

# AN IMPROVED EVAPOTRANSPIRATION MODEL FOR AN APPLE ORCHARD IN NORTHWESTERN CHINA

C. Liu, G. Sun, S. G. McNulty, S. Kang

**ABSTRACT.** *Accurately estimating evapotranspiration (ET) is essential for orchard managers to design irrigation schedules and conserve water resources in semi-arid environments where water is often the limiting factor for successful production. Improving water use efficiency helps irrigation scheduling and thus benefits water resource management and the sustainability of the local economy. This study examined three existing ET models that were developed based on the Shuttleworth-Wallace model (SW) for estimating ET from sparsely covered crops in the arid Shiyang River basin (mean annual precipitation = 164 mm) in northwest China. We improved the existing clumping model (C model), a modified version of the SW model that simulates soil evaporation under the tree canopy and from bare soils outside of the canopy using a fixed bare soil/canopy area ratio. Our new ET model (the seasonal clumping model, or Cj model) considered the hourly dynamics of the bare soil surface area both under and outside of the tree canopy in an irrigated apple (*Malus domestica* Borkh. cv. Golden Delicious) orchard. The Cj model provided an improved estimate of soil evaporation by simulating soil surface areas based on hourly changes in canopy shade patterns and the canopy gap fraction. We validated the SW, C, and Cj models with ET fluxes measured by multiple methods, including sap flow of apple trees, and ET estimated by the micro-lysimeter and soil water balance methods for the 2008, 2009, and 2010 growing seasons. Soil water content, canopy characteristics (e.g., leaf area index), and leaf stomatal conductance were also measured periodically to parameterize the model. The growing season total ET rates estimated by the sap flow and micro-lysimeter method were 667, 674, and 583 mm in 2008, 2009, and 2010, respectively. The relative simulation errors of soil evaporation for the Cj, C, and SW models were 5%, 10%, and 30%, respectively. The absolute error for transpiration modeled by Cj ( $0.58 \text{ mm d}^{-1}$ ) was significantly lower than for the C model ( $0.65 \text{ mm d}^{-1}$ ) on a biweekly time scale. The growing season ET simulated by the Cj model was 628, 624, and 572 mm during 2008, 2009, and 2010, respectively, and the soil evaporation was 24% to 32% of the total ET. Over all, the Cj model was an improvement over the other two existing models for estimating apple orchard ET with a sparse tree cover. Our study also suggested that a supplement of 400 to 500 mm of irrigation water was essential to grow productive apple trees in the study region. The new model was successful in simulating the soil evaporation process and estimating the additional amount of water required to supplement natural rainfall by irrigation. The Cj model developed from this study was suitable for mature orchards or sparse forests with a bare soil surface, and it could efficiently estimate the water demand for irrigation scheduling.*

**Keywords.** *Apple trees, Evapotranspiration, Sap flow, Shuttleworth-Wallace model.*

**F**ruit production from apple orchards plays a key role in the local economy of northwestern China, a region that is known to suffer from water shortages, by providing income for farmers (Gong et al.,

2007). Irrigation scheduling is critical for farmers to use the limited water resources efficiently in this arid environment, with rainfall averaging less than 200 mm per year (Tong et al., 2007). Accurate measurement of orchard evapotranspiration (ET) is often costly due to the complex processes involved. Thus, ET simulation models provide a cost-effective approach for estimating ET used in irrigation management (Kang et al., 2003).

A bulk surface resistance term was introduced in modeling latent heat flux in the 1960s (Monteith, 1965; Penman and Long, 1960; Rijtema, 1965). Shuttleworth and Wallace (1985) developed an ET model by introducing canopy and soil resistance into the Penman-Monteith model because soil evaporation is a key component of water loss for sparse crops in an arid climate (Kool et al., 2014b). The Shuttleworth and Wallace model (SW model) is known as a two-source ET model. Brenner and Incoll (1997) further developed a clumping model that significantly improved the accuracy in modeling soil evaporation for sparse crops by recognizing the differences in soil evaporation processes under tree canopies and on bare soil surfaces. The Brenner-

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Incoll model (Brenner and Incoll, 1997) is called the C model in this article.

Because ET models are sensitive to canopy resistance ( $r_{sc}$ ), many recent ET studies have focused on *in situ* measurements or modeling of the  $r_{sc}$  variable. The  $r_{sc}$  can be estimated using measurements from a combined sap flow and micro-lysimeter method (Nicolas et al., 2008), and it can be determined by leaf stomatal resistance and leaf area index. A portable photosynthesis system is widely used to measure stomatal resistance at the leaf scale, which is then scaled to the canopy level using the Jarvis model (Cammalleri et al., 2010; Jarvis, 1976; Nicolas et al., 2008). The Jarvis model estimates  $r_{sc}$  using the minimum stomatal resistance, leaf area index (LAI), and environmental factors. Because ecosystem-scale ET is mainly controlled by LAI and mean stomatal resistance in the SW and clumping models (Domingo et al., 1999; Ortega-Farias et al., 2007), Li et al. (2010) and Stannard (1993) estimated canopy resistance by vapor pressure deficit (VPD) and photosynthetically active radiation (PAR). Moreover, the canopy resistance has been calculated by VPD, net radiation, air temperature, soil water content, and LAI (Forrester et al., 2010; Poyatos et al., 2007; Zeppel et al., 2008). Previous studies indicated that considering leaf water potential in  $r_{sc}$  estimation can improve the accuracy of the Jarvis model (Guan and Wilson, 2009; Strelcová et al., 2009; Rana et al., 1997). Hu et al. (2009) suggested that the Ball-Berry model can be used to calculate  $r_{sc}$  when the leaf photosynthetic rate is measured. In such a case, the  $r_{sc}$  can be estimated by fitting experimental data and back-calculating from measured ET. Environmental factors such as solar radiation, VPD, air temperature, soil water content, and leaf water potential are needed to estimate  $r_{sc}$ .

Soil evaporation is a main component of total ET for sparse crops (e.g., orchards) and during irrigation in apple orchard management. The soil evaporation in sparse crops varies diurnally as the proportion of the bare soil area varies according to the shade patterns across the inter-canopy (Agam et al., 2012; Kool et al., 2014b). However, soil evaporation is mainly controlled by growing season changes in LAI (Kool et al., 2014a; Liu et al., 2013; Shuttleworth and Wallace, 1985). Using both hourly changes of canopy shade patterns and canopy variation throughout the season may improve the accuracy of ET models. An accurate description of ET processes can improve model accuracy and irrigation scheduling (Kang et al., 2003; Lawrence et al., 2007).

Previous studies suggested that there was little difference between irrigation schedules based on soil water content and on long-term average daily ET values for managing water resources in orchards (Migliaccio et al., 2010). Effective irrigation schedules use actual ET that is estimated using long-term average ET in the field (Kisekka et al., 2010). Because an irrigation schedule based on long-term average ET is effective for orchard water management, accurately estimating soil evaporation and crop transpiration would be useful in designing irrigation systems.

