

RESEARCH ARTICLE

# Comparison of evapotranspiration and energy partitioning related to main biotic and abiotic controllers in vineyards using different irrigation methods

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**Abstract** Knowledge of evapotranspiration (ET) and energy partitioning is useful for optimizing water management, especially in areas where water is scarce. A study was undertaken in a furrow-irrigated vineyard (2015) and a drip-irrigated vineyard (2017) in an arid region of north-west China to compare vineyard ET and energy partitioning and their responses to soil water content (SWC) and leaf area index (LAI). ET and soil evaporation (E) and transpiration (T) were determined using eddy covariance, microlysimeters, and sap flow. Seasonal average E/ET, T/ET, crop coefficient ( $K_c$ ), evaporation coefficient ( $K_e$ ), and basal crop coefficient ( $K_{cb}$ ) were 0.50, 0.50, 0.67, 0.35, and 0.29, respectively, in the furrow-irrigated vineyard and 0.42, 0.58, 0.57, 0.29, and 0.43 in the drip-irrigated vineyard. The seasonal average partitioning of net radiation ( $R_n$ ) into the latent heat flux (LE), sensible heat flux (H) and soil heat flux (G) (LE/ $R_n$ , H/ $R_n$ , and G/ $R_n$ ), evaporative fraction (EF) and Bowen ratio ( $\beta$ ) were 0.57, 0.26, 0.17, 0.69 and 0.63, respectively, in the furrow-irrigated vineyard and 0.46, 0.36, 0.17, 0.57 and 0.97 in the drip-irrigated vineyard. The LE/ $R_n$ , H/ $R_n$ , EF, and  $\beta$  were linearly correlated with LAI. The E,  $K_c$ ,  $K_e$ , E/ET, LE/ $R_n$ , LEs/ $R_n$  (ratio of LE by soil E to  $R_n$ ), H/ $R_n$ , EF and  $\beta$  were closely correlated with topsoil SWC (10 cm depth). Responses of ET and energy partitioning to the LAI and SWC differed under the two irrigation methods. Drip irrigation reduced seasonal average E/ET and increased average T/ET. From the perspective of energy partitioning, seasonal average H/ $R_n$  increased whereas LE/ $R_n$ , especially LEs/ $R_n$ , decreased. Compared with furrow irrigation, drip irrigation decreased the proportion of unproductive water consumption thereby contributing to enhanced water use efficiency and accumulation of dry matter.

**Keywords** crop coefficient, eddy covariance, microlysimeter, sap flow, soil evaporation, transpiration

## 1 Introduction

The arid region of north-west China receives abundant solar radiation and is suitable for viticulture. However, there is little plant-available water in this region and agricultural water use has been poorly managed. Moreover, most vineyards are furrow-irrigated and this makes grape production unsustainable<sup>[1–3]</sup>. Use of drip irrigation has increased in recent years. Population growth, increased food demand and reduced water resources have all increased the importance of effective water management in arid and semiarid areas. Thus, sustainable agriculture in the region requires water-saving management and efficient irrigation methods<sup>[4–6]</sup>.

Knowledge of evapotranspiration (ET), evaporation (E) and transpiration (T), and of partitioning ET into E and T is of fundamental importance for optimizing water management in water-limited environments<sup>[7,8]</sup>. Moreover, T is beneficial water consumption or productive water use because T is associated with plant productivity whereas E is lost water (unproductive) because it does not directly contribute to plant development<sup>[7,9]</sup>. The soil surface in vineyards with widely-spaced rows forms a large proportion of total vineyard surface area and this makes E/ET relatively high<sup>[10,11]</sup>. Thus, in sparse vegetation, irrigation methods are a significant factor to consider in E. Lascano et al.<sup>[12]</sup> found T/ET to be only 0.23 in a flood-irrigated vineyard. Zhao et al.<sup>[13]</sup> reported E/ET values of 46%–62% and T/ET of 40%–43% in a furrow-irrigated vineyard. However, E/ET in a drip-irrigated vineyard was reported to be as low as 0.09, whereas T/ET reached nearly 0.91<sup>[11]</sup>. A high E/ET is unfavorable for the conservation of agricultural water, and decreasing E is also important in

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the optimization of crop water use efficiency<sup>[14]</sup>. Analysis of ET partitioning under different irrigation methods, especially in sparsely vegetated production systems such as vineyards, can indicate how much higher T/ET is under drip irrigation than under furrow irrigation. Adoption of the method will lead to increased plant accumulation of dry matter and crop water use efficiency.

The crop coefficient ( $K_c$ ) can be partitioned into the evaporation coefficient ( $K_e$ ) and the basal crop coefficient ( $K_{cb}$ ) ( $K_c = K_e + K_{cb}$ )<sup>[15,16]</sup>, both of which also reflect the ET partitioning. Numerous previous studies have demonstrated the effects of crop growth and canopy development on both  $K_c$  and  $K_{cb}$ <sup>[17,18]</sup>. However, few studies have examined the factors that influence  $K_e$ , especially in the case of sparse vegetation<sup>[13]</sup> and the influence of different irrigation methods on the response of  $K_e$  to the primary controllers. Thus, there is a need to identify the behavior of the crop coefficients using different irrigation methods in sparsely vegetated vineyards.

Energy partitioning is a key component in energy balance processes within the soil-canopy-atmosphere continuum and studying it will benefit the optimization of agricultural water use<sup>[19,20]</sup>. Various factors influence the energy partitioning of field production systems. Previous studies on vineyards show that leaf area index (LAI) and soil water content (SWC) were the two key controlling factors<sup>[20,21]</sup>. Air temperature, wind speed, vapor pressure deficit and other environmental factors, including irrigation, have also been reported to be correlated with field production system energy partitioning<sup>[10,20]</sup>, as well as in other systems<sup>[22–24]</sup>. Only a few studies have investigated the responses of energy partitioning to the LAI and SWC in production systems with sparse canopies subjected to different irrigation methods. Furthermore, in a sparsely vegetated production system with relatively high E/ET, investigation of LEs/Rn [ratio of latent heat flux (LE) by soil E to net radiation (Rn)], seems pivotal because it recognizes the transformation of radiant energy to soil latent heat as part of overall energy flux. However, few studies have investigated the factors affecting LEs/Rn in vineyards and under drip irrigation.

Here, we have compared ET and energy partitioning and their responses to the main controllers in two vineyards, one with furrow and the other with drip irrigation. The aims were to (1) investigate the differences in ET partitioning between the vineyards from the perspective of E/ET and T/ET,  $K_{cb}$  and  $K_e$  in quantity; (2) compare the responses of the ratios concerning ET partitioning to the primary controllers of the two vineyards; and (3) examine whether energy partitioning ratios respond differently to the biotic (LAI) and abiotic (SWC) factors under the two irrigation methods in order to determine a scientific basis for an irrigation program that optimizes crop water use efficiency.

## 2 Materials and methods

### 2.1 Study sites

The study sites are in the temperate zone in an arid region of north-west China (37°51' N, 102°53' E, 1585 m asl). The mean annual precipitation is 164.4 mm, annual mean temperature 8°C and total annual sunshine 3000 h. The region is very short of water, with the groundwater table below 25 m under the ground surface and the annual mean pan evaporation 1926 mm. The experiment was conducted at the Shiyanghe Experimental Station of China Agricultural University in the Shiyang River Basin. The early-ripening Merlot (*Vitis vinifera*) vineyard at Huangtai Station (which was studied in 2015) was 1650 m long by 1400 m wide. The vines were planted in 1999 in east–west rows. Row spacing was 2.7 m and plant spacing was 1 m. A vertical trellis system of three wires 0.5, 1.0 and 1.5 m high was used. The vines were trained in a bilateral cordon. The soil is a sandy loam with an average bulk density of 1.49 g·cm<sup>-3</sup> in the top 1 m of the soil profile. The saturated water content of the soil was 0.45 cm<sup>3</sup>·cm<sup>-3</sup>. The field capacity and wilting point were 0.31 and 0.11 cm<sup>3</sup>·cm<sup>-3</sup> in the top 1 m of the profile. The vineyard was furrow-irrigated five times during the growing season on April 22, May 27, June 27, July 27, and August 30 with 70 mm applied on each occasion. The early-ripening Pinot Noir (*V. vinifera*) vineyard at Mogao Station was studied in 2017. The vines were planted in 2014 in north–south rows. Row spacing was 3.3 m and plant spacing was 0.5 m. A vertical trellis system of three wires 0.4, 0.7 and 1.0 m high was used. The vines were trained in a single cordon. The soil is a loamy clay with an average bulk density of 1.67 g·cm<sup>-3</sup> and the saturated SWC was 0.38 cm<sup>3</sup>·cm<sup>-3</sup>. Field capacity was 0.22 cm<sup>3</sup>·cm<sup>-3</sup> in the top 1 m of the soil profile. The vineyard was drip-irrigated from 40 cm above the ground. The drip emitters had a discharge rate of 3 L·h<sup>-1</sup> with 40 cm between emitters. The vineyard was irrigated six times during the growing season on May 29, June 23, July 3, August 2 and 30, and September 16 with a total irrigation of 226 mm. The two vineyards are about 2 km apart.

