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Research paper

Seasonal variations in vineyard ET partitioning and dual crop coefficients correlate with canopy development and surface soil moisture

Peng Zhao, Shaozhong Kang*, Sien Li, Risheng Ding, Ling Tong, Taisheng Du

Center for Agricultural Water Research in China, China Agricultural University, Beijing, 100083, China

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ABSTRACT

The challenge of partitioning evapotranspiration (*ET*) components and figuring out the main factors controlling *ET* partitioning was addressed over four seasons in a furrow-irrigated vineyard located in northeast China. Based on the directly measured vineyard *ET* and its components (soil evaporation *E* and plant transpiration *T*) using eddy covariance, microlysimeters and sap flow sensors, respectively, dynamics and controlling factors of *ET* partitioning and dual crop coefficients were studied. The seasonal cumulative *ET* was 399, 398 and 392 mm, where *E* was 185, 245 and 224 mm, *T* was 173, 167 and 158 mm, and *E* + *T* was 358, 412 and 382 mm, in 2013, 2014 and 2015, respectively. Seasonal average *E* represented about 52–59% of *E* + *T* and *T* about 41–48% of *E* + *T*. Seasonal *ET* partitioning was mainly controlled by surface soil water content (*SWC*) and leaf area index (*LAI*). Previous studies have found *T*/*ET* was correlated to *LAI* using regression functions. In this study a more biophysically robust model to estimate *ET* partitioning from *LAI* and *SWC* is proposed, based on dual crop coefficient theory. The evaluation of the proposed model indicated that 46% of the vineyard *ET* partitioning was explained. Soil evaporation coefficients (K_e) were closely correlated to *SWC* and peaked after rain and irrigation (even exceeding 1.0), and basal crop coefficients (K_{cb}) were mainly correlated to *LAI*. The average K_{cb} was 0.12, 0.31, 0.40, 0.42, 0.31 and 0.18 from May to October, respectively.

1. Introduction

Increasing population and food demands and diminishing water resources in arid and semiarid regions warrant using water efficiently in agriculture. Hexi Corridor in northwest China, one of the largest agricultural production areas in China, is a severe water shortage region. However, most of the farmlands in this region were irrigated with water pumped from the groundwater or diverted from the rivers, resulting in a decline of water level and rivers drying up (Kang et al., 2017). In recent years large areas of wine grape were planted in this area (20533 ha in 2015, accounting for 11.8% of the total in China; the data was from the Annual report of the development situation of the wine industry in the world and China and Gansu province: http://www.gsjye.com/show.asp?id=2864), while most of them were furrow-irrigated with low water use efficiency (*WUE*) (Zhang et al., 2011). Different from dense planting crops, the vineyards have wide row spacing and soil makes up the largest proportion of the surface area. Thus soil evaporation (*E*) can be a substantial source of total evapotranspiration (*ET*) (Kool et al., 2014a). Compared with drip-irrigated vineyards where water is used more efficiently (with *E*/*ET* ranging from 0.09 to 0.31) (Fandiño et al., 2012; Ferreira et al., 2012; López-Urrea et al., 2012; Poblete-Echeverría et al., 2012; Cancela et al., 2015; Kool et al., 2016; Williams and Fidelibus, 2016), larger amounts of water are evaporated from soil when furrow-irrigation is applied (with *E*/*ET* about 0.48) (Zhang et al., 2010; Zhang et al., 2011). Thus there is a need for in-depth research about *ET* partitioning into soil evaporation and transpiration components for making reasonable irrigation strategies and improve *WUE* for furrow-irrigated vineyards.

Different functions within agriculture system and distinct contributions to crop production of *E* and plant transpiration (*T*) require separate study of individual components of farmland water loss: *T* is associated with plant productivity, while *E* does not directly contribute to plant production (Agam et al., 2012; Kool et al., 2014a). Many studies about *ET* partitioning in vineyard have been conducted, including direct measurements of *ET* components using several instruments, such as combining sap flow sensors (SP) and microlysimeters (MLY) with the Bowen ratio

* Corresponding author.
E-mail address: kangsz@cau.edu.cn (S. Kang).

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energy balance (BREB) technique (Yunusa et al., 2004; Zhang et al., 2011), combining SP and/or MLY with the eddy covariance system (Poblete-Echeverría et al., 2012; Poblete-Echeverría and Ortega-Farias, 2013), and using the weighing lysimeter covered with a waterproof canvas to eliminate soil evaporation (Montoro et al., 2016), and also indirect methods using models, such as the dual crop coefficients approach (Fandiño et al., 2012; López-Urrea et al.,2012), the Shuttleworth–Wallace model (Zhang et al., 2009; Zhao et al., 2015), and the below canopy energy balance approach (Kool et al., 2016). The processes and controlling factors of water loss from soil surface and canopy are different: soil evaporation is a physical process while transpiration is a physiological process. Both *E* and *T* are controlled by atmospheric evaporative demand, and *T* is also highly correlated with vegetation (leaf area index *LAI* or canopy cover *CC*), while *E* is highly correlated with surface soil water content (*SWC*) (Mitchell et al., 2009; Zhang et al., 2011; Raz-Yaseef et al., 2012; Jiang et al., 2016). Thus factors affecting *T* and *E* both have influences on *ET* partitioning. However, most previous studies paid more attention to the effects of vegetation on *ET* partitioning, mainly by generating regression functions between canopy size (*LAI* or *CC*) and *T*/*ET* or *E*/*ET* (Kang et al., 2003; Kato et al., 2004; Wang et al., 2010; Zhang et al., 2013; Wang and Yamanaka. 2014; Yan et al., 2015; Villegas et al., 2015; Gong et al., 2017; Wu et al., 2017). And it is not clear to what extent that *ET* partitioning is controlled by surface soil water content, though *SWC* has a strong control on soil evaporation, especially for sparse vegetation. Thus this study is aimed at establishing a quantitative biophysical robust function between vineyard *ET* partitioning and controls (*LAI* and *SWC*), to provide a better way to interpret and model the *ET* partitioning.

In order to implement an effective irrigation strategy, grapevine water requirements should be known. Measuring crop *ET* and relating it to reference crop evapotranspiration (ET_0) is the customary procedure to determine crop coefficients (K_c) for irrigation management (López-Urrea et al., 2012). For sparse vegetation, K_c can be separated into two different components, one related to plant transpiration (K_{cb}), and another that quantifies soil evaporation (K_e) (Wright, 1981, 1982; Allen et al., 1998). The K_c value changes during the growing season with plant growth and canopy development, with plants age and mature, and with soil water content fluctuates (Allen et al., 2007). Many studies reported that vineyard K_c and K_{cb} are highly correlated with parameters that characterize crop canopy, such as leaf area index, canopy cover, normalized difference vegetation index (NDVI) and the percent of shaded area (Williams and Ayars, 2005; López-Urrea et al., 2012; Er-Raki et al., 2013; Hochberg et al., 2016; Kool et al., 2016; Montoro et al., 2016; Williams and Fidelibus, 2016). While soil evaporation coefficients (K_e), which represent a large proportion of water loss in the vineyard, little research has been conducted. Anderson et al. (2017) studied seasonal variations of K_e at three irrigated agricultural sites, reporting that K_e decreased with increasing crop age, cover, and residue deposition on the ground, but made no quantitative assessments. Kool et al. (2016) recently reported seasonal variations of K_e in a drip-irrigated vineyard and explored the responses of K_e to irrigation events. Quantitative relationships between soil moisture and K_e are not yet clear, and how is K_e affected by canopy development also needs to be considered. To explore the biophysical controls on K_{cb} and K_e, it is necessary to relate them to the canopy parameters and soil moisture conditions.

The validity of a combination of sap flow sensors and microlysimeters to partition *ET* was evaluated and demonstrated by many studies, including vineyards (Heilman et al., 1994; Trambouze et al., 1998; Yunusa et al., 2004; Zhang et al., 2011; Ferreira et al., 2012; Poblete-Echeverría et al., 2012), maize filed (Jara et al., 1998; Ding et al., 2013; Jiang et al., 2016), cotton field (Ham et al., 1990; Agam et al., 2012; Colaizzi et al., 2012), olive orchards (López-Olivari et al., 2016), peach trees (Paço et al., 2011), and apple trees (Gong et al., 2007; Liu et al., 2012). A study was conducted in a furrow-irrigated vineyard in northwest China during four growing seasons based on direct measurements of evapotranspiration and its components by eddy covariance system, sap flow sensors, and microlysimeters, to (a) quantify vineyard *ET*, *T* and *E*; (b) explore the seasonal variations of *ET* partitioning (*E*/*ET*, *T*/*ET*) in terms of controlling factors (*SWC* and *LAI*) and establish a biophysical function between *T*/*ET* and controls; and (c) explore the seasonal dynamics of dual crop coefficients (K_{cb}, K_e) and controlling factors. The results of present work are expected to provide useful information for optimizing vineyard irrigation schedules and managing grapevine canopy growth, reducing water use (especially soil evaporation) and improving water use efficiency, and also providing useful information in developing models for *ET* partitioning.

2. Materials and methods

2.1. Study site

Measurements of evapotranspiration, sap flow, and soil evaporation were taken during the growing seasons in 2012–2015 in a flat and uniform Merlot (*Vitis vinifera* L.) vineyard with a length of 1650 m and a width of 1400 m, located in northwest China (37°52′ N, 102°50′ E, 1585 m a.s.l.). The experimental site is located in a continental temperate zone, with a mean annual precipitation of 164.4 mm, annual temperature of 8 °C and annual sunshine duration of over 3000 h. Water is in severe shortage in this region, the groundwater table is below 25 m, and the mean annual pan evaporation is about 2000 mm. The vineyard soil texture is sandy loam, with an average bulk density of 1.47 g cm^{-3} and field capacity of 0.28 cm^3 cm^{-3} to a depth of 1.6 m. The soil properties were determined by digging one trench (1m*1m) along one row of the vineyard at 20 cm intervals in the vertical direction in the position of ridge and furrow, respectively, then the soil samples were collected in the cutting ring and the physical properties were analyzed in the lab. Vineyard row orientation was approximately east-west, with 2.7 m distance between rows. The vines were planted 1.0 m apart in 1999 and the shoots were maintained on a vertical plane by three iron wires (at 0.5, 1.0 and 1.5 m height, respectively) supported by a 1.5 m high trellis system (Zhang et al., 2011). The vineyard was furrow irrigated with a trapezoid ditch on the north side of each row, with depth, bottom width and surface width of about 30, 90 and 100 cm, respectively (Fig. 1a). The wetted area by furrow irrigation was about 50%. The irrigation quota is about 70 mm each time, and irrigation dates during the experimental periods were: May 4, May 25, June 28, and August 26 in 2012; April 27, May 25, July 1, July 30, August 25 and October 13 in 2013; April 22, May 25, July 2, August 4, August 31 and October 18 in 2014; April 22, May 27, June 27, July 27, August 30 and October 15 in 2015. Except for 2012 when the experiment was from late May to early September, the experimental periods covered the whole vine growing season (from bud-break in late April to senescence in middle October) from 2013 to 2015.

