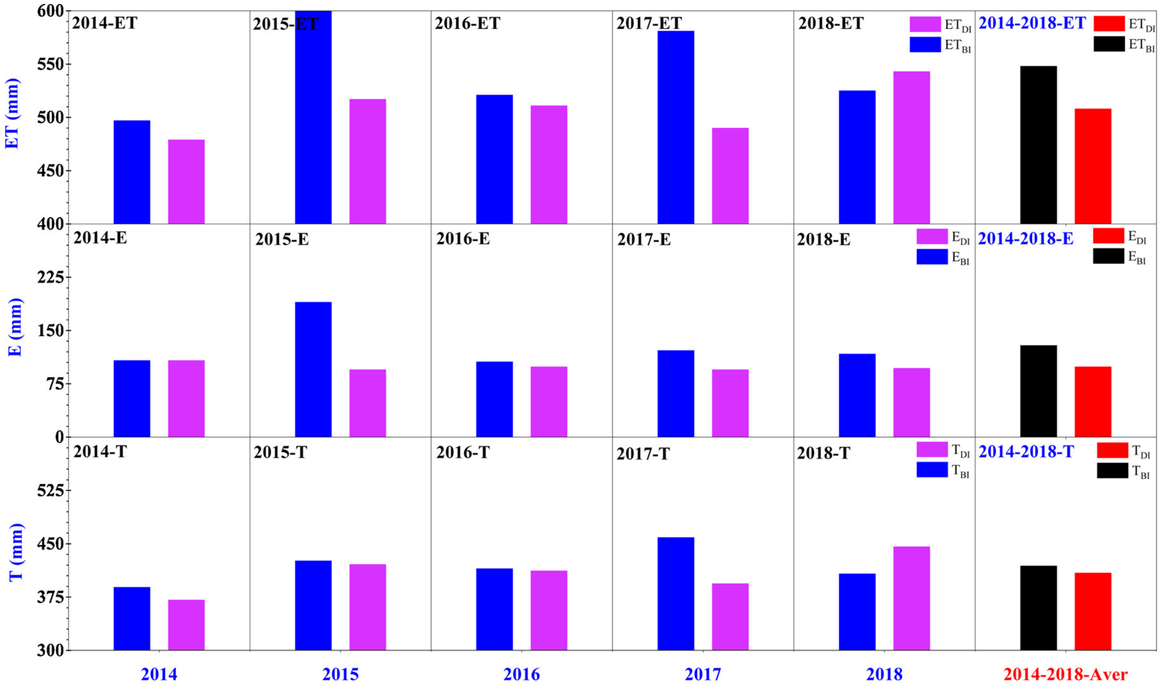


Fig. 11. Comparison of evapotranspiration (ET_{BI}), transpiration (T_{BI}) and evaporation (E_{BI}) under BI treatment with evapotranspiration (ET_{DI}), transpiration (T_{DI}) and evaporation (E_{DI}) under DI treatment during 2014-2018.

may decrease at the same time, the reduction of evaporation was greater than that of evapotranspiration. In addition, as the DI treatment accelerated crop growth, it had higher leaf area index values to capture radiation and larger daily average transpiration (Zhang et al., 2020), when compared with the BI treatment. The higher leaf area index may result in the higher surface canopy coverage, which was also attributable to the reduction in evaporation.

5. Conclusion

Based on the continuous flux measurements over the drip-irrigated and border-irrigated maize fields, we confirmed that the drip irrigation can averagely decrease soil evaporation by 30 mm and 23 %, shorten the growth days by 13 days and 9% compared with the traditional border irrigation on a five-year and regional scale. These resulted in a 7% reduction in total evapotranspiration under drip irrigation.

Here we provide an important scientific basis to explain the effects of drip irrigation on crop growth and its water saving mechanism under real field conditions over a 5-year period. With a clear advantage in crop growth, drip irrigation under mulch is anticipated to be more extensively applied in NW China and other similar regions in the world.

Declaration of Competing Interest

Author declares that no financial interest / personal relationship is considered a potential competitive advantage.

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