### 2.2 Eddy covariance measurement and data correction

ET was measured in both vineyards using the same eddy covariance (EC) system in the growing seasons of 2015 and 2017. The instruments were mounted 4 m above ground level in the south-east of the vineyard and met the requirement for adequate fetch so that the ratio of the fetch to the height of installation was 100:1. The EC equipment consisted of a CSAT3 three-dimensional sonic anemometer (Campbell Scientific, Logan, UT), an LI-7500 open-path CO<sub>2</sub> and H<sub>2</sub>O gas analyzer (Li-Cor Inc., Lincoln, NE), an NR-Lite net radiometer (Kipp and

Zonen, Delft, Netherlands), an HMP45C temperature and humidity probe (Vaisala Inc., Helsinki, Finland), HFP01 soil heat flux (G) plates (Hukseflux, Delft, Netherlands), and a CR5000 data logger (Campbell Scientific). Wind speed, ultrasonic virtual temperature, and air and water vapor densities were measured every 0.1 s to obtain both latent and sensible heat observations. In 2015, two G plates were installed 5 cm below the soil surface in the ditch and on the ridge. In 2017, five G plates were installed 8 cm below in the soil surface at five points across the interrow. The sensors were connected to the CR5000 data logger and a value averaged over 30 min was recorded.

The correction of the raw EC data was conducted using EddyPro 4.2.1 (Li-Cor Inc.) in express mode. The correction comprised 30-min block averaging, time-lag compensation, statistical tests<sup>[25]</sup>, WPL density correction<sup>[26]</sup>, the planar fit coordination rotation<sup>[27,28]</sup>, correction for the ultrasonic virtual temperature<sup>[29]</sup>, spectral correction<sup>[30,31]</sup>, data quality control flags<sup>[32]</sup> and footprint analysis<sup>[33]</sup>. EC data, after correction by EddyPro, were flagged with 0 (highest quality), 1 and 2 (lowest quality). LE and sensible heat flux (H) data with flag 2 were discarded. Data gaps caused by instrument problems, power failure, data filtration and correction were filled. Short gaps ( $\leq 2$  h) were filled via linear interpolation and longer gaps ( $> 2$  h) using multiple linear regressions for the main controlling factors, Rn, LAI and SWC<sup>[34]</sup>.

The closure of the measured energy budget component for the daytime EC data was forced using the  $\beta$  forced closure method in accordance with the assumption that the  $\beta$  was correctly measured by the EC system (the daytime and nighttime were identified through T/F (daytime/nighttime) flags obtained from EC data after correction via EddyPro). Assuming that H was accurately measured, the residual-LE closure method was used for the nighttime EC data, and residual LE was calculated by the energy balance equation  $LE = Rn - G - H$ <sup>[35]</sup>. Numerous studies indicate the value of this method of data correction<sup>[13,36,37]</sup>. ET was calculated from LE after energy balance closure as  $LE = \lambda ET$ , where  $\lambda$  is the latent heat of vaporization.

Energy balance closure has customarily been used to evaluate the accuracy of EC measurements through linear regression between turbulent fluxes (LE + H) and available energy ( $Rn - G$ )<sup>[35,38]</sup>. Linear regression using 0.5 h EC data filtered and corrected by EddyPro gave gradients of 1.10 and 0.84, respectively, for the 2015 and 2017 regression equations and the corresponding coefficients of determination ( $R^2$ ) were 0.91 and 0.90. The values were within the common results from previous studies<sup>[38,39]</sup>.

### 2.3 Soil evaporation and transpiration

Daily E was measured using PVC tube microlysimeters (MLs) with an internal diameter of 10 cm and height of 20 cm. In 2015, three replicates of six MLs were used. They were pressed into the soil at distances of 0.05, 0.55,

1.05, 1.55, 2.05 and 2.55 m from the row center along a cross-section of the interrow from south to north. In 2017, six replicates of five MLs were installed at distances of 0.2, 0.5, 1.65, 2.8 and 3.1 m from the row center along a cross-section of the interrow from west to east. The tops of the MLs were deployed level with the soil surface and the MLs were weighed daily at 19:00 local time with an electronic scale with a precision of 0.1 g<sup>[13]</sup>. Daily vineyard E was calculated for both vineyards using the mean value of the daily E measured from the MLs.

A sap flow system (Flow32-1K, Dynamax, Houston, TX) was used to determine vine T. Three vines (2015) and eight vines (2017) were randomly selected in a circle with a radius of 15 m centered on the EC system. The types of sensors used were SGB 25 in 2015 and SGA 10 and 13 and SGB 16 and 25 in 2017. In 2015, the sensors were disconnected before irrigation and were reinstalled 2–3 d after furrow irrigation to prevent damage to the sensors from flooding<sup>[3,40]</sup>. Sap flow was measured every 60 s and the average over 15 min was recorded with a CR1000 data logger (Campbell Scientific, Logan, UT). Using the average ground area of each vine the sap flow ( $L \cdot d^{-1}$ ) was scaled to vine T ( $mm \cdot d^{-1}$ ) and the mean value for the monitored vines was used to calculate vineyard T<sup>[41]</sup>.

### 2.4 Leaf area index, topsoil soil water content and meteorological parameters

LAI in 2015 was estimated using the relationship between shoot length and the total leaf area per shoot described by Ortega-Farias et al.<sup>[39]</sup> for all shoots on the vine. Branches were randomly selected and the total leaf area per shoot was measured with an AM300 portable leaf area meter (ADC BioScientific Ltd., Hoddesdon, UK) at the early and intermediate growth stages. The total shoot length per vine of the selected vines was measured every 7–10 d during the experimental period. The LAI of the vineyard was calculated from the average leaf area of the selected vines and plant spacing. Details of the calculation of LAI in the furrow-irrigated vineyard are given by Zhao et al.<sup>[40]</sup>. The LAI of the drip-irrigated vineyard was measured with an LAI-2200C plant canopy analyzer (Li-Cor Bioscience Inc., Lincoln, NE) on clear days between 18:30 and 19:30 local time every 5–7 d in 2017 following the instructions for row crops<sup>[42]</sup>. Six sets of measurements were undertaken during each LAI measurement. Each set of measurements consisted of seven readings with one reading above the canopy and the other six readings below the canopy taken at consecutive positions with the line sensor parallel to the row direction, running from one row center to another adjacent row center. An estimate of seasonal canopy development including unmeasured LAI days was obtained by linear regression between successive observations.

The topsoil volumetric SWC (10 cm depth) was continuously monitored using ECH<sub>2</sub>O soil moisture

sensors (Decagon Devices, Inc., Pullman, WA) connected to EM50 data loggers (Decagon Devices, Inc.). Six (2015) and 15 (2017) sensors were used and SWC was calculated every 10 min. The mean value of the measured data was used to calculate topsoil SWC in each vineyard.

The meteorological parameters (air temperature, relative humidity, wind speed, precipitation, and solar radiation) were measured with a Hobo automatic weather station (Onset Computer Corporation, Bourne, MA, USA) located near the vineyards 2 m above the soil surface. Daily reference evapotranspiration (ET<sub>o</sub>) was calculated using the FAO Penman-Monteith equation<sup>[15]</sup>. The monthly average values of the main meteorological parameters during the 2015 and 2017 growing seasons are shown in Table 1, and Fig. 1 shows their seasonal dynamics. According to the average seasonal standardized precipitation index which was recommended for tracking meteorological drought, both of the growing seasons were classified as non-drought relative to the local climatic conditions<sup>[43]</sup>.