2.2. Measurement set-up

2.2.1. Vineyard evapotranspiration

The energy balance of the vineyard including *ET* was measured by an eddy covariance system (Campbell Scientific Inc., USA) located in the northwest of the vineyard and upwind fetch of the prevailing wind direction was 600 m (Li et al., 2015). Net radiation (model NR-LITE, Kipp & Zonen, Delft, Netherlands) was measured at 4.0 m height between rows facing the south. Wind speed, ultrasound virtual temperature, the densities of atmosphere

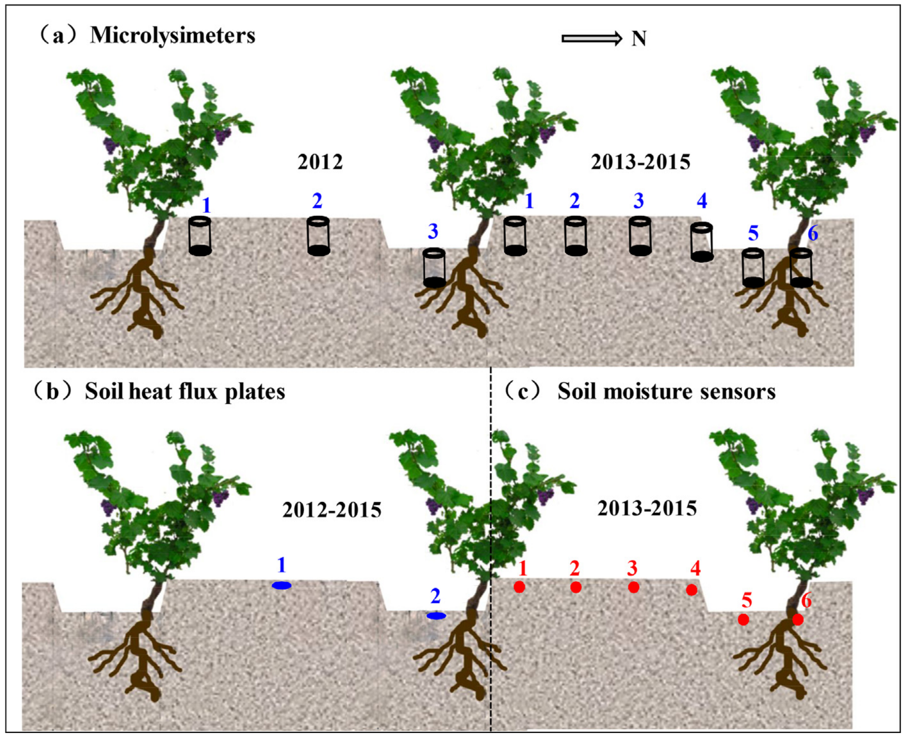

Fig. 1. A sketch of (a) the cross-section between two rows and the layout of microlysimeters, (b) soil heat flux plates and (c) soil moisture sensors from 2012 to 2015.

and water vapor were measured by a CSAT3 three-dimensional sonic anemometer (Gill Instruments, UK) and an open-path H2O & CO_2 analyzer (Li-Cor Inr., USA, Model LI-7500) every 0.1 s to obtain latent and sensible heat above the canopy at 4.0 m height. Soil heat flux (G) was calculated as an average value of two plates (Model HFP01, Hukseflux, Netherlands) placed at 5 cm below the soil surface in the ditch and ridge, respectively (Fig. 1b). All probes were connected with a data logger (model CR5000, Cambell Scientific, USA) and averages were computed in 30 min.

The procedures for correcting eddy covariance measurements included the planar fit method for coordinate rotation (Paw et al., 2000; Finnigan et al., 2003) and density correction according to Webb et al. (1980). Directly measured latent and sensible heat fluxes were excluded on rainy days and filled by regression functions with main controlling factors (R_n, LAI and SWC). Other gaps due to instrumental problems and power failure were also filled to calculate daily and seasonal energy fluxes. The short gaps ($\leq$2 h) were filled with linear interpolation, and longer data gaps (>2 h and <24 h) were filled using the mean diurnal average method (Falge et al., 2001), and gaps exceeding 24 h were filled by regression functions with controlling factors. Finally, the percentage of the half-hourly data (latent and sensible heat fluxes) that was gap-filled was 6.6% in 2012–2015.

2.2.2. Plant transpiration and soil evaporation

Grapevine transpiration was determined using a sap flow system (Flow32–1 K system, Dynamax, Houston, TX, USA). Eight vines from 2012 to 2014 were selected near the eddy covariance system to measure sap flow, while there were only three vines in 2015 because of instrument failure of sap flow sensors. And the grapevines selected to install sap flow sensors were different in each year, to prevent permanent damage to the vine trunks. The types of sap flow sensors were SGB19 and SGB25. Grapevine trunk diameters for sap flow measurements ranged in diameter from 1.71 to 3.40 cm, with an average diameter of 2.50 cm. Since another alternative method was not available to determine vine transpiration simultaneously in this study, it was impossible to calibrate the measurements of sap flow system. But Zhang et al. (2011) found that the sum of T measured by sap flow without calibration and E measured by MLS was very close to ET estimated by the BREB method in the same vineyard, demonstrating the applicability of sap flow for measuring grape water use in this region. And Zhao et al. (2015) also found that the sum of T measured by sap flow and E measured by MLS was very close to hourly and daily ET estimated by the EC method in the vineyard. Also Qiu et al., (2015) evaluated the good performance of the sap flow sensors by comparing the measured values with the simulated transpiration in a greenhouse hot pepper. Irrigation may result in flooding and damage the sensors, so the sensors were disconnected before irrigation and reinstalled within 2–3 days after irrigation (Zhang et al., 2011). The sap flow rate was measured every 60 s and recorded as 15-min averages with a CR1000 data logger (Cambell Scientific, USA). Sap flow (L d^{-1}) was scaled to tree transpiration (mm d^{-1}) using the average ground area of each vine (2.7*1.0 m, representing the distance of trees between row and within row, respectively), and the vineyard transpiration was averaged from all the monitored trees (Heilman et al., 1994).

Daily soil evaporation was measured by 18 micro-lysimeters (MLs) made of PVC tubes with 10-cm inside diameter and 20-cm depth from 2013 to 2015, while by 9 MLs in 2012. In 2012 three replicates of three MLs each was installed at three different positions: in the irrigation furrow's bottom and the shaded and non-shaded portions of the un-wetted furrow (Fig. 1a). In 2013–2015 three replicates of six MLs each were deployed level with the soil surface along a cross section of the interrow at distances from the row center of 0.05, 0.55, 1.05, 1.55, 2.05, 2.55 m from south to north (Fig. 1a). Previous studies reported that regular reinstallation of micro-lysimeter (MLY) to minimize the difference between soil moisture inside and outside the tubes was needed (Boast and Robertson, 1982). Thus in present study one replication (6 MLYs) was reinstalled every 3–5 d from April 30 to July 6 in 2013, and compared with three unchanged replications (18 MLYs). The difference between two methods was smaller ($E_{reinstalled} = 1.02E_{unchanged} - 0.11$, $R^2 = 0.89$, 49 *observations*), thus the unchanged micro-lysimeters were used (Zhao et al., 2015). Finally, the daily *E* was obtained from total nine (2012) and eighteen (2013–2015) MLs by weighing them using an electronic scale with a precision of 0.1 g at 19:00 local time every day.

2.2.3. Soil moisture, canopy and climate factors

Volumetric soil water content at a depth of 10 cm below the soil surface was continuously monitored from 2013 to 2015 using six soil moisture sensors (5TM Soil Moisture & Temperature Sensor, Decagon Devices, Inc. USA) across the interrow (Fig. 1c). Then the data were collected every 10 min using a data-logger (EM50, Decagon Devices Inc. USA), and the average *SWC* was calculated from the six sensors.

Leaf area per tree was estimated using a function of the length with total leaf area per shoot of all the shoots on the tree (Ortega-Farias et al., 2007). We selected 73 shoots samples and measured the total leaf area (TLA) and length of each shoot, and then obtained the relationship between TLA and length of the sampled shoots. Then we measured the length of all the shoots on eight sampled trees every 7–15 days in each year and then the average leaf area index was calculated. Details of the calibration of the model and calculation of vineyard *LAI* in our study were interpreted in Zhao et al. (2015). Linear interpolation was applied for the days in between the days of shoot length measurements to obtain a seasonal course of canopy development. Regular pruning of vine canopy to keep them under control and produce good fruit yields were needed throughout the growing season in present study. Once canopy pruning occurred, the area of pruned leaves was measured, and *LAI* after pruning was also measured to capture the sudden decrease of the vineyard leaf area index.

To determine the extinction coefficient of light attenuation (*C*), we measured the diurnal courses (every 1 h) of photosynthetically active radiation (*PAR*) above the canopy and near soil surface across the interrow using SunScan System (Channel Technology Group Limited, UK) on several sunny days from late August to early October in 2014 (with *LAI* ranged between 1.4 and 2.2 $m^2\,m^{-2}$). However, there was no significantly correlation between daily average *C* and canopy size ($C = 0.326 - 0.01 * LAI$, $n = 10$, $R^2 = 0.01$, $P = 0.82$). Thus we adopted the average value of observed *C* (0.322) for the whole growing seasons.

All climatic parameters (solar radiation, air temperature, relative humidity and wind speed) needed to calculate daily reference evapotranspiration (ET_0) by the FAO-Penman Monteith equation (Allen et al., 1998) and precipitation were measured by a standard automatic weather station (Hobo, Onset Computer Corporation, CapeCod, Massachusetts, USA) at a height of 2.0 m above the ground over a standard reference surface (alfalfa), about 3 km from the vineyard.