The objectives of this study were to (1) develop a canopy resistance model using key environmental factors to improve existing ET models, (2) improve the C model by

including the soil hydrologic dynamics under orchard canopies, and (3) determine the variations of the seasonal ET rate to minimize irrigation that maintains the health of apple trees.

## METHODS

### RESEARCH SITE

The field experiment was conducted during 2008-2010 at the Shiyanghe Experimental Station for Water-Saving in Agriculture and Ecology (37° 52' N, 102° 51' E, 1581 m altitude), managed by China Agricultural University, located in Wuwei city, Gansu Province, northwest China. The site has a continental temperate climate with a mean annual sunshine duration of more than 3000 h, mean annual temperature of 8°C, annual accumulated temperature (>0°C) of more than 3550°C, mean annual precipitation of 164 mm, mean annual pan evaporation of 2000 mm, and 150 frost-free days per year (Li et al., 2008). The groundwater table is below 40 m (Kang and Zhang, 2011). The soil is dominated by irrigated desert soil (Siltic-Orthic Anthrosols) with a sandy loam texture. The mean dry bulk density is 1.44 g cm<sup>-3</sup>, and the mean volumetric water content at field capacity is 0.31 ± 0.03 cm<sup>3</sup> cm<sup>-3</sup> based on two soils profile samples with 2 m depth among trees. Apple trees (*Malus domestica* Borkh. cv. Golden Delicious) were planted with an east-west row orientation in 1981, with row spacing of 6 m and plant spacing of 4 m. The experimental plots are irrigated four times per year by flood irrigation to avoid tree water stress. The irrigated water is pumped up from a deep groundwater well, and the irrigation amount for each tree is controlled by a water meter at the end of the pipes. The irrigation area has a 10 cm high border to ensure even distribution of irrigation.

### SAP FLOW AND MICRO-LYSIMETER METHOD

Compensation heat pulse sap flow sensors (model SF100, Greenspan Technology Pty Ltd., Warwick, Australia) consisting of two unheated probes and one heated probe were used to monitor trunk sap flow ( $SF$ ) every 30 min. Two sets of heat pulse probes were installed on the east and west sides of the trunk at depths of 1.5 and 2.0 cm, respectively. Six trees with diameters between 178 and 235 mm were randomly selected for sap flow measurements. The radius of sapwood and heartwood was assumed to be circular and was measured with an increment borer. Transpiration was calculated from the measured sap flow flux and the ratio of sapwood area, and the product of row spacing and plant spacing (Liu et al., 2012):

$$SF = 1000 \times \frac{SF_0}{S_A} \quad (1)$$

where  $SF$  (mm d<sup>-1</sup>) and  $SF_0$  (L d<sup>-1</sup>) are the sap velocity and original sap flux, respectively, and  $S_A$  is the area of the plot (mm<sup>2</sup>).  $SF_0$  was calculated using Sapflow Sensor Calculations software (version 2.53, Greenspan Technology) based on the ratio of sapwood area.

Soil evaporation was measured using 16 weighing micro-lysimeters with a diameter of 10 cm and a height of 20 cm

installed around the base of apple tree trunks. The micro-lysimeters were installed at distances of 0.5, 1.0, 1.5, and 2.0 m from the trunks. The micro-lysimeters were pushed into the ground to retrieve an undisturbed soil sample and packed with permeable filter paper and a piece of gauze in the bottom. The micro-lysimeters were weighed daily at sunset, except during raining days, with a balance (PL 6001-L, Mettler Toledo, Greifensee, Switzerland).

### SOIL WATER BALANCE METHOD

Soil volumetric water content was measured continuously using time domain reflectometry (Trime-Pico IPH/T3, IMKO GmbH, Ettlingen, Germany) for three randomly chosen apple trees. Four tubes were installed with a depth of 180 cm and distances of 100, 100, 200, and 200 cm, and the soil water content in the vertical profile at each tube was measured in 10 cm soil layer increments every five days. The measured soil water content was calibrated using the oven-drying method every month. Using a 5 cm diameter soil auger, three soil samples were collected 50 to 150 cm away from the tubes for the 10 to 180 cm soil profile at 10 cm vertical intervals. After weighing, the samples were dried for 8 h. The soil moisture measurements were used for estimating ET based on the soil water balance equation. The total ET between the two measurements was calculated as follows:

$$ET = P + I - R - \Delta W \quad (2)$$

where  $\Delta W$  is the change in soil water content during the two measurements (mm),  $P$  is the effective precipitation (mm),  $I$  is the irrigation amount (mm), and  $R$  is water loss through runoff and deep seepage beneath the 2 m soil zone, which was negligible in this study.

### LEAF AREA INDEX

Leaf area index (LAI,  $m^2 m^{-2}$ ) was measured with a Winscanopy canopy analysis system (Winscanopy, Regent, Quebec, Canada). The hemispherical photography was taken on sunny days, every 5 to 7 days, following the procedures described by Zhang et al. (2005) and analyzed using Winscanopy software. Daily LAI was interpolated by year with a quadratic equation between LAI and day of year (DOY) for calculating the variable canopy resistance used in the ET models.

### STOMATAL CONDUCTANCE

Stomatal conductance of three fully expanded leaves of apple trees was measured at 2 h intervals on four sunny days in 2008 using a portable photosynthesis system (LI 6400, Li-Cor, Lincoln, Neb.). When choosing leaves, we selected the third to fifth leaf from random branches on both the south and north sides of the tree. The stomatal conductance varied during the measurement period, normally reaching the peak around 9:00 to 11:00 a.m., so we measured stomatal conductance at 9:00 to 11:00 a.m. as the maximum stomatal conductance during 11 sunny days in 2008-2010.

### MICRO-METEOROLOGY

The hourly net radiation, relative humidity, air tempera-

ture, wind speed, and soil heat flux were recorded using a meteorological monitoring system (Jauntering International, Taipei, Taiwan) that was installed at 3 to 6 m distance from the evaluated trees in the experimental apple orchard. The instrument installation heights were 3 m, 2 m, 2 m, and 4 m above the ground and 10 cm below the ground, respectively. VPD was calculated from air temperature and relative humidity (Allen et al., 1998). Rainfall was measured at a weather station (tipping bucket, 200 mm diameter,  $\pm 0.1$  mm) 200 m distant from the research plot.