## 2.5 Data analysis

To estimate the seasonal variation of E/ET, T/ET, Ke, Kcb and their magnitudes during each growing stage, gaps of E and T were filled. When the daily E was available and daily T was unavailable,  $T = ET - E$  (the regression equation between the sums of observed E and T and the observed ET using EC was  $E + T = 0.92ET$  for the two growing seasons,  $R^2 = 0.50$ ,  $P < 0.001$ ). When the daily T was available and the daily E was unavailable,  $E = ET - T$ . When both the daily E and T were unavailable, E was filled using the regression between the observed daily E and Rn and the SWC (10 cm), and  $T = ET - E$ <sup>[13,44]</sup>. Missing E/ET values were calculated using interpolated E and  $T/ET = 1 - E/ET$ . The interpolated values of E and T were used only to calculate the seasonal totals and the

averages of different growing stages but were not used to analyze any correlation with the controlling factors.

The daily Kc, Ke and Kcb were calculated using values of daily ET, E, T and ET<sub>o</sub> ( $Kc = ET/ET_o$ ,  $Ke = E/ET_o$ ,  $Kcb = T/ET_o$ )<sup>[15]</sup>. The analyses of the relationships between daily E, E/ET, Ke and the governing factors were undertaken using only observed data. The daily ET, Rn, LE, H and G were calculated as the sums of the 30-min values. Daily  $\beta$  was calculated as the ratio of average daily H to daily LE.

LAI was normalized to RLAI ( $RLAI = LAI/LAI_{max}$ ) to better reflect the growing stage and facilitate the analysis of the relationships between ratios concerning energy partitioning and LAI. SWC was normalized to RSWC ( $RSWC = SWC/SWC_{sat}$ ,  $SWC_{sat}$ , i.e., the volumetric saturated SWC) to better reflect the SWC status of the two vineyards. Two-tailed significance tests were conducted using the SPSS 25.0 software package (SPSS Inc., Chicago, IL, USA).

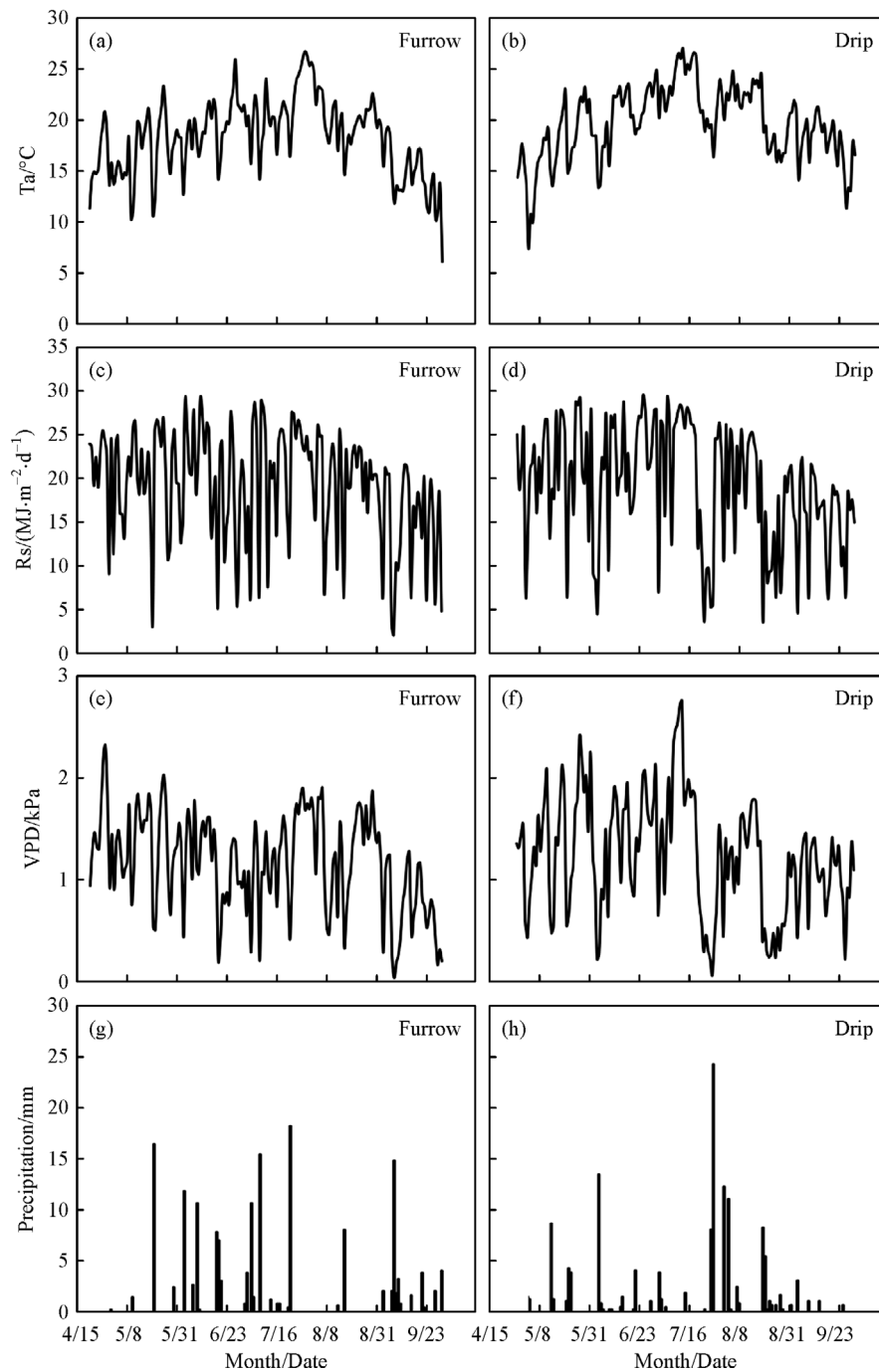
## 3 Results and discussion

### 3.1 Evapotranspiration partitioning

Figure 2 shows the seasonal variation in daily ET<sub>o</sub>, ET and LAI for the 2015 and 2017 growing seasons together with daily precipitation and irrigation. The monthly averages of these parameters are listed in Table 2. The sums of precipitation and irrigation were 512 mm (2015) and 359 mm (2017). Cumulative ET<sub>o</sub> for the growing season was 611 mm (furrow irrigation) and 609 mm (drip irrigation) and cumulative ET was 404 mm (furrow irrigation) and 339 mm (drip irrigation). The seasonal trends of daily ET were similar for the two vineyards, maintaining a relatively high value in the middle of the season and low values early and late in the season.

**Table 1** Monthly mean air temperature (Ta), solar radiation (Rs), vapor pressure deficit (VPD), monthly total precipitation (P), soil water content (SWC, 10 cm depth), and leaf area index (LAI) in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017

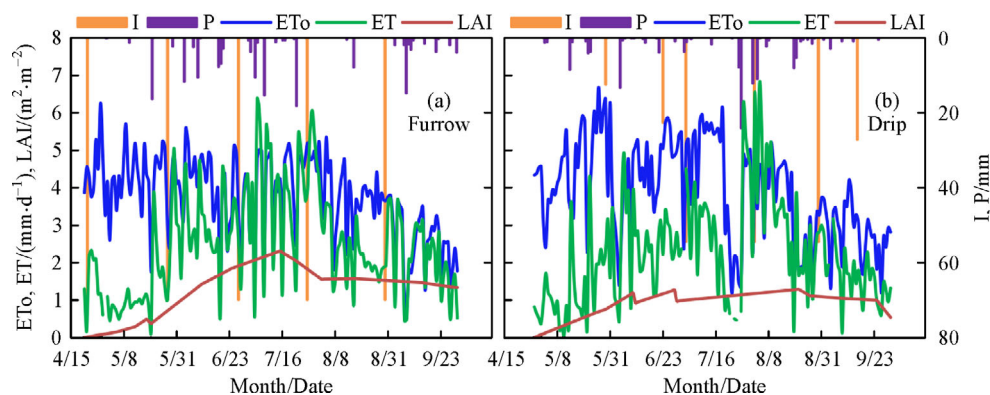
Year	Month	Ta/°C	Rs/(MJ·m <sup>-2</sup> ·d <sup>-1</sup> )	VPD/kPa	P/mm	SWC/(m <sup>3</sup> ·m <sup>-3</sup> )	LAI/(m <sup>2</sup> ·m <sup>-2</sup> )
2015	Late Apr.–May	16.58	20.42	1.38	5.10	0.13	0.31
	Jun.	19.27	19.84	1.17	43.00	0.15	1.53
	Jul.	21.02	21.18	1.22	53.40	0.15	2.05
	Aug.	20.25	19.66	1.30	8.60	0.11	1.55
	Sep.	14.52	14.07	0.71	36.40	0.14	1.43
	Late Apr.–Sep.	18.24	19.14	1.17	161.80	0.14	1.31
2017	Late Apr.–May	17.05	21.11	1.38	3.06	0.13	0.40
	Jun.	20.20	21.24	1.38	21.80	0.13	1.06
	Jul.	22.87	20.50	1.40	39.60	0.14	1.07
	Aug.	20.62	17.39	0.99	44.40	0.17	1.19
	Sep.	17.84	15.49	1.05	6.20	0.12	0.97
	Late Apr.–Sep.	19.67	19.19	1.24	133.40	0.14	0.93



**Fig. 1** Seasonal variation in daily (a, b) mean air temperature ( $T_a$ ), (c, d) mean solar radiation ( $R_s$ ), (e, f) mean vapor pressure deficit (VPD), and (g, h) total precipitation ( $P$ ) in the furrow-irrigated vineyard studied in 2015 (left) and the drip-irrigated vineyard studied in 2017 (right).