2.3. Data analysis

The sum of latent and sensible heat fluxes ($LE + H$) should equal to the vineyard available energy ($R_n - G$), but energy balance closure is seldom achieved with *EC* system due to systematic underestimation of turbulent fluxes and misses of absorbed energy in the system (Wilson et al., 2002). In the present study, energy balance closure was evaluated by linear regression of half hourly turbulent fluxes ($LE + H$) against $R_n - G$, and the intercept, slope, and R^2 (determination coefficient) were 24.75 $W\,m^{-2}$, 0.90 and 0.88, respectively. The values were within the common results found in previous studies (Wilson et al., 2002; Li et al., 2005). Twine et al. (2000) reported that the error of turbulent fluxes was the primary reason for *EC* underestimation and suggested that adjusting measured turbulent fluxes was necessary using the Bowen-ratio forced closure (BRFC) method. In the same region, both Ding et al. (2010) in a maize field and Li et al. (2008) in a vineyard demonstrated the necessary of the BRFC adjustment. Thus in this study, we forced closure with the BRFC approach reported by Twine et al. (2000) to adjust the original half hourly latent and sensible heat fluxes.

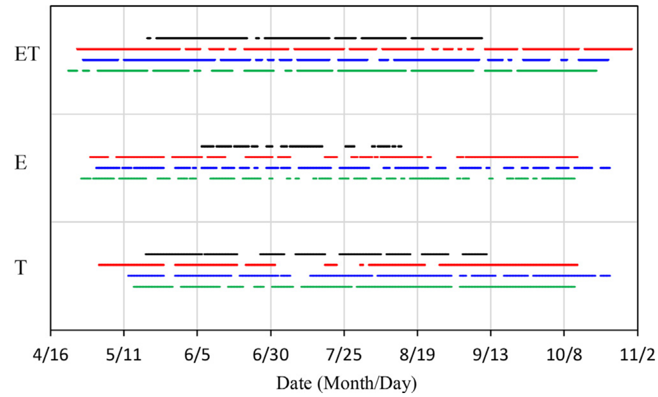

Fig. 2. Measurements dates of vineyard evapotranspiration (*ET*) by eddy covariance, transpiration (*T*) by sap flow sensors and soil evaporation (*E*) by microlysimeters in 2012 (dark line), 2013 (red line), 2014 (blue line) and 2015 (green line), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Parameters of the relationship between vineyard daily soil evaporation (E, mm d^{-1}) as a function of volumetric soil water content (*SWC*, at 10 cm depth, $cm^3\,cm^{-3}$) and daily average net radiation flux (R_n, $W\,m^{-2}$) in 2013–2015.

$E = a + b * \exp(c * SWC) + d * R_n$						
a	b	c	d	R^2	N	p
−0.828	0.080	20.25	0.007	0.799	331	<0.0001

R^2 is the determine coefficient; N is the number of observations; p is the p-value for statistical hypothesis testing.

To calculate the proportion of daily transpiration to vineyard evapotranspiration (*T*/*ET*), the following strategies were adopted: when *T* was directly measured by sap flow sensors, *T*/*ET* were used and *ET* was obtained from the eddy covariance system after the BRFC adjustment; when *T* was not directly measured while *E* was directly measured by microlysimerers, $(ET - E)/ET$ were used; while when both directly measured *E* and *T* were not available, *T*/*ET* was unavailable.

The daily soil evaporation coefficient (K_e) and basal crop coefficient (K_{cb}) was calculated as the ratio of directly measured daily soil evaporation and transpiration to daily reference evapotranspiration (ET_0) (Allen et al., 1998).

The measurement periods of the vineyard *ET*, *E* and *T* obtained directly by eddy covariance system, microlysimeters, and sap flow sensors in 2012–2015 were presented in Fig. 2, respectively. Previous studies reported that soil evaporation (*E*) was mainly controlled by the surface soil water content (*SWC*) and net radiation (R_n) (Mitchell et al., 2009; Raz-Yaseef et al., 2010; Zhang et al., 2011; Raz-Yaseef et al., 2012; Kool et al., 2014b; Jiang et al., 2016; Kool et al., 2016). Thus in this study, the gaps of missing daily *E* without direct microlysimeters measurements were filled by multiple regression between daily directly measured *E* and R_n, *SWC* in 2013–2015 (Table 1). Similar functions of gap-filling soil evaporation based on *SWC* and radiation fluxes were also reported and demonstrated by Raz-Yaseef et al. (2010) in a semi-arid pine forest. Then the gaps of missing daily *T* without sap flow measurements were filled by the difference between daily *E* and *ET* ($T = ET - E$), to estimate the seasonal total grapevine transpiration. Note that the interpolated *E* and *T* values were only used in calculating seasonal

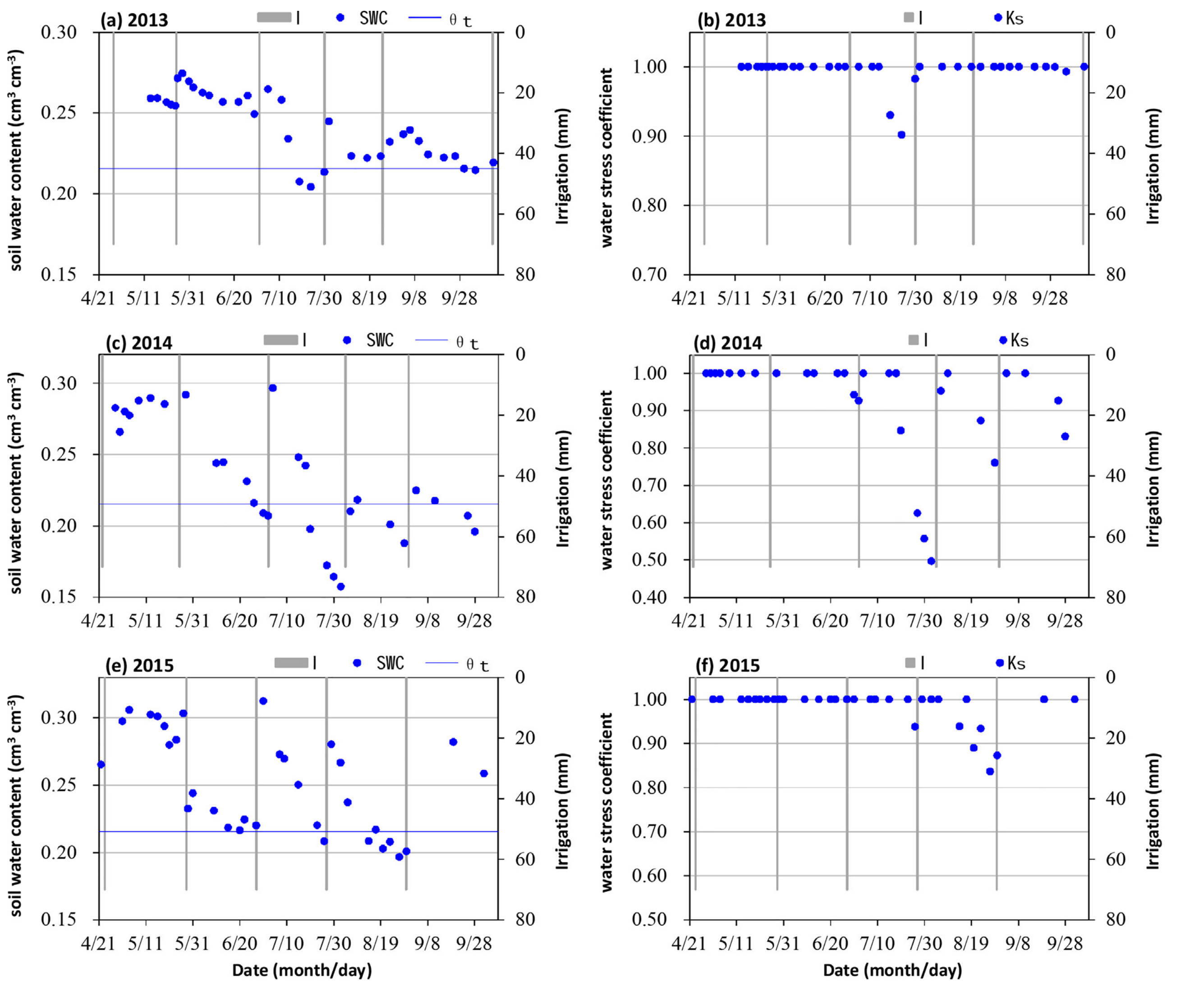

Fig. 3. Seasonal patterns of root zone soil moisture (SWC) and water stress coefficient (K_s) in 2013 (a,b), 2014 (c,d) and 2015 (e,f). θ_t and the mount of irrigation (I) are also displayed.

total soil evaporation and transpiration, while not used in analyzing relationships between daily *E* or *T*/*ET* against controlling factors.

2.4. Theoretical approach

To explore the biophysical relationships between *ET* partitioning and relevant controlling factors, the commonly used dual crop coefficients method (Dual K_c) proposed by FAO-56 was adopted in the present study (Allen et al., 1998).

In the Dual K_c method, soil evaporation and plant transpiration were calculated as follows (Allen et al., 1998):

$$E = K_e * ET_0 \quad (1)$$

$$T = K_s * K_{cb} * ET_0 \quad (2)$$

$$ET = (K_e + K_s * K_{cb}) * ET_0 \quad (3)$$

where K_{cb}, K_e and K_s are basal crop coefficient, soil evaporation, and water stress coefficients, respectively; and ET_0 is the reference evapotranspiration (mm d^{-1}).