### REVISED SEASONAL CLUMPING MODEL

#### Clumping Model (C model)

Shuttleworth and Wallace (1985) calculated sparse crop soil evaporation from total ET by incorporating canopy and soil resistance into the Penman-Monteith model. The resulting SW model is known as a two-source ET model (fig. 1a). Brenner and Incoll (1997) further developed a clumping model (the C model) that significantly improved the accuracy in modeling soil evaporation for sparse crops

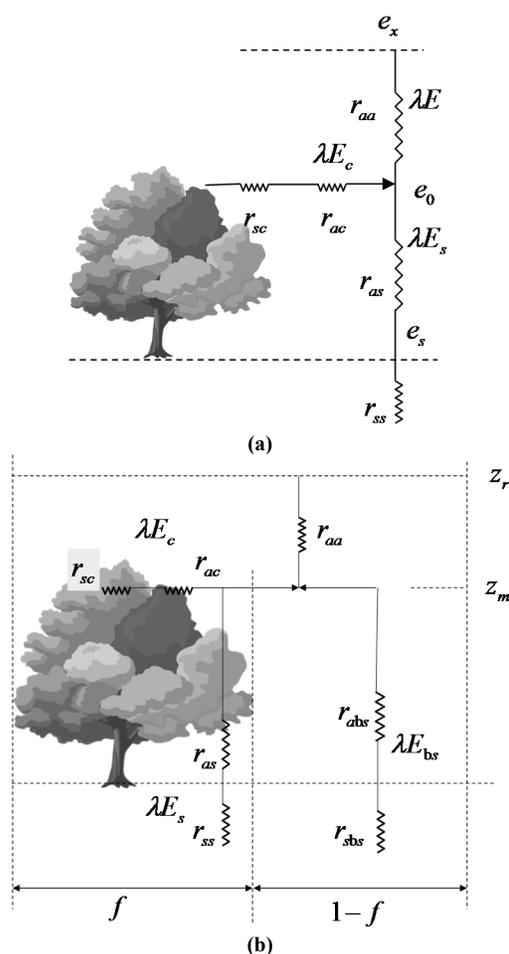


Figure 1. Diagram of (a) SW model and (b) C model (Agam et al., 2010; Brenner and Incoll, 1997; Lagos et al., 2009; Shuttleworth and Wallace, 1985; Villagarcia et al., 2010). The models compute latent flux ( $\lambda E$ ) from the soil surface under the canopy, the bare soil surface, and the canopy (subscripts  $s$ ,  $b$ , and  $c$ ). Fluxes are regulated by transport aerodynamic resistances ( $r_{at}$ ), bulk leaf boundary layer ( $r_{ac}$ ), and soil surface boundary layer ( $r_{as}$  and  $r_{abs}$ ). The canopy and soil resistances are clarified as  $r_{sc}$  and  $r_{ss}$  ( $r_{sbs}$ ), and  $f$  is the ratio of soil under the canopy and bare soil outside the canopy.

(fig. 1b). The soil evaporation under and outside of the tree canopy is calculated separately in the C model. Aerodynamic and soil resistances are described by the eddy diffusion theory and surface soil moisture, respectively (Shuttleworth and Wallace, 1985; Zhang et al., 2008). The variables used for the apple orchard are listed in table 1.

We calculated the canopy resistance ( $r_{sc}$ ) using the Jarvis model, which was based on the hypothesis that stomatal resistance is independently affected by every environmental variable (Jarvis, 1976; Shuttleworth and Wallace, 1985). Matsumoto et al. (2008) suggested that regional differences exist in the environmental factors used for calculating canopy resistance. Thus, we used solar radiation and VPD to calculate the canopy resistance. The equation was fitted as follows:

$$r_{ST} = \frac{r_{ST\min}}{\prod_i F_i(X_i)} \quad (3)$$

$$r_{sc} = \frac{r_{ST}}{\text{LAI}_e} \quad (4)$$

where  $r_{ST}$  and  $r_{ST\min}$  are mean and minimum leaf stomatal resistance ( $\text{s m}^{-1}$ ), respectively. The value of  $r_{ST\min}$  is approximately  $70 \text{ s m}^{-1}$  for apple trees depending on the measurements of stomatal conductance.  $\text{LAI}_e$  is effective leaf area index, which is calculated from measured LAI (Shuttleworth and Wallace, 1985; Zhang et al., 2008),  $X_i$  is solar radiation and VPD, and  $F_i(X_i)$  is the response function of the two environmental factors, which are expressed as follows:

$$F_1(R_s) = \left( \frac{R_s}{1100} \right) \left( \frac{1100 + a_1}{R_s + a_1} \right) \quad (5)$$

$$F_2(\text{VPD}) = e^{-a_2 \text{VPD}} \quad (6)$$

where  $R_s$  is the incoming shortwave solar radiation ( $\text{W m}^{-2}$ ), VPD is vapor pressure deficit (kPa), and  $a_1$  and  $a_2$  are derived from a multivariate optimization and equal  $751 \text{ W m}^{-2}$  and  $0.34$ , respectively. In this study, the apple trees were irrigated based on long-term mean ET to avoid a water deficit, so the soil water content and air temperature were considered less important as controlling variable (Forrester et al., 2010), and VPD and  $R_s$  are most important in ET simulation (Wallace and McJannet, 2010).

The apple orchard was irrigated, so the surface soil evaporation was large after irrigation. However, the soil in the shade of the canopy was apparently different from the bare soil in sunshine (Kool et al., 2014b; Zhang et al., 2009); therefore, the errors can be large when using a fixed

cover rate (fig. 1). The different soil evaporation rates can be estimated by complex models (Zhang et al., 2009). In this study, we introduced a variable cover ratio to improve the C model.

### Seasonal Clumping Model (Cj Model)

In general, LAI is low and the gap fraction for the canopy is large during the early growing season. In addition, evaporation is different between soil surfaces directly and indirectly exposed to sunlight (Kool et al., 2014b). Therefore, we developed a seasonal model, called the Cj model (fig. 2), based on the clumping model (C model). The new model combined hourly changes in canopy shade patterns and canopy gap fraction to calculate the cover ratio ( $f$ ) of soil under the canopy and bare soil outside the canopy for soil evaporation, which was constant in the C model.

The cover ratio ( $f$ ) is controlled by the solar zenith angle ( $\alpha$ ) and the canopy gap fraction sensitively (fig. 2). Thus, the leaf projected area for the incident direction of sunlight is relative to the gap fraction of the canopy:

$$S = FS' \quad (7)$$

where  $S$  is the leaf projection area for the sunlight incident direction ( $\text{m}^2$ ),  $S'$  is the canopy projection area for the sunlight incident direction ( $\text{m}^2$ ), and  $F$  is the gap fraction, which can be calculated from the hemispherical photography. In  $\Delta OAB$  (fig. 2), the canopy projection area for the sunlight incident direction ( $S'$ ) is:

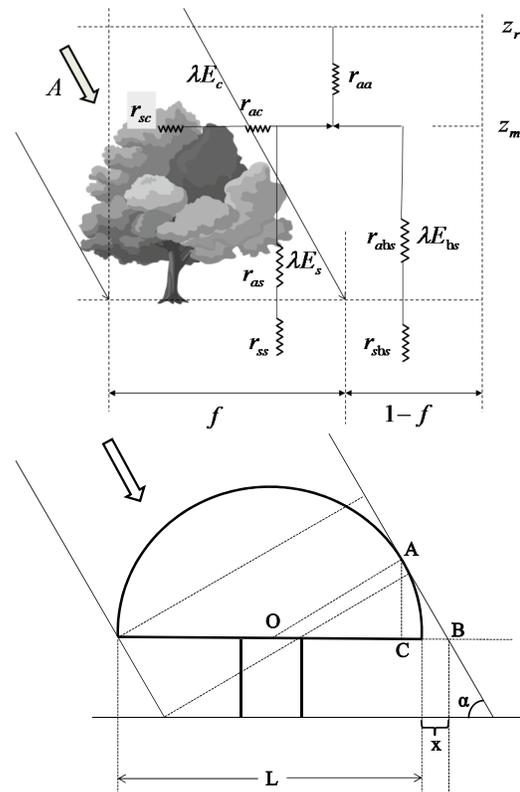


Figure 2. Diagram of seasonal clumping model (Cj model);  $f$  is the ratio of soil in the canopy shade and bare soil exposed to sunlight.