Figure 3 shows the seasonal change in the proportional ET partitions,  $E/ET$  and  $T/ET$  for both vineyards. Table 2 shows the monthly averages of these ratios. For both vineyards  $E/ET$  was higher in the early and late growth stages, and lower in the middle stage with  $T/ET$  showing the opposite trend.  $T$  was low in the early growth stage because of the small canopy, with a large proportion of

bare soil resulting in  $E/ET$  being higher than  $T/ET$ . Canopy cover ( $CC$ ), increased as the vines grew and  $T$  increased, leading to an increase in  $T/ET$ . Leaf senescence in the later part of the growing season reduced daily  $T$  and increased the proportion of bare soil, thus  $E/ET$  increased and  $T/ET$  decreased. During the first half of the growing season in the furrow-irrigated vineyard (from May 20 to July 22,



**Fig. 2** Seasonal variation in daily evapotranspiration (ET) measured by eddy covariance and reference evapotranspiration (ETo) in the furrow-irrigated vineyard studied in 2015 (left) and the drip-irrigated vineyard studied in 2017 (right). Leaf area index (LAI), irrigation (I) and precipitation (P) are shown.

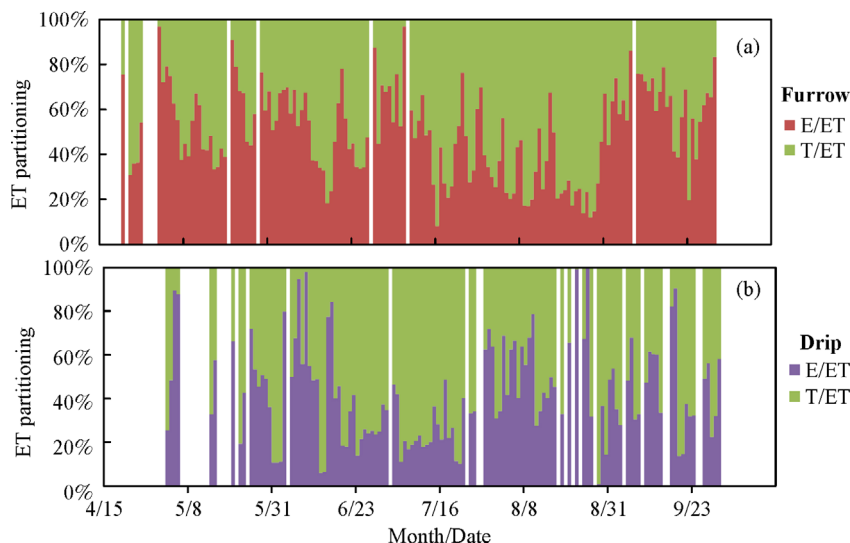
**Table 2** Monthly mean values of reference evapotranspiration (ETo), evapotranspiration (ET), evaporation (E), transpiration (T), E/ET, T/ET, crop coefficient (Kc), soil evaporation coefficient (Ke), and basal crop coefficient (Kcb) during the growing season in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017

Year	Month	ETo/(mm·d <sup>-1</sup> )	ET/(mm·d <sup>-1</sup> )	E/(mm·d <sup>-1</sup> )	T/(mm·d <sup>-1</sup> )	E/ET	T/ET	Kc	Ke	Kcb
2015	Late Apr.–May	4.23	1.42	0.96	0.53	0.56	0.44	0.34	0.21	0.15
	Jun.	3.97	2.94	1.62	1.19	0.50	0.50	0.74	0.38	0.31
	Jul.	4.16	3.96	2.07	1.59	0.49	0.51	0.92	0.47	0.38
	Aug.	3.73	2.33	0.71	1.30	0.31	0.69	0.62	0.20	0.34
	Sep.	2.46	2.08	1.26	0.74	0.62	0.38	0.82	0.51	0.28
	Late Apr.–Sep.	3.75	2.48	1.30	1.04	0.50	0.50	0.67	0.35	0.29
2017	Late Apr.–May	4.58	1.30	0.99	0.55	0.49	0.51	0.30	0.22	0.28
	Jun.	4.31	2.47	1.07	1.58	0.41	0.59	0.57	0.25	0.36
	Jul.	4.34	2.77	0.98	1.52	0.31	0.69	0.57	0.20	0.35
	Aug.	3.42	3.14	1.66	1.79	0.50	0.50	0.89	0.48	0.55
	Sep.	2.80	1.60	0.61	1.43	0.45	0.55	0.55	0.26	0.54
	Late Apr.–Sep.	3.91	2.23	1.06	1.36	0.42	0.58	0.57	0.29	0.43

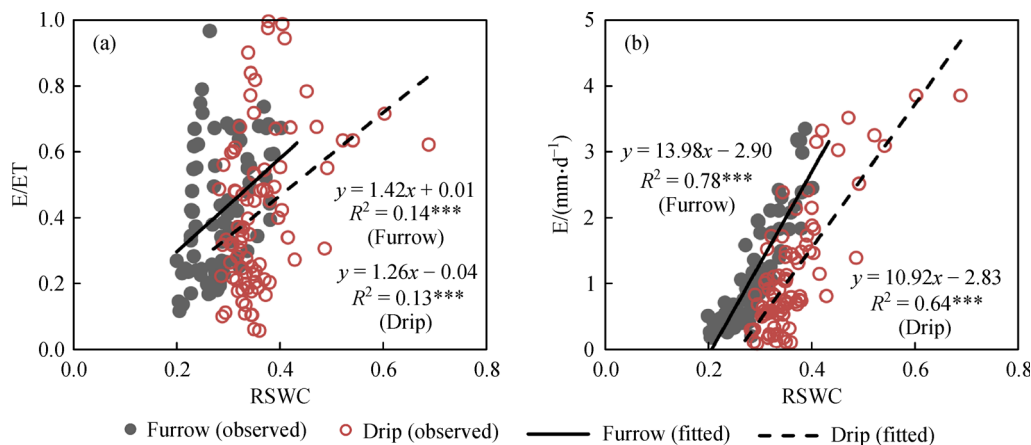
2015) E/ET was higher because of greater precipitation<sup>[13]</sup>. E/ET was higher in the drip-irrigated vineyard from late July to mid-August because of intense rain events which resulted in a greater SWC, and hence led to a higher E. The average E/ET values of the vineyards were 0.50 (furrow irrigation) and 0.42 (drip irrigation), with corresponding T/ET values of 0.50 and 0.58. Notably, the seasonal average E/ET decreased and average T/ET increased under drip irrigation. López-Urrea et al.<sup>[45]</sup> also reported that the irrigation method affected E/ET. Yunusa et al.<sup>[46]</sup> found that seasonal average E/ET was higher (0.46–0.51) than average T/ET (0.18–0.19) (T/ET of cover crops ranged between 0.30 and 0.36) for a furrow-irrigated vineyard. However, in a drip-irrigated vineyard in the same region, Yunusa et al.<sup>[47]</sup> found lower seasonal average E/ET (0.41) and higher T/ET (0.55). Moreover, for drip-irrigated vineyards E/ET was found to range from 0.09 to 0.31,

with T/ET ranging from 0.69 to 0.91 as reported by Kool et al.<sup>[11]</sup>, Teixeira et al.<sup>[16]</sup>, Poblete-Echeverría et al.<sup>[48]</sup>, Poblete-Echeverría and Ortega-Farias<sup>[49]</sup>. Kool et al.<sup>[7]</sup> reported seasonal average E/ET of  $0.41 \pm 0.21$  and T/ET of  $0.57 \pm 0.21$  for vineyards, and seasonal average E/ET of  $0.30 \pm 0.12$  and T/ET of  $0.69 \pm 0.13$  for drip-irrigated vineyards. In sparsely vegetated vineyards, E is a relatively large component of ET because of the large proportion of bare soil in the interrow. It is therefore essential to choose the irrigation method that best reduces unproductive water consumption in sparse vegetation.