Based on Eqs. (1) and (2), the proportion of transpiration to evapotranspiration can be calculated as follows:

$$\frac{T}{ET} = \frac{K_s * K_{cb}}{K_e + K_s * K_{cb}} \quad (4)$$

The root zone (40–140 cm depth in the furrow, where more than 84% of the grape roots propagated) soil moisture (*SWC*) and θ_t (the water content threshold below that the root zone depletion exceeds $p * TAW$ and the water stress exits) and the water stress coefficient (K_s) were presented in Fig. 3. And *p* is the average fraction of Total Available Soil Water (*TAW*) that can be depleted from the root zone before moisture stress (reduction in *ET*) occurs [0−1], and is set to be 0.45 in present study based on FAO-56 (Allen et al., 1998). As shown in Fig. 3, water stress existed in late July and late August before the following irrigation, when both canopy (*LAI*) and evaporative demand (ET_0) were at high levels (Fig. 4). Thus we focused the analysis on days without water deficit (K_s = 1) to calibrate and validate the proposed model in present study, and Eq. (4) can be simplified as follows:

$$\frac{T}{ET} = \frac{K_{cb}}{K_e + K_{cb}} \quad (5)$$

Based on Eq. (97) in FAO-56 (Allen et al., 1998), K_{cb} can be expressed as:

$$K_{cb} = K_{c\,min} + (K_{cbfull} - K_{c\,min}) * [1 - \exp(-C * LAI)] \quad (6)$$

where K_{cmin} is the minimum K_c for bare soil, $K_{cb\,full}$ is the estimated basal K_{cb} during the mid-season (at peak plant size or height) for vegetation having full ground cover or LAI >3, C is the extinction coefficient of light attenuation (0.322 in this study).

Based on direct EC measurements in early April 2015 when the vine canopy was not existent (LAI = 0), K_{cmin} was observed to be 0.004 in the present study. Thus we assumed that K_{cmin} = 0, and Eq. (6) can be simplified as:

$$K_{cb} = K_{cbfull} * [1 - \exp(-C * LAI)] \quad (7)$$

Based on Eq. (71–74) in FAO-56 (Allen et al., 1998), K_e can be expressed as:

$$K_e = K_r * (K_{c\max} - K_{cb}) \leq f_{ew} * K_{c\max} \quad (8)$$

where K_{cmax} is the maximum value of K_c following rain or irrigation, f_{ew} is the fraction of the soil that is both exposed (1.0) and wetted (1.0 for rainfall and 0.5 for irrigation), K_r is the dimensionless evaporation reduction coefficient dependent on the cumulative depth of water depleted (evaporated) from the topsoil, which is expressed as follows based on Eq. (73, 74) in Allen et al. (1998):

$$K_r = \frac{TEW - D_e}{TEW - REW} = \frac{1000 * (SWC - 0.5 * \theta_{wp}) * Z_e}{TEW - REW} \quad (9)$$

where TEW is total evaporable water (mm), which is the maximum depth of water that can be evaporated from the soil when the topsoil has been initially completely wetted (Eq. (73) in Allen et al., 1998); D_e is the cumulative depth of evaporation (depletion) from the soil surface layer (mm); REW is the readily evaporable water, which is the maximum depth of water that can be evaporated from the topsoil layer without restriction during stage 1 (4–8 mm for loamy sand soil, Table 19 in Allen et al., 1998); SWC is the actual surface volumetric soil water content and θ_{wp} is the surface soil water content at wilting point (0.10 $m^3 m^{-3}$ in this study); Z_e is the depth of the surface soil layer that is subject to drying by way of evaporation (0.10-0.15m, Eq. (73) in Allen et al., 1998).

In Eq. (8), $K_r * (K_{cmax} - K_{cb})$ was less than $f_{ew} * K_{cmax}$ in most cases in present work (data not shown), thus K_e can be simplified and calculated from Eq. (8) and (9) as follows:

$$K_e = (K_{c\max} - K_{cb}) * \frac{1000 * Z_e}{TEW - REW} * (SWC - 0.5 * \theta_{wp}) \quad (10)$$

Thus the daily proportion of plant transpiration to evapotranspiration (T/ET) can be calculated from Eqs. (5), (7) and (10) as follows:

$$\frac{T}{ET} = \frac{1 - \exp(-C * LAI)}{\left[\exp(-C * LAI) + (\frac{K_{c\max}}{K_{cbfull}} - 1)\right] * \frac{1000 * Z_e}{TEW - REW} * (SWC - 0.5 * \theta_{wp}) + [1 - \exp(-C * LAI)]} \quad (11)$$

Results in Eq. (11) indicate that ET partitioning was mainly controlled by leaf area index (LAI) and surface soil water content (SWC), we changed the form of Eq. (11) as follows:

$$\frac{T}{ET} = \frac{1 - \exp(-C * LAI)}{[\exp(-C * LAI) + m] * n * (SWC - 0.5 * \theta_{wp}) + [1 - \exp(-C * LAI)]} \quad (12)$$

where C was directly measured (0.322); θ_{wp} was 0.10 $m^3 m^{-3}$; m and n were constant, representing $(\frac{K_{c\max}}{K_{cbfull}} - 1)$ and $\frac{1000 * Z_e}{TEW - REW}$, respectively.

3. Results and discussion

3.1. Seasonal variations in vineyard ET and its components

The seasonal variations of daily vineyard evapotranspiration (ET) and plant transpiration (T) measured by eddy covariance system and sap flow sensors from 2012 to 2015 were shown in Fig. 4, and the daily reference evapotranspiration (ET_0) and water inputs (irrigation and precipitation) were also displayed.

ET_0 was relatively stable in April (4.17 ± 0.37 mm d^{-1}), May (4.22 ± 0.20 mm d^{-1}), June (4.10 ± 47 mm d^{-1}) and July (3.94 ± 0.51 mm d^{-1}), then decreased from 3.50 ± 0.23 mm d^{-1} in August to 2.55 ± 0.23 mm d^{-1} in September and to 1.82 ± 0.22 mm d^{-1} in October (Fig. 4). The seasonal variations of ET_0 indicated that the atmosphere evaporative demand maintained at a higher level in first half seasons and then decreased in the second half seasons.

For the whole growing seasons, average vineyard ET increased from 1.61 ± 0.34 mm d^{-1} in April to 3.08 ± 0.66 mm d^{-1} in July, and decreased to 0.80 ± 0.28 mm d^{-1} in October. It displayed a pattern similar to canopy growth and was also affected by water input events, and increases of ET were observed after irrigation or rain (Fig. 4). The seasonal average of ET was 2.09 mm d^{-1}, 2.10 mm d^{-1}, 2.21 mm d^{-1}, and 2.15 mm d^{-1} in 2012–2015, respectively. Zhang et al. (2007) reported daily ET ranging from 0.1 to 4.3 mm d^{-1} in a nearby furrow-irrigated vineyard and also observed that ET increased in response to rainfall or irrigation events. In a drip-irrigated vineyard in Israel, maximum ET was around 3.5 mm d^{-1} occurring either on the day of, or on the day following irrigation when the canopy was fully developed (Kool et al., 2016). Similar results were also reported by Poblete-Echeverría et al. (2012) who observed peak daily ET of 3.5-4.0 mm d^{-1} in a drip-irrigated vineyard in Chile. However, Williams and Fidelibus (2016) reported a maximum $ET$of 9 mm d^{-1} and Netzer et al. (2009) also reported a maximum ET ranged from 7.26 to 8.59 mm d^{-1} in drip-irrigated vineyards, and the larger ET in their studies resulted from the bigger canopy size than our study.

Seasonal patterns of vine transpiration (T) resembled those of canopy development (Fig. 4). Average T increased from 0.52 ± 0.17 mm d^{-1} in May to 1.51 ± 0.31 mm d^{-1} in July and decreased to 0.37 ± 0.35 mm d^{-1} in October because of leaf senescence. In October of 2014 and 2015, sudden decreases in T were observed due to a heavy frost in each year, causing most of the leaves to die (Fig. 4c, d). The seasonal average of T was between 0.98-1.00 mm d^{-1} in 2013–2015 and 1.38 mm d^{-1} in 2012. Similar results were reported by Zhang et al. (2011) that seasonal vine T was dynamic from 0.13 to 2.69 mm d^{-1} with an average of 1.25 mm d^{-1}. Zhang et al. (2010) also observed a seasonal average T of 1.2-1.4 mm d^{-1} in a furrow-irrigated vineyard. However, Ferreira et al. (2012) reported grapevine transpiration exceeding 4.0 mm d^{-1} using sap flow techniques, and the canopy (seasonal average LAI of 1.96-2.39 $m^2 m^{-2}$) was bigger than our study (seasonal average LAI about 1.4 $m^2 m^{-2}$). Higher values were also reported by Poblete-Echeverría et al. (2012) with transpiration ranging from 0.8 to 3.2 mm d^{-1} and averaged at 1.8 mm d^{-1}.

Dynamics of soil evaporation (E) indicated high fluxes during the wetting periods after irrigation or rain (a maximum of 4.9 mm d^{-1}) and lower fluxes about 0.1-0.5 mm d^{-1} during the drying periods, while they didn't display seasonal variation correlated with canopy development (Fig. 5). Soil evaporation correlated well with soil water content at 10 cm depth (SWC), while relatively low values of E were observed in October 2014 under wet conditions due to the

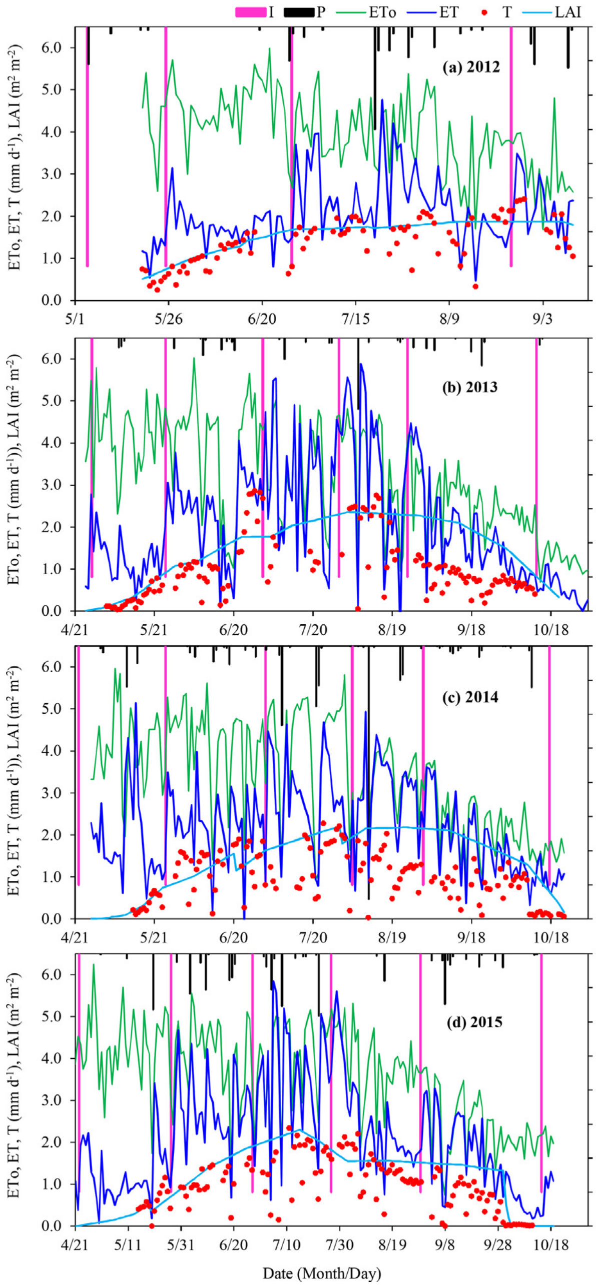

Fig. 4. Variations of daily vineyard evapotranspiration (*ET*) by eddy covariance, transpiration (*T*) by sap flow sensors and reference evapotranspiration (ET_0) in 2012–2015. Leaf area index (*LAI*), irrigation (*I*) and precipitation (*P*) are also displayed.