Table 1. Variables used in clumping model (C) and seasonal clumping model (Cj) (Zhang et al., 2008).

Variable	Value
Average canopy height ( $h_c$ )	5.21 m
Extinction coefficient of the eddy diffusion ( $n$ )	3.32
Reference height ( $z$ )	7.21 m
Mean boundary layer resistance ( $r_b$ )	$50 \text{ s m}^{-1}$
Minimum soil surface resistance ( $r_{s\min}$ )	$100 \text{ s m}^{-1}$

$$S' = \pi \left( \frac{L+x}{2} \right)^2 = \frac{1}{4} S_0 \left( 3 + \frac{1}{(\sin \alpha)^2} \right) \quad (8)$$

where  $L$  is the diameter of the canopy area (m),  $S_0$  is the canopy projection area for the vertical direction (m<sup>2</sup>), which can be considered constant if we do not prune the tree during the season,  $x$  is the difference between the diameter of  $S'$  and  $S_0$  (m), and  $\alpha$  is the solar zenith angle, which can be expressed by:

$$\sin \alpha = \frac{0.5L}{0.5L + x} \quad (9)$$

The cover ratio ( $f$ ) for the apple trees can be solved by equations 7 through 9:

$$f = \frac{S}{ab} = \frac{FS_0}{4ab} \left( 3 + \frac{1}{(\sin \alpha)^2} \right) \quad (10)$$

where  $a$  and  $b$  are the row and plant spacing (m), respectively, and the solar zenith angle can be calculated as follows:

$$\sin \alpha = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \left( \frac{t_h}{24} \times 360^\circ \right) \quad (11)$$

$$\delta = 23.5 \sin(0.986m - 78.9) \quad (12)$$

where  $\varphi$  is the latitude,  $\delta$  is the declination angle of the sun,  $m$  is the day of year, and  $t_h/24 \times 360^\circ$  is the solar hour angle, which is zero in mid-noon and positive in the afternoon (Allen et al., 1998; Shuttleworth, 2012).

#### MODEL EVALUATION STATISTICS

The modeled transpiration and evaporation were evaluated by measured sap flow and micro-lysimeter, respectively. The simulated variable and the measured data were compared through a regression forced to the origin. The following four criteria were chosen to evaluate the model performance (Moriasi et al., 2007; Zhang et al., 2013).

The coefficient of determination ( $r^2$ ), which describes the degree of linear relationship between model-simulated and measured data, is as follows:

$$r^2 = \left[ \frac{\sum_{i=1}^N (P_i - \bar{P})(Q_i - \bar{Q})}{\sqrt{\sum_{i=1}^N (P_i - \bar{P})^2} \sqrt{\sum_{i=1}^N (Q_i - \bar{Q})^2}} \right]^2 \quad (13)$$

where  $N$  is the number of data series,  $P_i$  and  $Q_i$  (mm d<sup>-1</sup> or mm h<sup>-1</sup>) are simulated and measured data, respectively, and  $\bar{P}$  and  $\bar{Q}$  (mm d<sup>-1</sup> or mm h<sup>-1</sup>) are averages of the simulated and measured data, respectively.

The root mean square error (RMSE, mm d<sup>-1</sup> or mm h<sup>-1</sup>), which shows the variance of the errors, is as follows:

$$\text{RMSE} = \left[ \frac{\sum_{i=1}^N (P_i - Q_i)^2}{N} \right]^{0.5} \quad (14)$$

The mean absolute error (MAE, mm d<sup>-1</sup> or mm h<sup>-1</sup>) and the index of agreement ( $d$ ) are expressed as follows:

$$\text{MAE} = \sum_{i=1}^N |P_i - Q_i| / N \quad (15)$$

$$d = 1.0 - \frac{\sum_{i=1}^N |Q_i - P_i|}{\sum_{i=1}^N (|Q_i - \bar{Q}| + |P_i - \bar{P}|)} \quad (16)$$

Nash and Sutcliffe modeling efficiency (NSE) is a normalized statistic that evaluates the residual variance compared to the measured data variance (Moriasi et al., 2007; Nash and Sutcliffe, 1970). NSE is expressed as follows:

$$\text{NSE} = 1 - \frac{\sum_{i=1}^N (P_i - Q_i)^2}{\sum_{i=1}^N (Q_i - \bar{Q})^2} \quad (17)$$

## RESULTS AND DISCUSSION

### LAI, COVER RATIO, AND MAXIMUM STOMATAL CONDUCTANCE FOR THE Cj MODEL

LAI is a main determinate of ET (Domingo et al., 1999; Ortega-Farias et al., 2007). The LAI increased at the beginning of the growing season and leveled off at the end of the season (fig. 3a), and the maximum LAI for the apple trees was about 1.5 to 2.0 m<sup>2</sup> m<sup>-2</sup> during 2008-2010 (Liu et al., 2013). Similar results have been found for other apple orchards (Gong et al., 2006). Given the rapid expansion of the canopy LAI, the apple orchard needs large amounts water to maintain normal physiologic activity. LAI is a determinant parameter to calculate canopy resistance in the Jarvis model and to determine the cover ratio in the Cj model.

The daily minimum ratio of the soil shadow area under the canopy to the total soil area (the daily minimum cover ratio) for the apple orchard varied throughout the growing season (fig. 3b), with the daily minimum value of the cover ratio increasing rapidly at the start of the growing season and increasing more slowly until the end of the season. The daily variation of the cover ratio was determined by the solar elevation and was set to 1 at night. Individual tree canopy projection areas might overlap if the orchard was planted with a different row orientation and spacing. Moreover, the cover ratio might be influenced by the site position and the surface slope of the orchard.