Figure 4(a) shows that E/ET was linearly related to RSWC in production systems under a sparse canopy and, moreover, E/ET was higher in the furrow-irrigated vineyard than in the drip-irrigated vineyard with the same RSWC which can be explained by the differential responses of E to RSWC under the two irrigation methods



**Fig. 3** Seasonal variation in daily evapotranspiration (ET) partitioning (E/ET, T/ET) in the furrow-irrigated vineyard studied in 2015 (upper) and the drip-irrigated vineyard studied in 2017 (lower). E/ET, the ratio of soil evaporation (E) to ET; and T/ET, the ratio of transpiration (T) to ET.



**Fig. 4** Relationships between (a) E/ET and (b) E and relative soil water content (RSWC, 10 cm depth) in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017. E, evaporation; and ET, evapotranspiration. \*\*\*,  $P < 0.001$ .

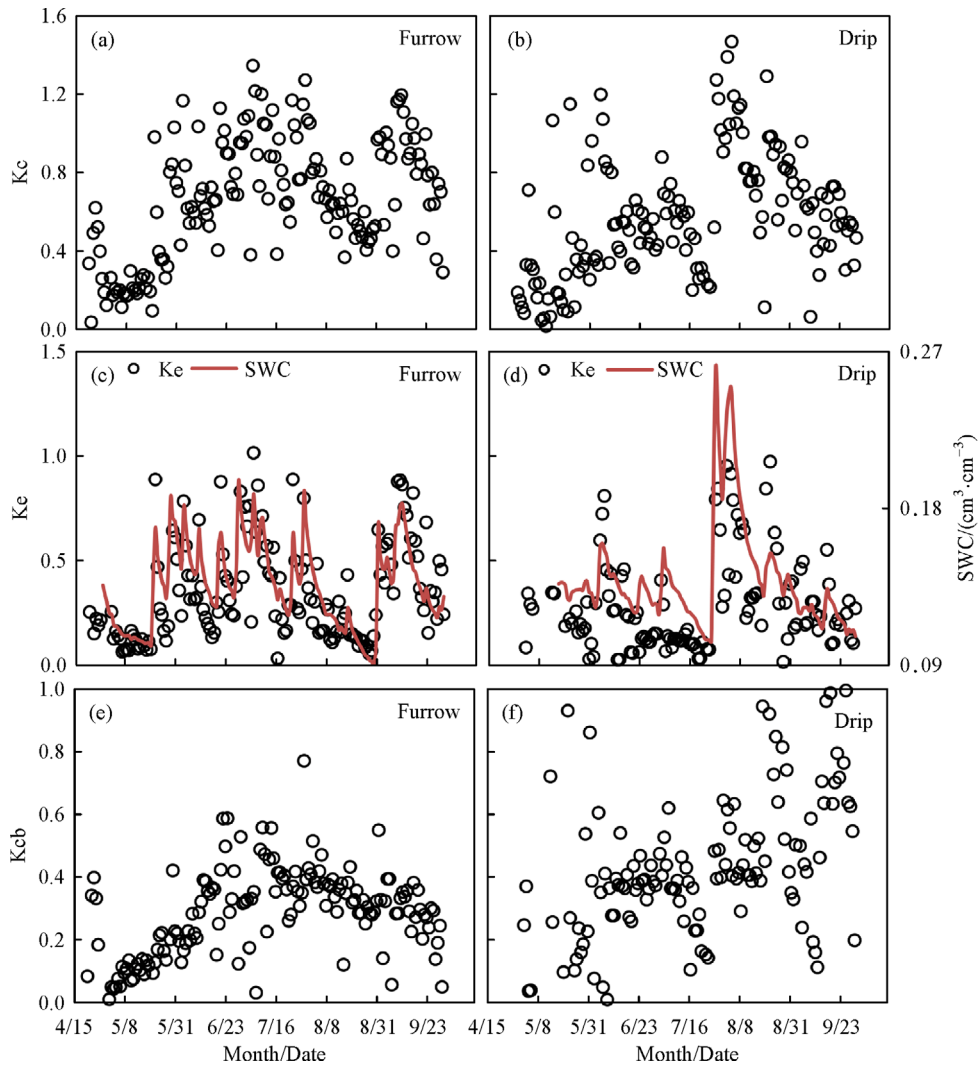
as shown in Fig. 4(b). For any given RSWC, the proportion of the soil surface that was wet was greater in the furrow-irrigated vineyard and thus E increased due to the effect of solar radiation.

It is concluded that when considering total seasonal water use, more water is used productively with T, which indicates increased plant accumulation of dry matter and increased water use efficiency in a drip-irrigated vineyard than in a furrow-irrigated vineyard. Drip irrigation also decreased the proportion of unproductive water use (i.e., E) which also reduced the non-beneficial water consumption.

### 3.2 Crop coefficient and dual crop coefficient

Figure 5 shows seasonal variation in the daily Kc (Fig. 5(a)

and 5(b)), the daily Ke and SWC (10 cm deep) (Fig. 5(c) and 5(d)), and the daily Kcb (Fig. 5(e) and 5(f)) during the two growing seasons in the furrow-irrigated vineyard in 2015 and the drip-irrigated vineyard in 2017. The monthly variation in Kc and Kcb coincided with canopy development. Kc increased abruptly in early September 2015 and in the period from late-July to mid-August 2017. The increases may be attributed to the favorable conditions for E and T during these periods as a result of more irrigation and precipitation events. The seasonal variation in Ke corresponded to the fluctuation in SWC. The average Kc for the two vineyards was 0.67 (furrow-irrigated) and 0.57 (drip-irrigated). The average Ke was 0.35 (furrow-irrigated) and 0.29 (drip-irrigated) and the average Kcb



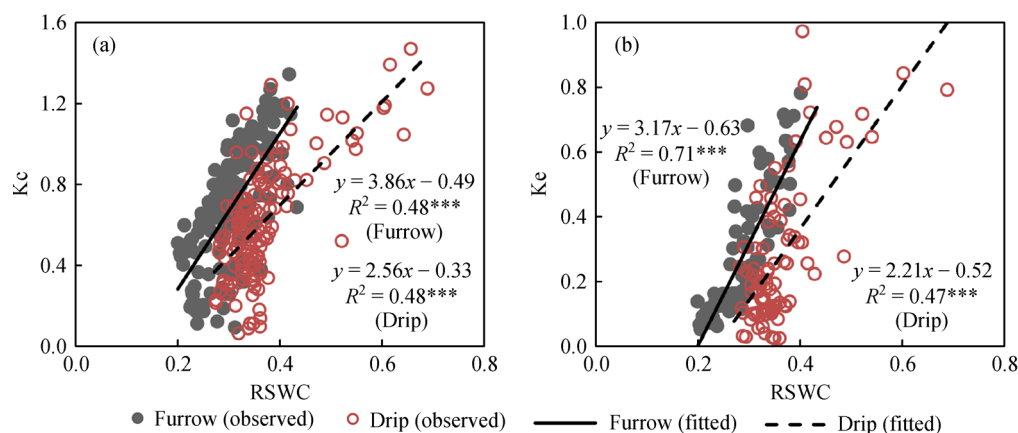
**Fig. 5** Seasonal variation in daily (a, b) crop coefficient ( $K_c$ ), (c, d) evaporation coefficient ( $K_e$ ) and topsoil soil water content (SWC, 10 cm depth), (e, f) basal crop coefficient ( $K_{cb}$ ) in the furrow-irrigated vineyard studied in 2015 (left) and the drip-irrigated vineyard studied in 2017 (right).

was 0.29 (furrow-irrigated) and 0.43 (drip-irrigated). Seasonal average  $K_e$  was larger than average  $K_{cb}$  in the furrow-irrigated vineyard but showed the opposite trend in the drip-irrigated vineyard. Lascano et al.<sup>[12]</sup> found that, due to high E, average  $K_e$  was up to 0.46 in a flood-irrigated vineyard. Teixeira et al.<sup>[16]</sup> reported an average range of  $K_{cb}$  of 0.66–0.69 but a much lower average  $K_e$  of 0.08–0.09 in a drip-irrigated vineyard in Brazil. Zhao et al.<sup>[13]</sup> reported that maximum  $K_e$  was reached after precipitation but not after irrigation as the wetted fraction of the soil was about 50% after irrigation but nearly 100% after precipitation in a furrow-irrigated vineyard. Yunusa et al.<sup>[47]</sup> found a  $K_e$  of 0.03 during a dry period (without rainfall or irrigation) and 0.26 during a wet period (irrigated days), indicating that the increased surface area of the wetted fraction of the soil, which can vary according

to irrigation method, significantly affected the proportion of E to total water consumption.