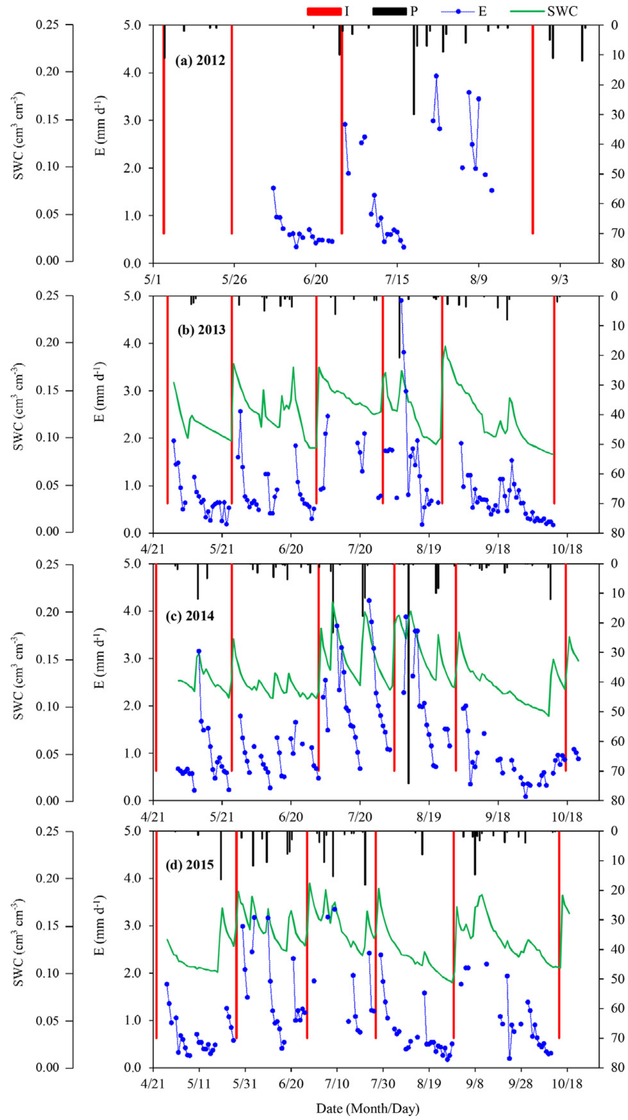

Fig. 5. Variations of daily soil evaporation (*E*) and volumetric soil water content (*SWC*, at 10 cm depth) from 2013 to 2015.

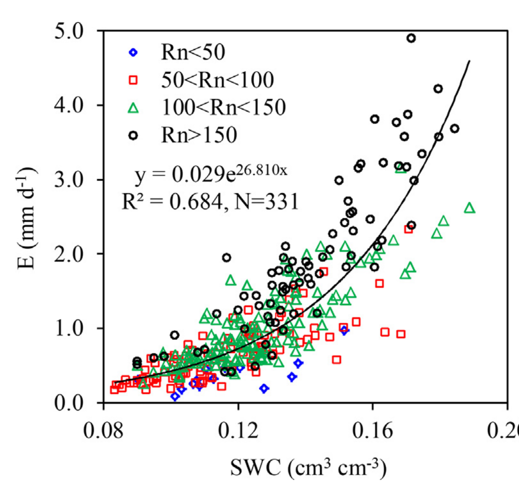

Fig. 6. The relationship between daily soil evaporation (*E*) obtained from microlysimeter measurements and the volumetric soil water content (*SWC*, at 10 cm depth) in the vineyard from 2013 to 2015. *E* was separated into different datasets based on daily average net radiation flux (R_n, $W\,m^{-2}$).

lower solar radiation (Fig. 5c). The seasonal average soil evaporation in 2013–2015 was 0.95 mm d^{-1}, 1.28 mm d^{-1} and 1.05 mm d^{-1}, respectively. Similar results were also reported by Raz-Yaseef et al. (2012) in a forest that seasonal dynamics of soil evaporation were highly correlated with soil water content at 5 cm depth. Ding et al. (2013) reported higher soil evaporation after irrigation and rainfall events in early growing seasons of maize field when the canopy was small. Kool et al. (2016) reported that *E* remained relatively stable throughout the whole season in a drip-irrigated vineyard, but *E* was also affected by wetting events: with *E* of 0.35 ± 0.06 mm d^{-1} on days with irrigation, 0.19 ± 0.05 mm d^{-1} on the day after, and 0.10 ± 0.04 mm d^{-1} on following days. Higher values of *E* in present study may be due to the higher wetting fraction of soil surface under furrow irrigation (about 50%). The wetted soil surface (on the

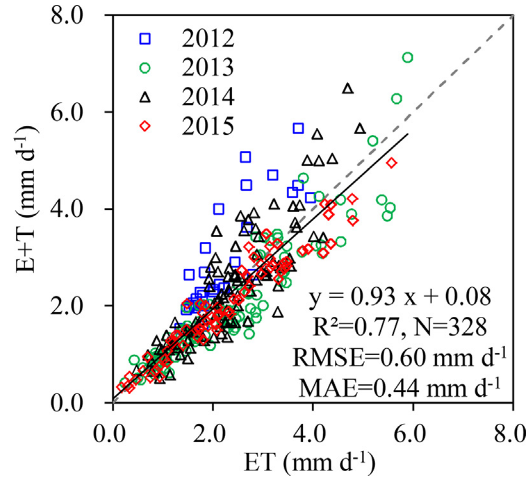

Fig. 7. Eddy covariance measured daily vineyard *ET* versus calculated *E* + *T* based on microlysimeters and sap flow sensors. The dashed line represents the 1:1 line.

north half of the irrigated furrow) was also exposed to the sunlight directly during the majority of the growing seasons under sparse canopies (Fig. 1). And Williams and Fidelibus (2016) reported lower soil evaporation rates in a vineyard which was due to the wetted soil surface being covered by the canopy for the majority of the growing season. Thus *E* was mainly controlled by the atmospheric demand and soil surface moisture while not sensitive to the variation in canopy growth in present work, which was similar to the results reported by Flumignan et al. (2011) for coffee trees. The relationship between daily *E* and *SWC* was shown in Fig. 6, and the effects of radiation on soil evaporation were also displayed, indicating that *E* was simultaneously affected by the available energy and soil moisture (Table 1). Similar exponential functions between *E* and *SWC* were also reported by Zhang et al. (2011) in a vineyard, Jiang et al. (2016) in a maize field, and Mitchell et al. (2009) in semi-arid eucalypt woodlands.

In the present study, both vineyard *ET* and component (*T* and *E*) were directly measured by eddy covariance, sap flow sensors, and

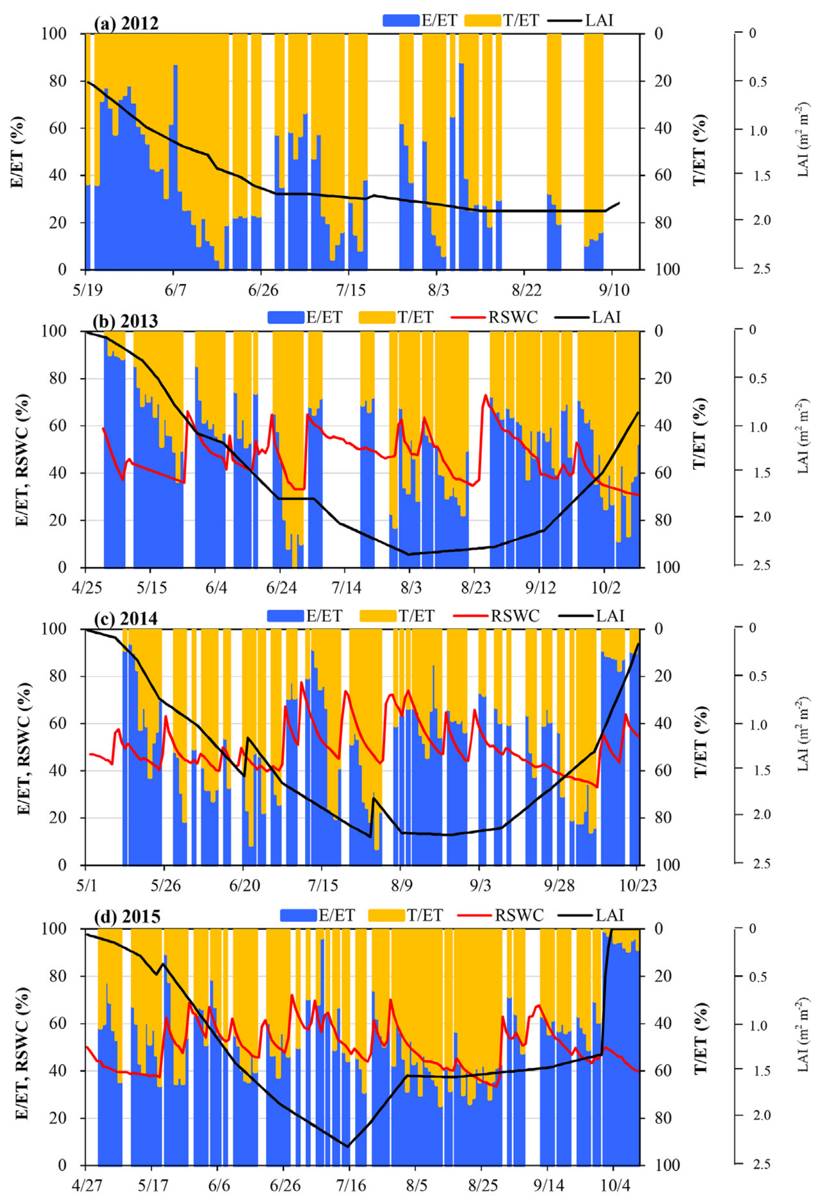

Fig. 8. Seasonal variations in daily vineyard *ET* partitioning (*E*/*ET*, *T*/*ET*) during experimental periods from 2012 to 2015. The relative soil water content (*RSWC*, the ratio of *SWC* to field capacity, at 10 cm depth) and leaf area index (*LAI*) are also displayed.

microlysimeters, respectively. Thus a comparison between daily *ET* and the sum of *T* and *E* was evaluated and shown in Fig. 7. Results indicated that the combination of sap flow and microlysimeters can provide reasonable measurements of total *ET* and its components in the vineyard. The reliability was evaluated by linear regression of daily *E* + *T* against *ET*, the slope, intercept and R^2 were 0.93, 0.08 mm d^{-1} and 0.77, and the root mean square error (*RMSE*) and mean absolute error (*MAE*) were 0.60 mm d^{-1} and 0.44 mm d^{-1}, respectively (Fig. 7).