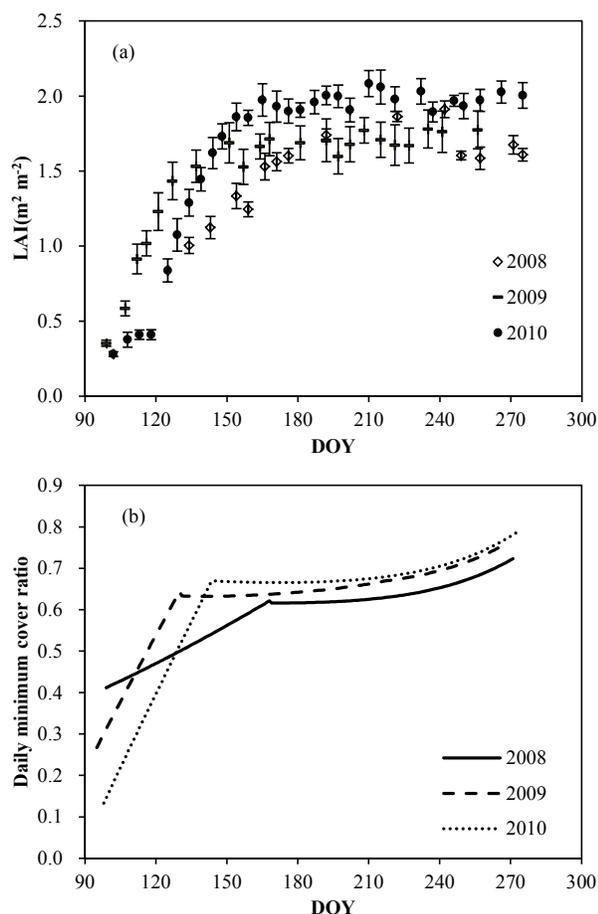


Figure 3. Leaf area index (LAI) and daily minimum cover ratio ( $f$ ) for apple trees in the 2008-2010 growing seasons: (a) measured LAI ( $\text{m}^2 \text{m}^{-2}$ ) and (b) calculated daily minimum cover ratio for the Cj model.

We measured the stomatal conductance during 9:00-11:00 a.m. on sunny days. The stomatal conductance reached  $0.2 \text{ mol H}_2\text{O m}^{-2} \text{ s}^{-1}$  at 9:00-11:00 a.m., and the resistance was  $200 \text{ s m}^{-1}$  (McDermitt, 1990) (fig. 4). The total 15 measurements of stomatal conductance at 9:00-11:00 a.m. indicated that the minimum stomatal resistance was about  $70 \text{ s m}^{-1}$ .

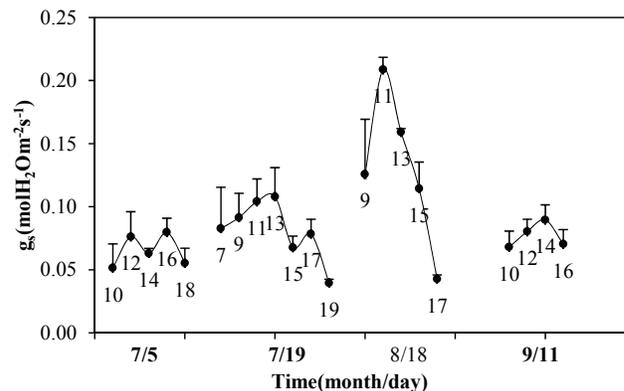


Figure 4. Measured hourly variations of leaf stomatal conductance ( $g_s$ ) of apple trees during four days in 2008.

### ET ESTIMATED BY SOIL WATER BALANCE AND BY SAP FLOW AND MICRO-LYSIMETER

The total growing season precipitation was 109, 119, and 82 mm, and irrigation added another 478, 478, and 529 mm during 2008, 2009, and 2010, respectively (table 2). Thus, irrigation was the main water supply to the orchard. The total growing season ET calculated by the water balance method was 654, 692, and 627 mm for the 2008, 2009, and 2010 growing seasons, respectively. The sap flow and micro-lysimeter method estimated ET of 667, 674, and 583 mm, with relative errors of 2.0%, -2.6%, and -7.2%, for 2008, 2009, and 2010, respectively (table 2). Precipitation less than 5 mm per day was deleted to obtain effective precipitation because each event was relatively small and the mature apple canopy could intercept part of the total rainfall (Calheiros et al., 1986; Guswa, 2012).

The ET rates were calculated using the soil water balance method for several days. As there was little rain in the arid apple orchard, the elevated soil water content was maintained by irrigation. Figure 5 shows the variation in soil moisture during June to July in 2010. The soil moisture was  $0.33$  to  $0.16 \text{ cm}^3 \text{ cm}^{-3}$  from June 13 to July 6. The variation in soil water content was obviously larger in the 0-120 cm depth than in the 120-180 cm depth. Thus, the irrigation had no deep seepage. Irrigated mature apple root-

Table 2. Evapotranspiration (ET) estimated by water balance method ( $ET_{WB}$ ) and by sap flow and micro-lysimeter ( $ET_{SL}$ ) method for an arid apple orchard during 2008-2010 ( $E_s$  is soil evaporation measured by micro-lysimeter, and RE is relative error)<sup>[a]</sup>

Year	Water Balance Calculation Period	Irrigation Date	Irrigation (mm)	Precipitation (mm)	$ET_{WB}$ (mm)	$E_s$ (mm)	Sap Flow (mm)	$ET_{SL}$ (mm)	RE (%)
2008	5 April to 10 May	23 Apr	115	29	109	42	65	107	-2.3
	11 May to 21 June	10 June	152	5	179	24	137	161	-9.9
	22 June to 1 Sept.	23 July	149	43	272	70	230	300	10.4
	2 Sept. to 1 Oct.	5 Sept.	63	33	95	23	76	100	5.0
	Total growing season	-	478	109	654	159	508	667	2.0
2009	5 April to 7 May	14 April	115	4	109	37	57	93	-14.8
	8 May to 13 June	26 May	152	13	179	40	134	174	-2.8
	14 June to 22 Aug.	4 July	149	62	311	55	235	290	-6.7
	23 Aug. to 27 Sept.	25 Aug.	63	40	93	31	85	117	25.9
	Total growing season	-	478	119	692	163	511	674	-2.6
2010	9 April to 14 May	3 May	169	9	139	52	55	107	-23.2
	15 May to 20 June	17 June	125	33	167	42	125	167	-0.1
	21 June to 1 Sept.	23 July	149	29	255	71	175	246	-3.5
	2 Sept. to 28 Sept.	29 Aug.	86	11	67	21	43	63	-5.2
	Total growing season	-	529	82	627	185	398	583	-7.2

[a]  $RE (\%) = (ET_{SL} - ET_{WB}) / ET_{WB} \times 100$ .

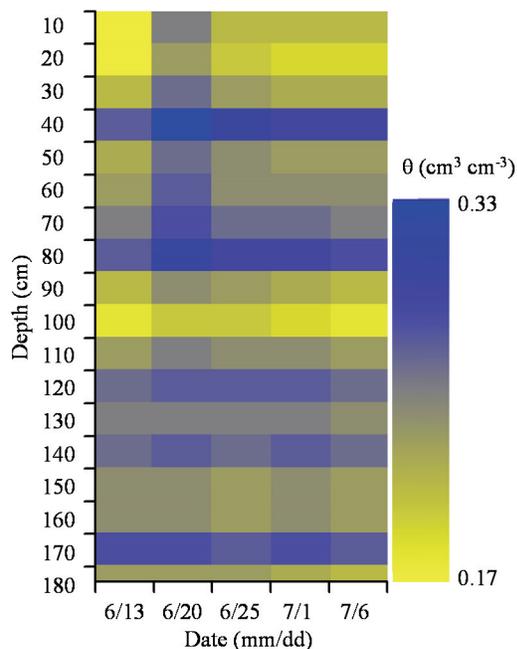


Figure 5. Average soil volumetric water content ( $\theta$ ) at different depths during June 13 to July 6 in 2010.