Figure 6 shows the relationship between daily vineyard  $K_c$ ,  $K_e$  and RSWC in the furrow-irrigated vineyard in 2015 and the drip-irrigated vineyard in 2017. Both  $K_c$  and  $K_e$  increased linearly as RSWC increased and  $K_e$  was more closely correlated with RSWC than  $K_c$ . Notably,  $K_c$  was greater in the furrow-irrigated vineyard than in the drip-irrigated vineyard at any given RSWC, largely due to the greater  $K_e$  in the furrow-irrigated vineyard than in the drip-irrigated vineyard at the same RSWC. This is explained by the larger soil wetted fraction in the furrow-irrigated vineyard. The differential responses of  $K_c$  and  $K_e$  to RSWC under the two irrigation methods also indicates the effectiveness of a suitable irrigation method in saving water in irrigated vineyards<sup>[50]</sup>.





**Fig. 6** Relationships between (a) daily crop coefficient ( $K_c$ ) and (b) evaporation coefficient ( $K_e$ ) and relative soil water content (RSWC, 10 cm depth) in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017. \*\*\*,  $P < 0.001$ .

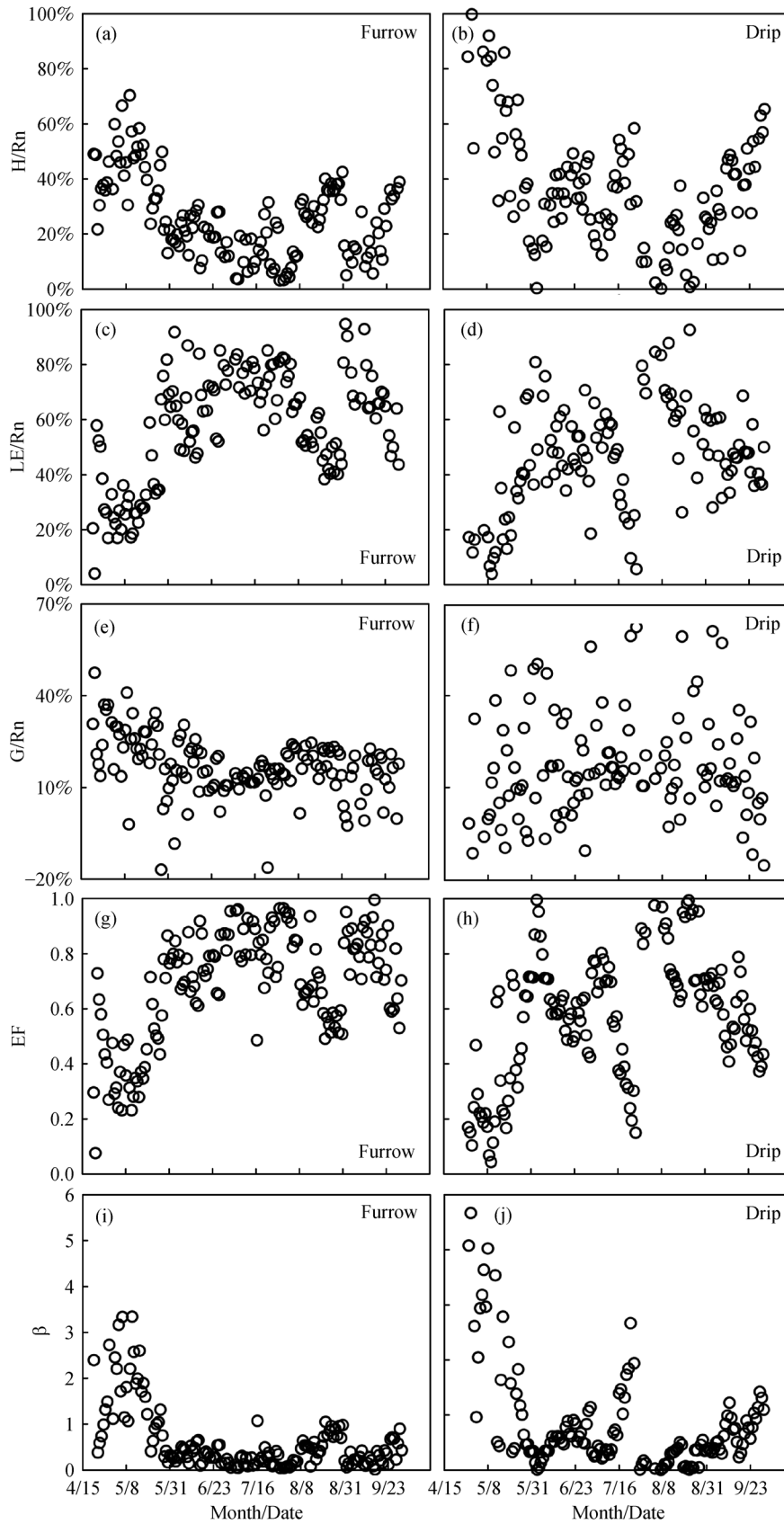
### 3.3 Energy partitioning

Figure 7 shows the seasonal variation in daily vineyard proportional energy partitioning terms  $LE/R_n$ ,  $H/R_n$ ,  $G/R_n$ , evaporative fraction (EF), and  $\beta$  in the furrow-irrigated vineyard in 2015 and the drip-irrigated vineyard in 2017. The monthly averages of these ratios are given in Table 3. Seasonal  $LE/R_n$  and EF maintained relatively high values in the middle of the season and low values early and late in the season whereas  $H/R_n$  and  $\beta$  showed the opposite trend. Seasonal  $G/R_n$  exhibited no obvious variation. Seasonal average  $LE/R_n$  was 0.57 (furrow-irrigated) and 0.46 (drip-irrigated) and average  $H/R_n$  was 0.26 (furrow-irrigated) and 0.36 (drip-irrigated). Seasonal average EF ( $EF = LE / (R_n - G)$ ) was 0.69 (furrow-irrigated) and 0.57 (drip-irrigated) and average  $\beta$  was 0.63 (furrow-irrigated) and 0.97 (drip-irrigated). Seasonal average  $G/R_n$  was 0.17 in both vineyards. The minimum monthly average  $H/R_n$  and  $\beta$  and the maximum monthly average  $LE/R_n$  and EF occurred in July (furrow-irrigated) and August (drip-irrigated) when the vines were at the high water-consuming growth stages of berry development and veraison. Greater seasonal average  $LE/R_n$  and EF values with lower  $H/R_n$  and  $\beta$  were observed in the furrow-irrigated vineyard than in the drip-irrigated vineyard. Teixeira et al.<sup>[16]</sup> reported an  $LE/R_n$  of 78%–83% and an  $H/R_n$  of 18% in two growing seasons in a drip-irrigated vineyard in Brazil, and a higher  $LE/R_n$  of 87%–91% and lower  $H/R_n$  of 12% in a microsprinkler-irrigated vineyard due to a more moist microclimate and soil conditions which were suitable for ET. Yunusa et al.<sup>[47]</sup> reported that  $H/R_n$  was 55% during a six-day warm dry period and 49% during a six-day cool humid period in a drip-irrigated vineyard in Austria and that EF was higher during cool humid days because of the greater availability of soil water. Kool et al.<sup>[11]</sup> reported an  $H/R_n$  of 42%,  $LE/R_n$  of 44%, and  $G/R_n$  of 3% in a drip-irrigated vineyard. The results further indicate that energy partitioning differed under different moisture conditions

which could be induced by different irrigation methods, and drip irrigation resulted in a lower proportion of LE and higher proportion of H to the available energy than in the furrow-irrigated vineyard.