3.2. Evapotranspiration partitioning

Based on the directly measured daily vineyard *ET* and its components, seasonal dynamics and biophysical controls of *ET* partitioning were analyzed.

Partitioning of daily *ET* showed that *E* was the dominant component of vineyard *ET* in early season, and displayed a roughly seasonal decline trend with canopy developing (Fig. 8). However, in 2015 the rain was more equally distributed, especially in the first half of the season (from 20 May to 22 July), which resulted in a relative higher soil moisture content and *E*/*ET*. Thus no obvious correlation between *E*/*ET* and canopy development was observed in the first half of the season in 2015. And before 20 May in 2015, relative lower *E*/*ET* values compared with 2013 and 2014 were observed though the canopy was very small, which could be caused by the discrepancy of the eddy covariance and microlysimeters. Thus the data of *T*/*ET* before 20 May in 2015 were excluded in the calibration and validation of the parameters in the proposed model (Eq. (12)). In October 2014 and 2015, *E* took a high proportion of *ET* (about 90%) due to a heavy frost that happened in both years, resulting in a sharp decrease of plant transpiration (Figs. 8c,d and 4c,d). What is more remarkable is that daily *ET* partitioning (*E*/*ET*, *T*/*ET*) was closely correlated with soil surface water content (*SWC*). *E*/*ET* increased after wetting events (irrigation and rain) and then gradually declined with drying of the soil. Even in middle season when the canopy was fully developed, *E*/*ET* can exceed 80% under wet conditions (Fig. 8c,d). While under dry conditions in middle season, *E*/*ET* was low (less than 20% or even 10%) (Fig. 8b,c). Similar results were also reported by Jara et al. (1998) that the highest values of *E*/*ET* in a maize field were obtained at the beginning of the season after irrigation. Kool et al. (2016) reported in a drip-irrigated vineyard that *E* was a relatively large fraction of *ET* and *E*/*ET* was variable and sensitive to wetting events in the early season, while after a few weeks *T* dominated *ET* (comprising 90% of *ET*) and *E*/*ET* was quite stable and less sensitive to wetting events when the canopy was fully developed. The higher proportion of soil evaporation in the present study is attributed to the large wetting fraction of soil surface under furrow irrigation and abundantly available energy for *E* because of the sparse vine canopy (Fig. 1).

To interpret the main factors affecting *ET* partitioning, the commonly used method is to use simple regression functions between related variables against measured *E*/*ET* or *T*/*ET* (Table 2). Most of the previous studies focused on the effects of the canopy on *ET* partitioning and lacked biophysical meanings, and didn't consider the effects of *SWC*. However, for sparse vegetation in this study, *E* took a large proportion of *ET* and was strongly affected by *SWC*, thus it was necessary to consider the effects of *SWC* on *ET* partitioning (Table 2). In the present study, a more biophysically robust model between *T*/*ET* and biophysical factors (*LAI*, *SWC*) derived from the Dual crop coefficient method were used to interpret how vineyard *ET* partitioning was regulated across the whole growing seasons. According to Eq. (12), the relationships between vineyard daily *T*/*ET* and *LAI* and *SWC* fitted to the directly observed data in 2013–2015 were obtained in Fig. 9. The original value of parameters "m" and "n" obtained from ($\frac{K_{c\max}}{K_{cbfull}} - 1$) and $\frac{1000*Z_e}{TEW-REW}$ was 0.304–0.680 and

Table 2
Summary of relationship between *ET* partitioning and controls.

Source	Relationship	Vegetation
Kang et al. (2003)	$\frac{T}{ET} = \frac{a*LAI}{LAI+b}$	wheat, maize
Kato et al. (2004)	$\frac{T}{ET} = 1-\exp(-a*LAI)$	sorghum
Wang and Yamanaka (2014)	$\frac{T}{ET} = a*\log(LAI)+b$	grassland
Wang et al. (2014)[1]	$\frac{T}{ET} = 1-\exp(a*LAI+b*s+c)$	variable
Villegas et al. (2015)	$\frac{T}{ET} = a*LAI^2+b*LAI+c$	tree mosaics
Wu et al. (2017)	$\frac{T}{ET} = a*LAI^b$	maize
Gong et al. (2017)	$\frac{T}{ET} = 1-a*\exp(-b*LAI)$	maize
Zhang et al. (2013)	$\frac{E}{ET} = a-b*\log(LAI)$	maize
Yan et al. (2015)	$\frac{E}{ET} = a-b*\ln(LAI)$	buckwheat
Gong et al. (2017)	$\frac{E}{ET} = \frac{1}{1+a*LAI^b}$	maize
Present study	$\frac{T}{ET} = 0.13*LAI+0.26,\ p<0.001$	vineyard
Present study	$\frac{T}{ET} = -4.04*SWC+0.97,\ p<0.001$	vineyard

[1] s is a time function relating the time of measurement to the timing of peak *LAI*; a, b and c are constant values; *T*/*ET* and *E*/*ET* are the proportion of transpiration and soil evaporation to total evapotranspiration, respectively; *LAI* is leaf area index ($m^2\ m^{-2}$); *SWC* is volumetric soil water content at 10 cm depth ($cm^3\ cm^{-3}$).

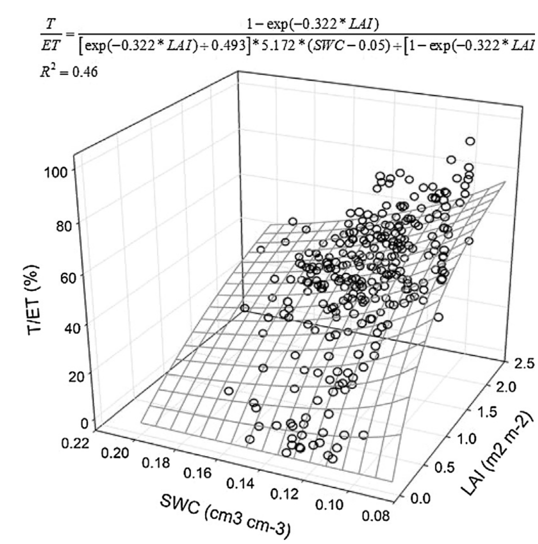

Fig. 9. The relationship between daily transpiration fraction (*T*/*ET*) as a function of leaf area index (*LAI*) and the volumetric soil water content (*SWC*, at 10 cm depth) in the vineyard from 2013 to 2015.

5.172 respectively. Since "m" was variable in different years, we set "n" to be constant (5.172) and only "m" needed to be fitted. Then the fitted parameter "m" was 0.522, 0.495 and 0.491 in 2013, 2014 and 2015 respectively, and it was within the range of the original values (0.304–0.680) (Table 3).

Then we used the parameters obtained in 2013 in Eq. (12) to simulate the daily *T*/*ET* in 2014 and 2015, then compared with the directly measured values to validate the proposed model (Fig. 10). Results indicated that large discrepancies existed between the observed and estimated *T*/*ET* in 2014, while in 2015 the differences were small.

The performance of the proposed model in present study was not very high (with a R^2 of 0.46). However, if we use the simple regression between *T*/*ET* and *LAI*, and between *T*/*ET* and *SWC*, the corresponding coefficient of determination (R^2) was 0.17 and 0.19, respectively (data not shown). And previous studies estimating *T*/*ET* or *E*/*ET* based on the influencing factors also reported rela-

Table 3
Parameters of the relationship between vineyard daily transpiration fraction (*T*/*ET*, %) as a function of volumetric soil water content (*SWC*, at 10 cm depth, $cm^3\ cm^{-3}$) and leaf area index (*LAI*, $m^2\ m^{-2}$) based on Eq. (12) in 2013–2015.

$$\frac{T}{ET} = \frac{1-\exp(-0.322*LAI)}{[\exp(-0.322*LAI)+m]*n*(SWC-0.05)+[1-\exp(-0.322*LAI)]}$$

year	m	n	R^2	N	p
2013	0.522	5.172	0.59	106	<0.0001
2014	0.495	5.172	0.29	84	<0.0001
2015	0.491	5.172	0.53	93	<0.0001
2013–2015	0.493	5.172	0.46	283	<0.0001

m and n are the parameters in Eq. (12); R^2 is the determine coefficient; N is the number of observations; p is the p-value for statistical hypothesis testing.

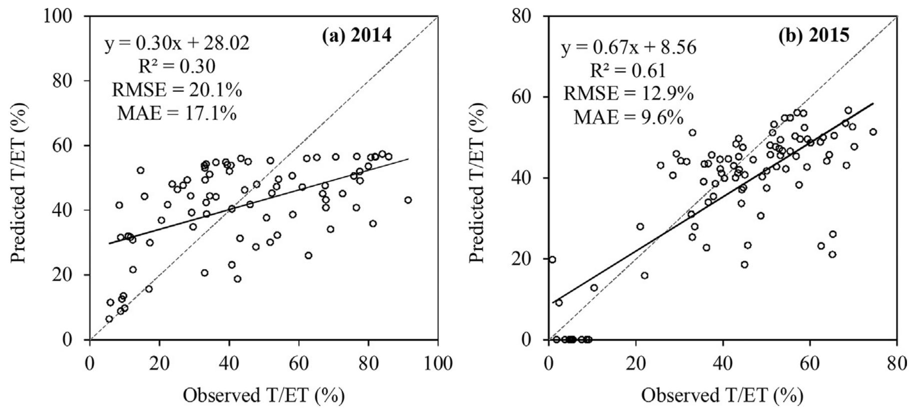

Fig. 10. Comparison of observed and predicted values of vineyard daily transpiration fraction (*T*/*ET*) in 2014 and 2015. The daily predicted *T*/*ET* was calculated by Eq. (11) obtained in 2013. The dashed line represents the 1:1 line.