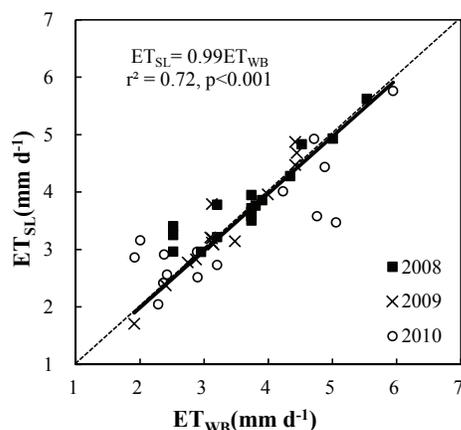


Figure 6. Daily evapotranspiration measured by the sap flow and micro-lysimeter method ( $ET_{SL}$ ,  $\text{mm d}^{-1}$ ) compared to the water balance method ( $ET_{WB}$ ,  $\text{mm d}^{-1}$ ) using a 5 to 30 day time interval.

ing depth is as deep as 120 cm (Liu et al., 2012). The ET measured by the sap flow and micro-lysimeter method ( $ET_{SL}$ ) correlated with the ET calculated by the water balance method ( $ET_{WB}$ ) using a 5 to 30 day interval (fig. 6) ( $ET_{SL} = 0.99ET_{WB}$ ,  $r^2 = 0.72$ ,  $p < 0.001$ ). The comparison suggests that the sap flow and micro-lysimeter method was suitable to evaluate ET for the apple trees (Gong et al., 2007).

## COMPARISON OF ESTIMATED AND MEASURED TRANSPIRATION OVER THE GROWING SEASON

The relationship between simulated hourly transpiration and measured sap flow was closer for the seasonal clumping (Cj) model than for the clumping (C) model. The  $r^2$  was 0.55 and 0.53, the MAE was 0.084 and 0.093  $\text{mm h}^{-1}$ , the RMSE was 0.104 and 0.116  $\text{mm h}^{-1}$ , and  $d$  was 0.60 and 0.58, respectively (table 3).

The daily transpiration simulated by the Cj model was 2.49  $\text{mm d}^{-1}$ , which was more accurate than the C model (2.40  $\text{mm d}^{-1}$ ), as the measured sap flow was 3.17  $\text{mm d}^{-1}$ . The  $r^2$  was 0.49 and 0.46, the MAE was 0.94 and 1.00  $\text{mm d}^{-1}$ , the RMSE was 1.15 and 1.22  $\text{mm d}^{-1}$ , and  $d$  was 0.55 and 0.52, respectively (table 3). The slope of the linear regression equation between simulated transpiration and sap flow measurement was 0.78 for the Cj model and 0.75 for the C model (table 3).

The average simulated ET was 2.49, 2.40, and 2.97  $\text{mm d}^{-1}$  for the Cj model, C model, and sap flow method, respectively, so the biweekly transpiration simulated by the Cj model was closer than that simulated by the C model. The  $r^2$  was 0.75 and 0.73, the MAE was 0.58 and 0.65  $\text{mm d}^{-1}$ , the RMSE was 0.67 and 0.75  $\text{mm d}^{-1}$ , and  $d$  was 0.58 and 0.55 for the Cj and C models, respectively (table 3). However, the slope of the linear regression equation between transpiration simulated by the Cj model (0.84) and the sap flow measurement was almost the same as the C model (0.81).

As shown in table 3, The NSE for simulated hourly transpiration was -0.52 and -0.22 for the C and Cj models, respectively. The negative NSE values indicate that neither model simulated hourly transpiration well. However, the Cj model performed better on daily and biweekly time scales than the C model based on comparison with sap flow measurements. Two reasons may explain this phenomenon. First, the Cj model was mainly optimized for the soil evaporation of the orchard. Secondly, mature apple trees have large water storage, especially when the canopy is developing, and the time lag for sap flow is longer, which could cause the large simulation errors for the C and Cj models (Liu et al., 2012). The NSE for simulated daily transpiration was -0.09 and 0.03 for the C and Cj models, and the biweekly NSE was 0.34 and 0.46 (table 3), respectively. The positive NSE value for the Cj model indicates that the Cj model was acceptable for simulation of daily transpiration (Moriasi et al., 2007).

## COMPARISON OF MODELED AND MEASURED EVAPORATION OVER THE GROWING SEASON

The daily average simulated evaporation was similar to

Table 3. Relationship between mean simulated transpiration and measured sap flow.<sup>[a]</sup>

Time Scale	Model	$T_{sap}$	$T_{sim}$	$b$	$r^2$	MAE	RMSE	NSE	$d$
Hourly	C	0.132	0.115	1.04	0.53	0.093	0.116	-0.52	0.58
	Cj	0.132	0.105	0.96	0.55	0.084	0.104	-0.22	0.60
Daily	C	3.17	2.40	0.75	0.46	1.00	1.22	-0.09	0.52
	Cj	3.17	2.49	0.78	0.49	0.94	1.15	0.03	0.55
Biweekly	C	3.17	2.40	0.81	0.73	0.65	0.75	0.34	0.55
	Cj	3.17	2.49	0.84	0.75	0.58	0.67	0.46	0.58

<sup>[a]</sup>  $T_{sim} = b \times T_{sap}$ , where  $T_{sap}$  is the trunk sap flow rate ( $\text{mm h}^{-1}$  and  $\text{mm d}^{-1}$ ),  $T_{sim}$  is the average transpiration simulated by the C or Cj model ( $\text{mm h}^{-1}$  and  $\text{mm d}^{-1}$ ),  $b$  is the regression coefficient,  $r^2$  is the coefficient of determination, MAE is the mean absolute error ( $\text{mm h}^{-1}$  and  $\text{mm d}^{-1}$ ), RMSE is the root mean square error ( $\text{mm h}^{-1}$  and  $\text{mm d}^{-1}$ ), NSE is the Nash and Sutcliffe modelling efficiency, and  $d$  is the index of agreement.