### 3.4 Biotic and abiotic control of energy partitioning

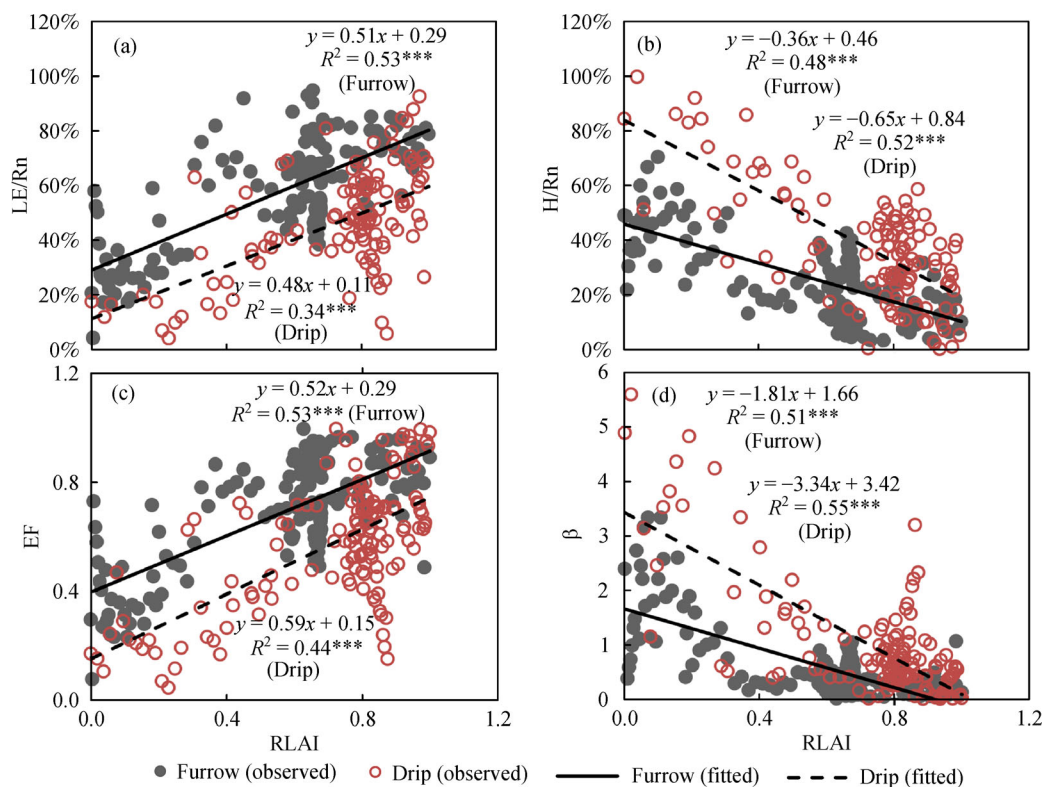
Figure 8 shows the relationship between energy partitioning terms  $LE/R_n$ ,  $H/R_n$ , EF,  $\beta$  and RLAI in the furrow-irrigated vineyard in 2015 and the drip-irrigated vineyard in 2017. There were strong linear correlations between  $LE/R_n$ ,  $H/R_n$ , EF,  $\beta$  and RLAI.  $LE/R_n$  and EF increased as RLAI increased whereas  $H/R_n$  and  $\beta$  decreased with rising RLAI. At a given RLAI,  $LE/R_n$  and EF were lower whereas  $H/R_n$  and  $\beta$  were higher in the drip-irrigated vineyard than the corresponding values in the furrow-irrigated vineyard, indicating that a greater proportion of  $R_n$  was partitioned into LE in the furrow-irrigated vineyard. Numerous previous studies find a robust relationship between energy partitioning terms and LAI. Zhao et al.<sup>[20]</sup> showed that CC was a major factor determining energy partitioning and that LAI explained 41% of the seasonal variation in energy partitioning. Shen et al.<sup>[51]</sup> found a positive correlation between EF and LAI in a winter wheat-summer maize rotation in Luancheng, Hebei Province, China. Burba and Verma<sup>[22]</sup> reported a linear correlation between  $ET/R_n$  and LAI when there was no water stress and that  $ET/R_n$  increased as LAI increased in a tallgrass prairie and cultivated wheat production system in Oklahoma in the United States. A linear correlation between EF and LAI was reported by Li et al.<sup>[23]</sup> above a grazing steppe in central Mongolia. Hammerle et al.<sup>[24]</sup> reported that in a mountain grassland in Austria, both  $LE/R_n$  and  $H/R_n$  were closely correlated with LAI, and before LAI reached around 4–5  $m^2 \cdot m^{-2}$   $LE/R_n$  increased with increasing LAI and this was attributed to increasing topsoil conductance comprising contributions from both the soil surface and the canopy conductance, and



**Fig. 7** Seasonal variation in the proportional daily energy partitioning H/Rn, LE/Rn, G/Rn, EF, and  $\beta$  in the furrow-irrigated vineyard studied in 2015 (left) and the drip-irrigated vineyard studied in 2017 (right). LE/Rn, H/Rn, and G/Rn are the partitioning of net radiation (Rn) into latent heat flux (LE), sensible heat flux (H) and soil heat flux (G). EF, evaporative coefficient; and  $\beta$ , Bowen ratio.

**Table 3** Monthly mean energy fluxes of net radiation (Rn), latent heat flux (LE), sensible heat flux (H), and soil heat flux (G), proportional energy partitioning H/Rn, LE/Rn, G/Rn, evaporative fraction (EF) and Bowen ratio ( $\beta$ ) in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017

Year	Month	Rn/(MJ·m <sup>-2</sup> ·d <sup>-1</sup> )	LE/(MJ·m <sup>-2</sup> ·d <sup>-1</sup> )	H/(MJ·m <sup>-2</sup> ·d <sup>-1</sup> )	G/(MJ·m <sup>-2</sup> ·d <sup>-1</sup> )	H/Rn	LE/Rn	G/Rn	EF	$\beta$
2015	Late Apr.–May	8.75	3.19	3.55	2.02	0.41	0.35	0.23	0.45	1.49
	Jun.	10.25	6.65	2.10	1.51	0.20	0.65	0.15	0.76	0.34
	Jul.	11.50	8.96	1.28	1.26	0.13	0.75	0.12	0.84	0.21
	Aug.	9.23	5.28	2.40	1.55	0.27	0.55	0.18	0.69	0.52
	Sep.	6.34	4.69	1.26	0.39	0.20	0.68	0.12	0.79	0.30
	Late Apr.–Sep.	9.20	5.60	2.21	1.39	0.26	0.57	0.17	0.69	0.63
2017	Late Apr.–May	8.74	3.03	5.68	0.04	0.59	0.29	0.11	0.35	2.23
	Jun.	10.12	5.54	3.40	1.19	0.32	0.51	0.17	0.64	0.62
	Jul.	10.10	5.61	3.00	1.49	0.31	0.45	0.25	0.57	0.90
	Aug.	9.14	7.11	1.25	0.78	0.16	0.64	0.20	0.81	0.26
	Sep.	6.88	3.42	2.79	0.67	0.39	0.46	0.15	0.57	0.84
	Late Apr.–Sep.	9.00	4.91	3.27	0.81	0.36	0.46	0.17	0.57	0.97



**Fig. 8** Relationships between proportional daily energy partitioning LE/Rn, H/Rn, EF,  $\beta$  and relative leaf area index (RLAI) in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017. LE/Rn and H/Rn are the partitioning of net radiation (Rn) into latent heat flux (LE) and sensible heat flux (H). EF, evaporative coefficient; and  $\beta$ , Bowen ratio. \*\*\*,  $P < 0.001$ .

H/Rn decreased with increasing LAI, possibly induced by the decreased surface relative to the air temperature because of the vigorously transpiring canopy. Qiu et al.<sup>[19]</sup> obtained similar results with greenhouse-grown hot peppers under drip irrigation in north-west China, with

lower LE/Rn and higher H/Rn than the corresponding ratios under furrow irrigation and both LE/Rn and H/Rn were correlated with LAI. In the present study, the difference in LE/Rn between vineyards may be ascribed largely to the LE values. The lower soil wetted fraction in

the vineyard under drip irrigation might give lower LEs/Rn and thus lower LE/Rn. Higher H/Rn under drip irrigation might result from the greater temperature difference between soil and air than in the vineyard receiving furrow irrigation.