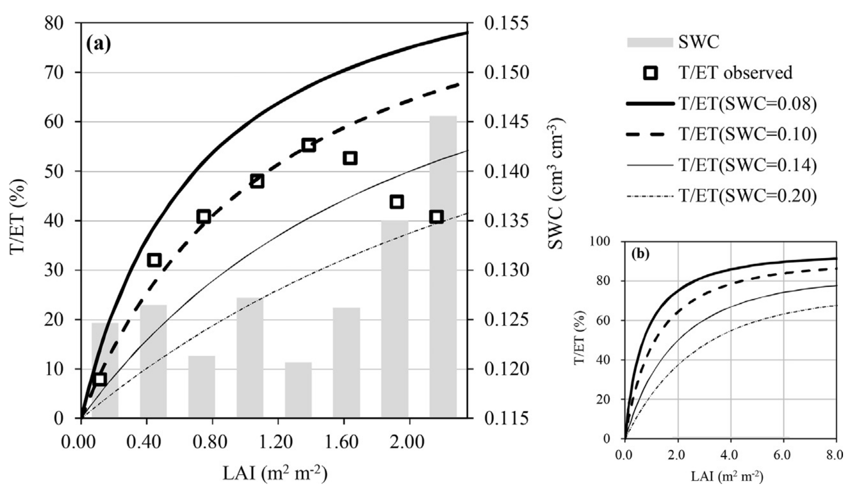

Fig. 11. Relationship between daily transpiration fraction (*T*/*ET*) and leaf area index (*LAI*). The curve lines represent analytical results calculated by Eq. (12) obtained in 2013–2015 under different soil surface moisture conditions (*SWC* = 0.08, 0.10, 0.14, 0.20 $cm^3\ cm^{-3}$). Mean observed values of daily *T*/*ET*, *LAI* and *SWC* from 2013 to 2015 are shown within an *LAI* interval of 0.3 $m^2\ m^{-2}$.

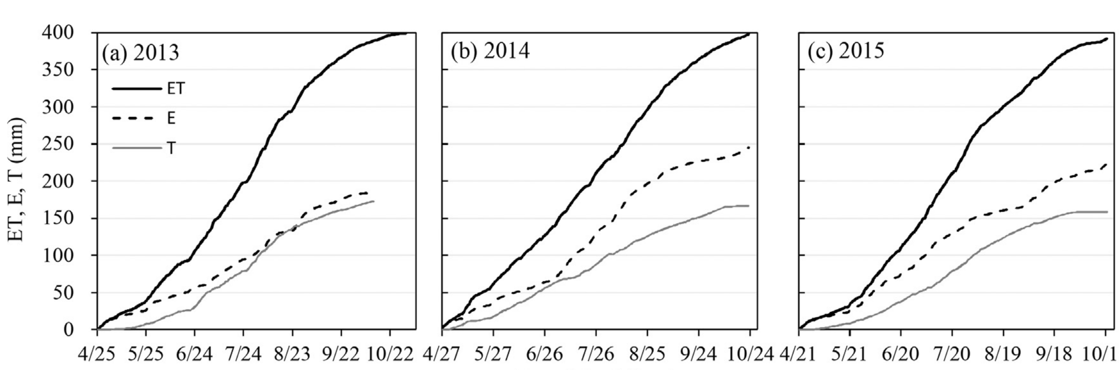

Fig. 12. Cumulative evapotranspiration (*ET*), soil evaporation (*E*) and vine transpiration (*T*) during growing seasons from 2013 to 2015.

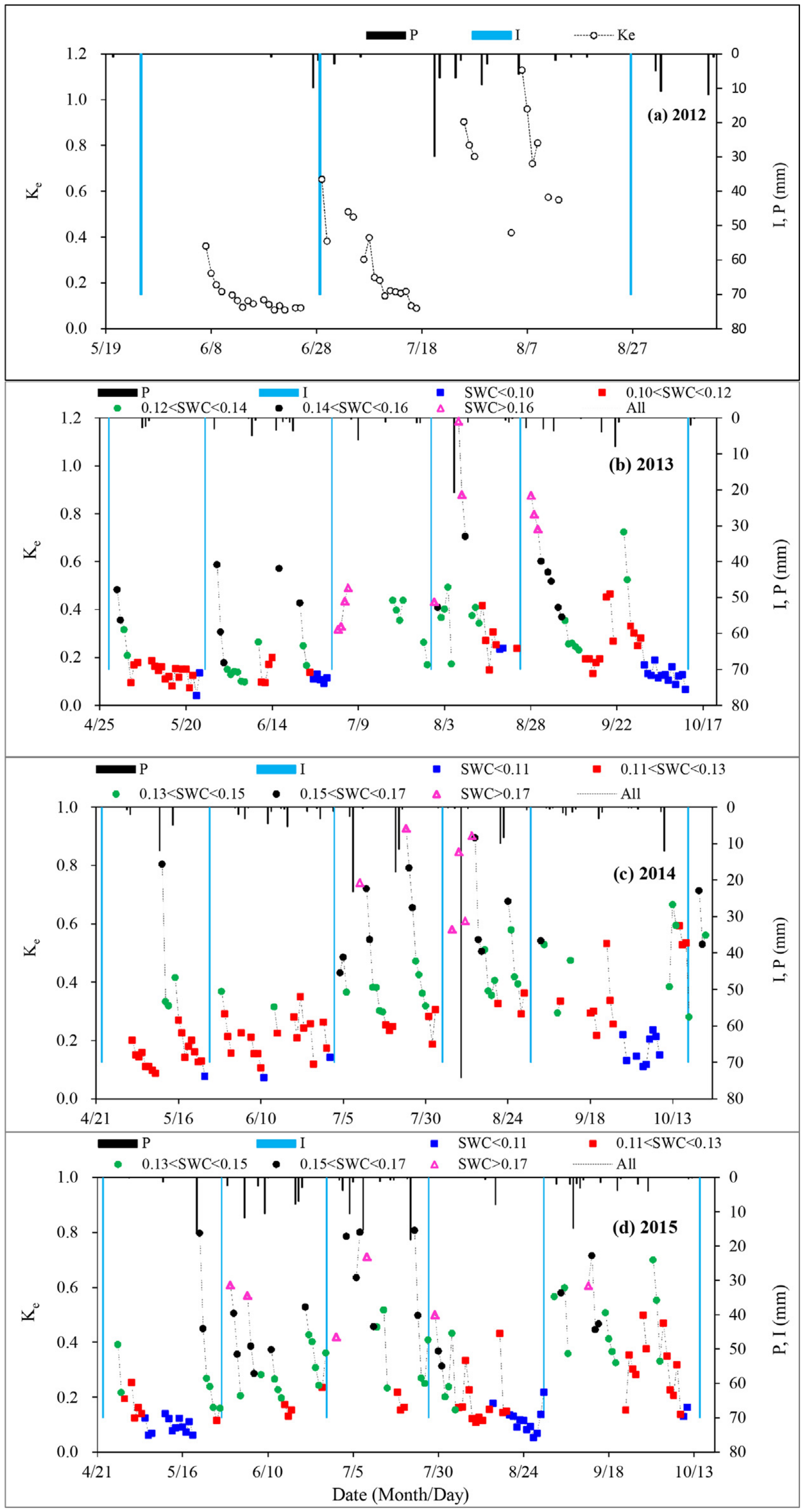

Fig. 13. Seasonal variations in daily soil evaporation coefficients (K_e) from 2012 to 2015. K_e was separated into different datasets based on volumetric soil water content (*SWC*, at 10 cm depth, $cm^3\ cm^{-3}$). The amount of irrigation (*I*) and precipitation (*P*) are also displayed.

tive lower accuracy, e.g. a R^2 of 0.43 by Wang et al. (2014) and poor performance by Zhang et al. (2013). The relative lower accuracy of the proposed model in present study could be caused by: (1) though a more biophysically robust model was used and both canopy and soil moisture were considered, other influencing factors such as the growing stages reported by Wang et al. (2014) relating to the physiological characteristics were ignored; (2) some assumptions were made in present study to simplify the model, such as expressing K_{cb} as a function of *LAI* and K_{cmin} was zero (Eq. (6) and (7)), and $K_r * (K_{cmax} - K_{cb})$ was less than $f_{ew} * K_{cmax}$ in Eq. (8) (data not shown); (3) the reliability of the dual crop coefficients method in partitioning *ET* in vineyard was reported by previous studies (Poblete-Echeverría and Ortega-Farias, 2013; Zhao et al., 2015), however an underestimation of *E* and overestimation of *T*

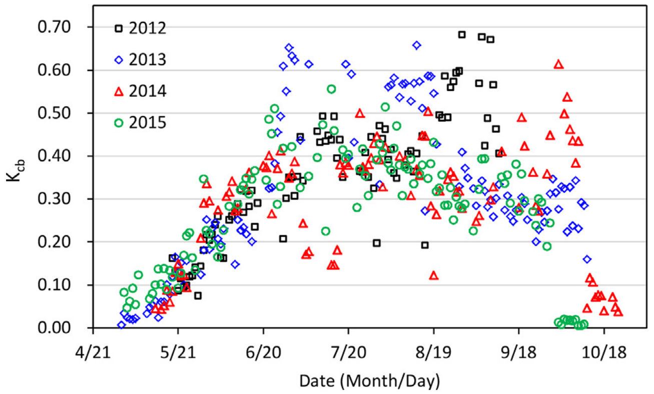

Fig. 14. Seasonal variations in daily basal crop coefficients (K_{cb}) from 2012 to 2015.

(or vice versa) could enlarge the deviation of estimated *T*/*ET* from the observed values, though the estimated *E* or *T* did not differ much from the observed values (Zhao et al., 2015); (4) the directly measured *E* and *T* were not absolute precise, though *E* + *T* was close to *ET* (Fig. 7), which could also induce errors of the parameters in the model.