**Table 4. Mean simulated evaporation and measured evaporation by the micro-lysimeter in 2008-2010.<sup>[a]</sup>**

Model	$E_L$	$E_{sim}$	$b$	$r^2$	MAE	RMSE	NSE	$d$
SW	1.14	0.79	0.68	0.48	0.42	0.25	-0.14	0.51
C	1.14	1.02	0.87	0.52	0.30	0.13	0.64	0.60
Cj	1.14	1.22	1.04	0.53	0.32	0.15	0.68	0.61

<sup>[a]</sup>  $E_{sim} = b \times E_L$ , where  $E_L$  is the evaporation measured by micro-lysimeter ( $\text{mm d}^{-1}$ ),  $E_{sim}$  is the daily average evaporation simulated by the C or Cj model in hourly steps ( $\text{mm d}^{-1}$ ),  $b$  is the regression coefficient,  $r^2$  is the coefficient of determination, MAE is the mean absolute error ( $\text{mm d}^{-1}$ ), RMSE is the root mean square error ( $\text{mm d}^{-1}$ ), NSE is the Nash and Sutcliffe modelling efficiency, and  $d$  is the index of agreement.

the measured evaporation from the micro-lysimeters. The slopes of the direct regression equation were 0.68, 0.87, and 1.04 for the SW, C, and Cj models, respectively. As its slope was closer to 1, the Cj model was more suitable for evaluating soil evaporation. The  $r^2$  was 0.52 and 0.53, the MAE was 0.30 and 0.32  $\text{mm d}^{-1}$ , the RMSE was 0.13 and 0.15  $\text{mm d}^{-1}$ , the NSE was 0.64 and 0.68, and  $d$  was 0.60 and 0.61 for the C and Cj models, respectively, which indicated that the C and Cj models were better than the SW model at simulating evaporation for these conditions (table 4). Zhang et al. (2009) suggested that the C model was more appropriate for calculating ET in a sparse grape orchard. After comparing ET simulated by the different models to the sap flow and micro-lysimeter method, the seasonal clumping model (Cj) was found more suitable to evaluate ET in the arid apple orchard. Juhász and Hrotkó (2014) simulated ET for a ten-years-old ‘Rita’ sweet cherry (*Prunus avium* L.) stand and suggested that the SW model was suitable for estimating ET after comparing the SW model with heat balance sap flow. If the mature orchard had a higher ratio of LAI to bare soil area (i.e., more shading), then soil evaporation modeling should separate the bare soil outside of the canopy from the soil under the canopy. Moreover, the less open airflow under the canopy in mature orchards also affects the differences in soil evaporation under the canopy and from bare soil outside the canopy.

Moreover, the evaporation measured using the micro-lysimeters used a daily time scale, so it may not be appropriate for evaluating the modeled hourly evaporation. The Cj model obviously performed better than the C and SW models; therefore, of the three models, the Cj model described the soil evaporation process best in this mature orchard.

#### COMPARISON OF MODELED AND MEASURED ET OVER THE GROWING SEASON

The total ET measured by the sap flow and micro-lysimeter method was 667, 674, and 583 mm in the 2008, 2009, and 2010 growing seasons, respectively (table 5). The ET simulated by the Cj model was almost the same as the measured ET. The average measured ET was 3.72, 3.85, and 3.39  $\text{mm d}^{-1}$  during 2008, 2009, and 2010, respectively (table 5). Seasonal peak values of apple orchard ET

were 5.79, 7.00, and 6.62  $\text{mm d}^{-1}$  with minimum values of 1.28, 1.19, and 1.00  $\text{mm d}^{-1}$  in 2008, 2009, and 2010, and the fluctuation of the simulated ET was larger than that of the measured ET (fig. 7). Consoli and Papa (2013) measured 15- to 25-year-old orange trees using the heat pulse velocity technique and found that the average  $ET_{SL}$  was 3.2 to 3.4  $\text{mm d}^{-1}$  during 2010 and 2011, and the Penman-Monteith modeled ET ranged from 6.7 to 1.2  $\text{mm d}^{-1}$ , which matched our results. Ouyang et al. (2013) found that the peak ET was 7.1  $\text{mm d}^{-1}$  in a 12-year-old peach orchard.

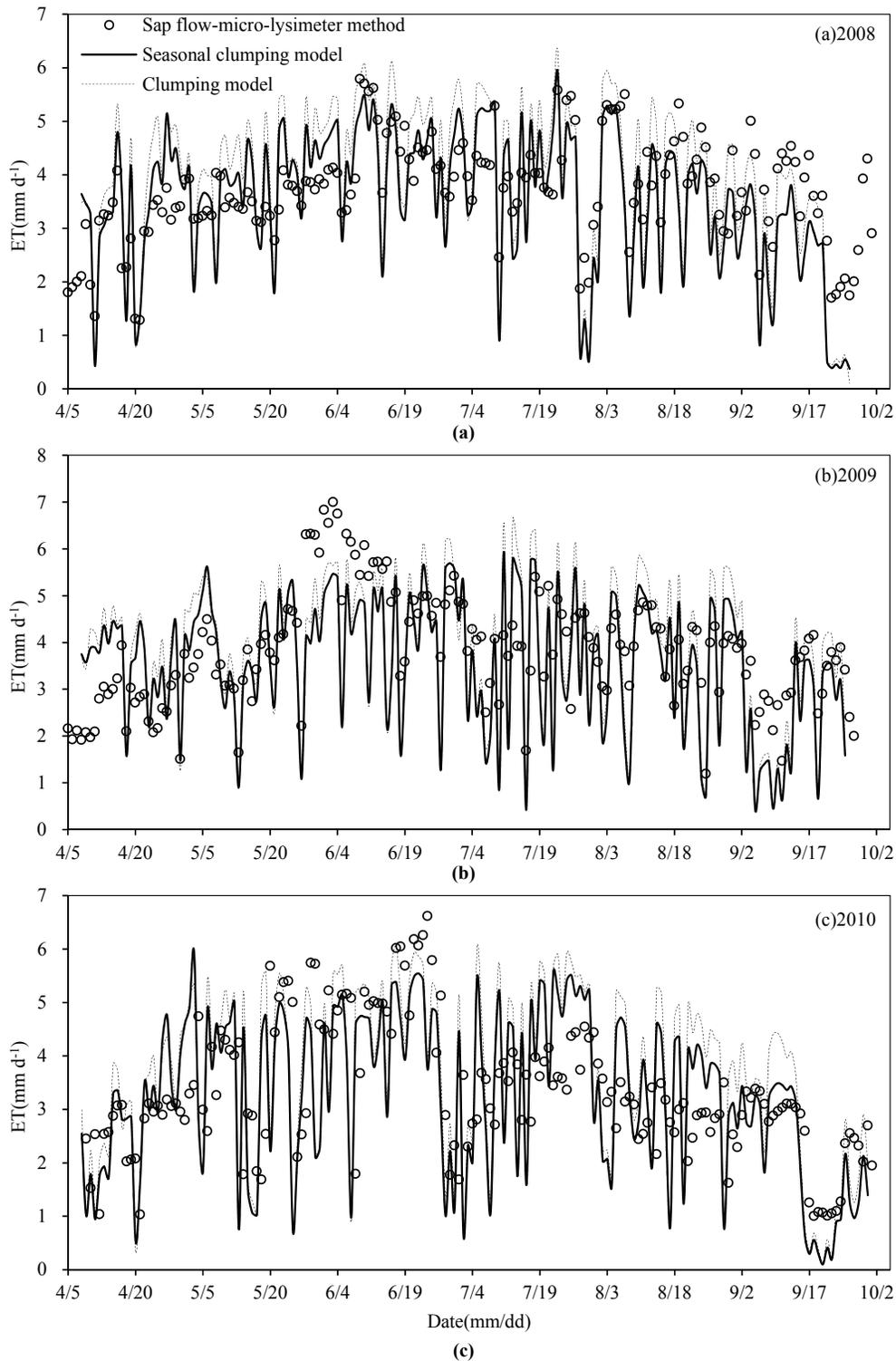
The fluctuations of sap flow and micro-lysimeter ET were less than the fluctuations modeled by the Cj model, which calculated ET using the principle of aerodynamics (fig. 7). Figure 7 shows that the ET simulated by the Cj model was closer to the measured ET than was the ET simulated by the C model. The water storage of mature apple trees decreases with transpiration (Liu et al., 2011), so the diurnal sap flow flux increased with a time lag, especially in the fruit bearing and maturing periods. The sap flow maintained a low value to supplement the water storage during the night, with little transpiration (Liu et al., 2012). The ET simulated by the Cj model was either higher or lower than the ET measured during the fruit bearing and maturing periods. The overestimation might be due to model calculation of canopy resistance with maximum leaf stomatal conductance. Our field measurements showed that the stomata closed by midafternoon on sunny days (fig. 4). The underestimation only occurred after irrigation or large precipitation events. The estimated surface soil resistance in the Cj model was measured at the 0-10 cm depth. Thus, the soil resistance variable in the Cj model might be set too high for periods after an irrigation and large precipitation event (Brenner and Incoll, 1997; Shuttleworth and Wallace, 1985). Further investigations are needed to evaluate the soil resistance for different soil moisture conditions.