Figure 9 shows the relationships between daily vineyard proportional energy partitioning terms LE/Rn, LEs/Rn, H/Rn, EF,  $\beta$  and RSWC (10 cm deep) in the furrow-irrigated vineyard in 2015 and the drip-irrigated vineyard in 2017. LE/Rn, LEs/Rn and EF increased with increasing RSWC. At any given RSWC, LE/Rn, LEs/Rn and EF were lower under drip irrigation than under furrow irrigation, indicating that a smaller fraction of Rn was partitioned into LE and LEs in the drip-irrigated vineyard. H/Rn and  $\beta$  decreased as RSWC increased, and the main factor might

be more moist soil conditions, leading to a smaller difference between the soil surface temperature and the air temperature. Furthermore, at any given value of RSWC, H/Rn and  $\beta$  were higher under drip irrigation possibly because the SWC of the bare soil in the interrow was lower and thus there was a greater discrepancy between the soil surface temperature and the air temperature (data not shown). Kool et al.<sup>[11]</sup> reported that LE/Rn and H/Rn responded strongly to irrigation in a drip-irrigated vineyard, with highest LE/Rn and lowest H/Rn values occurring on irrigated days followed by a decrease in LE/Rn and an increase in H/Rn, showing that SWC influenced energy partitioning. Baldocchi et al.<sup>[21]</sup> found that water status influenced stomatal behavior and thus regulated energy partitioning and that SWC explained 32%

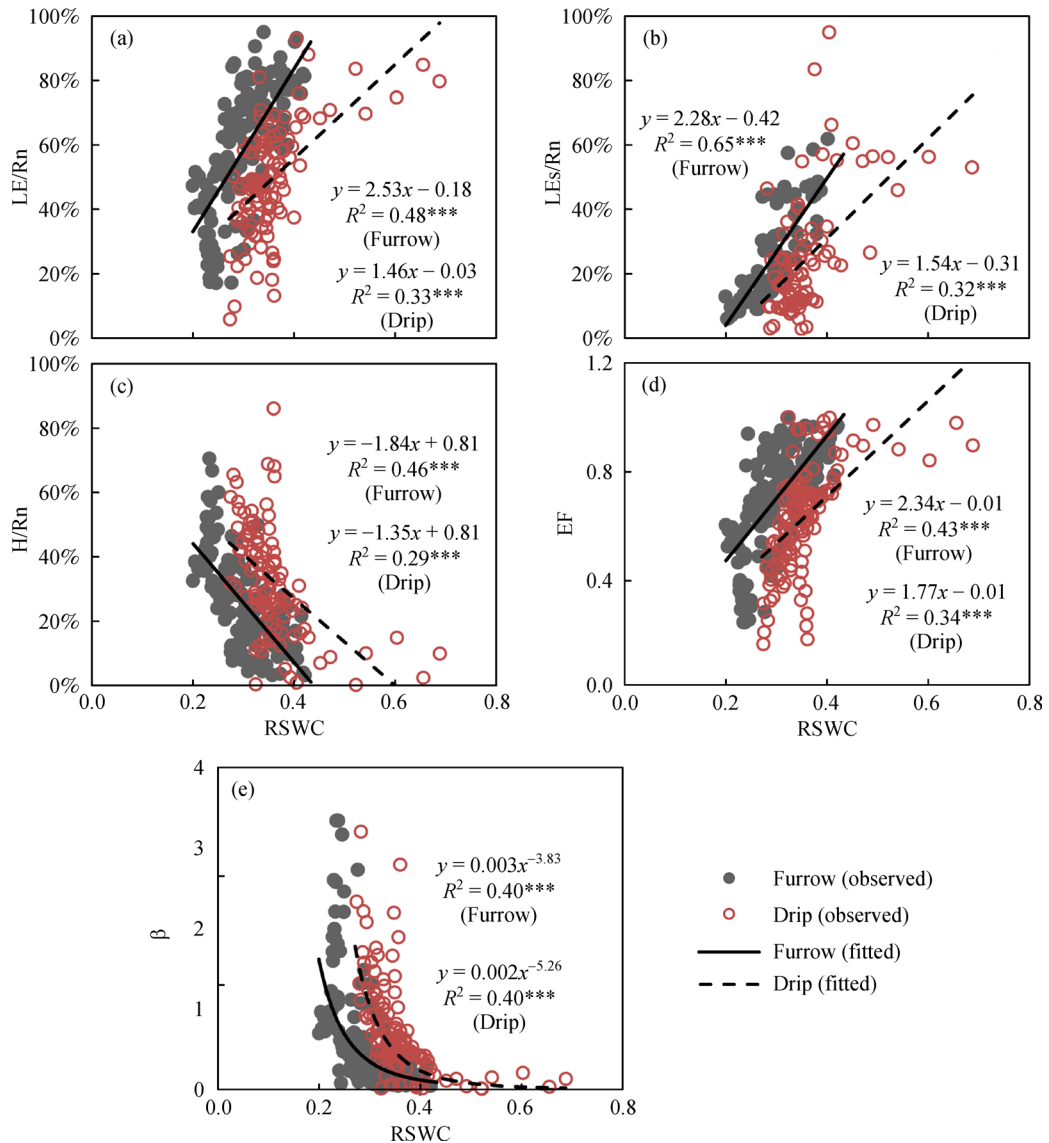


Fig. 9 Relationships between proportional daily energy partitioning LEs/Rn, LE/Rn, H/Rn, EF,  $\beta$  and relative soil water content (RSWC, 10 cm depth) in the furrow-irrigated vineyard studied in 2015 and the drip-irrigated vineyard studied in 2017. LEs/Rn, LE/Rn, and H/Rn are the partitioning of net radiation (Rn) into the latent heat flux by soil evaporation (LEs), latent heat flux (LE) and sensible heat flux (H). EF, evaporative coefficient; and  $\beta$ , Bowen ratio. \*\*\*,  $P < 0.001$ .

of the seasonal variation in energy partitioning. Zhao et al.<sup>[20]</sup> reported that SWC explained 32% of the seasonal variation in energy partitioning in a furrow-irrigated vineyard. Burba and Verma<sup>[22]</sup> reported a positive correlation between ET/Rn and SWC under water stress in a native tallgrass prairie and cultivated wheat production system in Oklahoma in central USA. They further suggested that the influence of SWC on ET/Rn decreased as CC developed. Li et al.<sup>[23]</sup> found that EF increased with increasing SWC and further demonstrated that the soil received most rainfall and returned to the atmosphere as E and T, indicating that energy partitioning was strongly correlated with SWC, an effect also observed in the present study. Hammerle et al.<sup>[24]</sup> reported that energy partitioning was influenced by SWC; low SWC induced stomatal closure, leading to a decrease in latent heat which was often compensated for by an increase in sensible heat. The present study also confirms the strong correlation between energy partitioning and SWC and further indicates that furrow and drip irrigation can produce differences in energy partitioning in sparsely vegetated vineyards.

## 4 Conclusions

Here, we have made continuous measurements of ET, E and T to compare ET and energy partitioning, crop coefficients, and the main factors that control them in a furrow-irrigated vineyard and a drip-irrigated vineyard. The results show that drip irrigation reduced seasonal average E/ET and increased average T/ET. Daily Kc and Ke were linearly correlated with RSWC. Kc and Ke were lower in the drip-irrigated vineyard than in the furrow-irrigated vineyard at the same RSWC. Seasonal average Kcb was larger than Ke under drip irrigation but showed the opposite trend under furrow irrigation. The findings indicate that the irrigation method influenced ET partitioning and drip irrigation was favorable in increasing water use efficiency in a sparsely vegetated vineyard.

LE/Rn, H/Rn, EF, and  $\beta$  were determined by RLAI and RSWC. Daily LE/Rn and EF were lower whereas H/Rn and  $\beta$  were higher in the drip-irrigated vineyard than in the furrow-irrigated vineyard at the same value of RLAI. The positive linear correlations between LE/Rn, LEs/Rn, EF and RSWC and the lower values of these ratios at the same RSWC in the drip-irrigated vineyard together indicate that drip irrigation resulted in less unproductive water use compared to furrow irrigation.

This study highlights the importance of using drip irrigation, especially in production systems with sparse canopies in arid regions. Longer observation periods in the same field using different irrigation methods in future studies would provide further insights into this important topic in arid agricultural environments.

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This article does not contain any studies with human or animal subjects performed by any of the authors.

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