Compared with previously reported relationships between *ET* partitioning and *LAI*, the biophysically robust model obtained in the present study considered the effects of surface soil moisture on *ET* partitioning. Under wet conditions when soil evaporation was high, *T*/*ET* was relatively low even when the canopy was fully developed (Fig. 9). And for a given *LAI*, *T*/*ET* decreased with increasing *SWC* because of the increasing of soil evaporation.

Previous studies have demonstrated the importance of *LAI* in regulating *ET* partitioning and the effects of *SWC* on soil evaporation, thus using the observed input parameters (*LAI*,*SWC*) to estimate vineyard *T*/*ET* by the proposed model in this study can provide useful information about the interaction effects of *LAI* and *SWC* on *ET* partitioning. Different surface soil water regimes (*SWC* = 0.08, 0.10, 0.14 and 0.20 $cm^3 cm^{-3}$) were selected to calculate the variability of *T*/*ET* under different *LAI* (Fig. 11). Under the same *SWC*, *T*/*ET* increased with *LAI*, which was similar to previous studies (Kato et al., 2004; Wang et al., 2014; Gong et al., 2017). For a given *SWC*, the *T*/*ET* increased significantly with increasing *LAI* when *LAI* was small, i.e. soil surface was not fully covered by the canopy, especially under dry conditions, then gradually became stable when canopy reaching maximum (Fig. 11b). As shown in Fig. 11a, the directly observed *T*/*ET* displayed a close relationship with canopy development when $LAI \leq 1.6\,m^2\,m^{-2}$. However, when the canopy was fully developed ($LAI > 1.6\,m^2\,m^{-2}$), the observed *T*/*ET* showed a decrease trend, because the soil evaporation was high caused by high *SWC* (Fig. 11a). Note that the parameters (m, n) obtained in the present study (with $LAI < 2.5\ m^2\,m^{-2}$) may produce errors when employing Eq. (12) to estimate *T*/*ET* under high *LAI* conditions ($LAI > 2.5\,m^2\,m^{-2}$), but the type of the function in Eq. (11) was universal across different ecosystems.

After the gap-filling of missing soil evaporation and transpiration without directly measurements, the cumulative *ET*and its components were shown in Fig. 12. Seasonal total *ET* from bud break until harvest (late April to middle October) was 399 mm, 398 mm and 392 mm, where *E* was 185 mm, 245 mm and 224 mm, *T* was 173 mm, 167 mm and 158 mm, and *E* + *T* was 358 mm, 412 mm and 382 mm, in 2013, 2014 and 2015, respectively (Fig. 12). Noted that in 2013 the measurements of *E* and *T* ended up earlier than *ET*, and the total *ET*obtained from eddy covariance was 389 mm during the measurement periods of *E* and *T* (Fig. 12a). The seasonal soil evaporation fraction (*E*/*E* + *T*) was higher in 2014 (59.5%) and 2015 (58.6%), with a seasonal average *SWC* of 0.134 $cm^3 cm^{-3}$ and 0.135 $cm^3 cm^{-3}$ respectively, while in 2013 the seasonal *E*/*E* + *T* was 51.7%, with an average *SWC* of 0.126 $cm^3 cm^{-3}$, indicating that surface soil moisture may have influences on the annual vineyard *ET* partitioning. Kool et al. (2016) reported seasonal cumulative *ET* in a drip-irrigated vineyard of 261 mm, where *E* (24 mm) was 9% of *ET*, and *T* (237 mm) accounted for 91% of. Poblete-Echeverría et al. (2012) also observed average *T*/*ET* about 72% in a drip-irrigated Merlot vineyard. Also in a drip-irrigated vineyard, López-Urrea et al. (2012) reported seasonal total soil evaporation of 114 mm, 71 mm and 98 mm, and vine transpiration of 426 mm, 290 mm and 416 mm in 2007–2009, respectively, with a seasonal *T*/*ET* of 79%, 80% and 81%, respectively. Compared with drip-irrigation, a larger proportion of water was evaporated from soil surface under furrow irrigation in the vineyard, indicating that the irrigation water could be used more efficiently in the future if the drip irrigation method were adopted.

3.3. Dual crop coefficients

The seasonal dynamic of soil evaporation coefficients (K_e) and basal crop coefficients (K_{cb}) in 2012–2015 was shown in Figs. 13 and 14. K_e (E/ET_0) and K_{cb} (T/ET_0) were calculated from the directly measurements by sap flow and microlysimeters. To investigate the effects of wetting events (irrigation and rain) and *SWC* on K_e, the datasets were classified into several sub-datasets based on the *SWC* values.

Development of daily K_e was mainly influenced by wetting events, after irrigation and rainfall K_e suddenly increased to a high level (even exceeding 1.0) and then gradually declined as soil

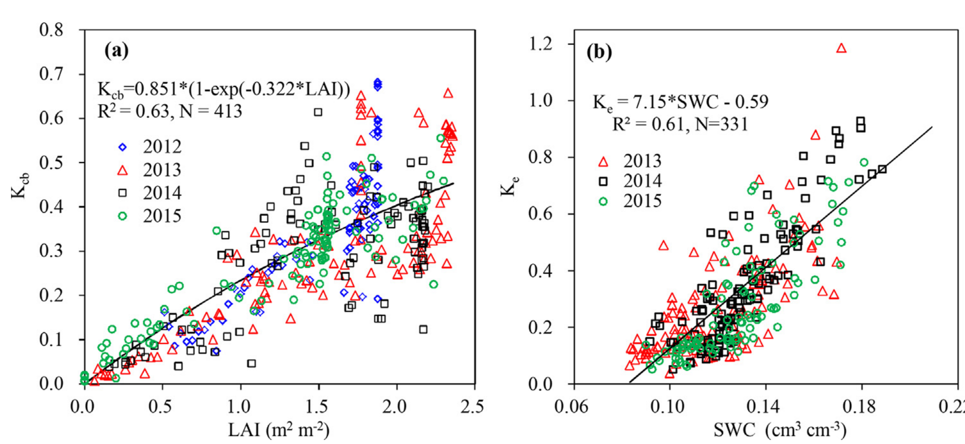

Fig. 15. The relationship between (a) daily basal crop coefficients (K_{cb}) and leaf area index (*LAI*), (b) daily soil evaporation coefficients (K_e) and volumetric soil water content (*SWC*, at 10 cm depth) from 2012 to 2015.

became dry (Fig. 13). Under dry conditions, K_e was relatively stable and less than 0.2. Note that the maximum K_e was observed after rainfall not after irrigation, due to the wetting fraction of soil surface after irrigation was 50% but nearly 100% after precipitation. The seasonal trend of K_e was not related to canopy development, due to the canopy was small and has low effects on soil surface available energy.

K_{cb} displayed a seasonal trend with canopy development, the average K_{cb} was 0.12 ± 0.03, 0.31 ± 0.05, 0.40 ± 0.10, 0.42 ± 0.08, 0.31 ± 0.03 and 0.18 ± 0.10 from May to October, respectively (Fig. 14). In October of 2014 and 2015, a sudden decrease of K_{cb} was observed due to a heavy frost, causing most of the leaves to die and a sudden decrease in transpiration (see Fig. 4c, d).

Compared with previous studies in the vineyard, the K_e observed in present work was much higher, while K_{cb} was similar to other studies. In a drip-irrigated vineyard, López-Urrea et al. (2012) reported K_e about 0.08–0.16, 0.07–0.19 and 0.05, K_{cb} about 0.18–0.22, 0.33–0.46 and 0.46–0.69 in early, middle and late seasons, respectively, and the maximum daily K_e was less than 0.3. Also in a drip-irrigated vineyard, Kool et al. (2016) reported that K_e were highest on 0 days after irrigation (DAI 0), averaging about 0.05 and reducing to 0.03 and 0.01 on DAI 1 and DAI >1, respectively, and K_e appeared to remain constant and was less than 0.06 throughout the whole growing season, and the peak values of K_{cb} around 0.4-0.5 were observed in middle season. While Williams and Fidelibus (2016) reported a maximum K_{cb} of 1.2 and a seasonal average K_{cb} of 0.93 during the vine growing seasons, with a bigger canopy than our study. And Cancela et al. (2015) in a vineyard reported that K_e was very close to K_c because of the high number of rainfall events, and the daily K_e ranged between 0 and 0.9, which was similar to our study. Also in a drip-irrigated vineyard, Montoro et al. (2016) reported higher values of K_{cb} (0.20–1.0) and lower K_e (less than 0.25) than our study. Similar results of vineyard K_{cb} were also reported by Fandiño et al. (2012) (between 0.07 and 0.57) and by Poblete-Echeverría and Ortega-Farias (2013) (between 0.20 and 0.55). Overall, higher K_e values in our study under furrow irrigation indicated that large fractions of irrigated water were evaporated from surface soil compared with drip-irrigation.

Based on Eq. (7), the relationship between daily K_{cb} and *LAI* was obtained in 2012–2015, similar results in the vineyard were also reported by previous studies (Ferreira et al., 2012; López-Urrea et al., 2012; Montoro et al., 2016) (Fig. 15a). K_e was strongly controlled by surface soil moisture, and a linear relationship was observed between K_e and *SWC* in our study, which has not been reported by previous studies (Fig. 15b).

4. Conclusions

Based on the directly measured vineyard *ET* and its components, dynamics and controlling factors of *ET* partitioning and dual crop coefficients were studied. Main findings are outlined as follows:

(1) Seasonal total *ET* from bud break until harvest was 399, 398 and 392 mm, where *E* was 185, 245 and 224 mm, *T* was 173, 167 and 158 mm, and *E* + *T* was 358, 412 and mm, in 2013, 2014 and 2015, respectively. Seasonal average *E* represented about 52–59% of *E* + *T*and *T* about 41–48% of *E* + *T*.
(2) Seasonal *ET* partitioning was controlled by surface soil water content (*SWC*) and leaf area index (*LAI*), and annual *ET* partitioning was related to *SWC*.
(3) A biophysically robust model based on the dual crop coefficients method which can describe the effects of *LAI* and *SWC* on *ET* partitioning was proposed in the present study and explained 46% of the vineyard *ET* partitioning.
(4) Soil evaporation coefficients were strongly affected by wetting events (irrigation and rain) and closely correlated to *SWC*, and basal crop coefficients were mainly correlated with canopy development.

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