The soil evaporation was 24% to 32% of ET (table 5 and fig. 8), suggesting that evaporation was an important flux in the apple orchard. By comparison, evaporation from a semi-arid cactus pear orchard was 26% of total ET (Consoli et al., 2013). However, Cammalleri et al. (2013) found a much lower E/ET (18%) in a drip-irrigated olive orchard. Many researchers have suggested methods for minimizing

**Table 5. Annual sap flow and micro-lysimeter measured ET and simulated ET.<sup>[a]</sup>**

Year	Period	Sap Flow and Micro-Lysimeter Method					Cj Model Simulation				
		$T_{sap}$	$E_L$	$ET_{SL}$	$Avg_{SL}$	E/ET	$T_{sim}$	$E_{sim}$	$ET_{sim}$	$Avg_{sim}$	E/ET
2008	5 April to 1 Oct.	508	159	667	3.72	0.24	441	187	628	3.51	0.30
2009	5 April to 27 Sept.	511	163	674	3.85	0.24	474	150	624	3.56	0.24
2010	9 April to 28 Sept.	398	185	583	3.39	0.32	390	181	572	3.32	0.32

<sup>[a]</sup>  $E_L$  and  $E_{sim}$  are the annual evaporation measured by micro-lysimeter (mm) and the total evaporation simulated by the Cj model (mm),  $T_{sap}$  and  $T_{sim}$  are the annual transpiration measured by sap flow (mm) and the total transpiration simulated by the Cj model (mm),  $ET_{SL}$  and  $ET_{sim}$  are the annual evapotranspiration measured by the sap flow and micro-lysimeter method (mm) and the total evapotranspiration simulated by the Cj model (mm), and  $Avg_{SL}$  and  $Avg_{sim}$  ( $\text{mm d}^{-1}$ ) are the averages of the total  $ET_{SL}$  and  $ET_{sim}$ , respectively.



**Figure 7.** Seasonal variation in evapotranspiration ( $\text{mm d}^{-1}$ ) measured by the sap flow and micro-lysimeter method and simulated by the seasonal clumping model (Cj model) and the clumping model (C model) in (a) 2008, (b) 2009, and (c) 2010.

soil evaporation, such as drip or sprinkler irrigation (Alber to et al., 2014; Du et al., 2008; Zhou et al., 2012) or covering the bare soil with plastic sheeting or straw mulch (Ding et al., 2013; Hou et al., 2010; Jalota and Prihar, 1998; Li et al., 2013; Mukherjee et al., 2012). Flood irrigation is the

primary tool used to maintain agriculture in the study region (fig. 8). Although climate and vegetation variations control ET and water cycles at the regional scale (Sun et al., 2014), the influence of human intervention might be greater for crops in this arid region.

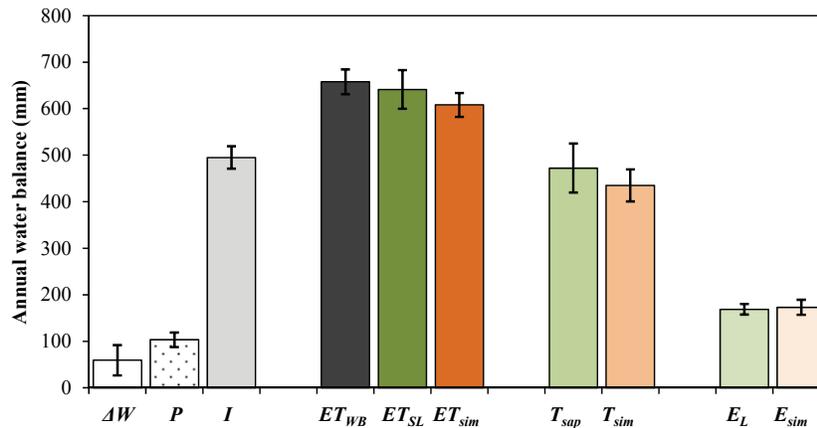


Figure 8. Components of water balance method and ET simulated by the Cj model for the 2008-2010 growing seasons:  $\Delta W$  is the total change in soil water content in the 0-180 cm depth (mm),  $P$  is the total precipitation (mm),  $I$  is the total irrigation (mm),  $ET_{WB}$  is the total ET for the water balance method (mm),  $ET_{SL}$  is the total ET for the sap flow and micro-lysimeter method (mm),  $ET_{sim}$  is the total ET simulated by the Cj model (mm),  $T_{sap}$  is the total transpiration measured by sap flow (mm),  $E_L$  is the total evaporation measured by micro-lysimeters (mm), and  $T_{sim}$  and  $E_{sim}$  are the total transpiration and evaporation simulated by the Cj model (mm).

## CONCLUSIONS

Three-year field ET measurements on apple trees using the sap flow and micro-lysimeter method were comparable to ET based on the water balance method. The sap flow and micro-lysimeter method was suitable to measure the daily ET and can be considered a standard method to evaluate ET models in these ecosystems.

Both the SW and C models are based on the Penman-Monteith model and are widely used in sparse crops. This study offered an improved model by combining hourly changes in canopy shade patterns and canopy gap fraction to better represent soil evaporation processes. The cover ratio introduced in the Cj model was useful for estimating seasonal ET in the arid apple orchard. The simulated relative soil evaporation error was significantly lower for the Cj model than for the SW and C models.

The ET simulated by the Cj model suggested that soil evaporation consumed over 30% of total water inputs (i.e., precipitation and irrigation). Both simulated and measured ET suggested that irrigation was essential to the apple trees to avoid a water deficit during the growing season. As the demand for water increases, water saving through managing evaporation by agronomy or engineering techniques is becoming more important. Our new model can be used in this effort in this apple growing region.

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