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Measured and Estimated Evapotranspiration of Jujube (*Ziziphus jujuba*) Forests in the Loess Plateau, China

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Abstract

Evapotranspiration (ET), which is the sum of plant transpiration and soil evaporation, is a continuous process of water loss in the soil-plant-atmosphere continuum. An accurate prediction of ET is necessary for developing agricultural management strategies to improve water use efficiency and ensure sustainable agricultural production, especially for regions subjected to water scarcity. This study used the dual-source Shuttleworth-Wallace (SW) model to quantify the subsequent components of ET (transpiration and evaporation) in jujube (*Ziziphus jujuba* Mill.) plantations in the fragile, semi-arid, hilly Loess Plateau region of Mengcha Village in Shaanxi Province, China. Thermal Diffuse Probe (TDP) measuring transpiration and estimated evapotranspiration (ET) via local water balance method were used to validate the SW-model estimations for the 2012 jujube growth seasons. The estimated precision of the hourly and daily transpiration varied with weather conditions and the accuracy of ET depended on the growth stage. However, the estimated transpiration and ET were within acceptable values. During the growth seasons, jujube forest consumed some 463 mm (≈103%) of the annual precipitation (451 mm), ≈65% of which is transpiration and 35% evaporation. This corresponds to a significant water stress under the rain-fed cultivated jujube plant in the study area. Nighttime transpiration was small and ≈81% of the total transpiration occurred in the daytime. This study further verified the suitability of the SW-model application in semiarid, rain-fed conditions and is useful for managing local jujube water consumption.

Keywords: Jujube; Evapotranspiration; Loess Plateau; Semi-arid climate; SW-model

Introduction

Jujube is a traditional Chinese fruit tree that is tolerant to drought (Liu, 2010). Because jujube is adaptable to semi-arid conditions and has significant economic benefits, it has been widely cultivated over the years in the Loess Plateau region and currently covers some one million hectares of land. Moreover as several varieties of forest trees have high water consumption rate inducing drying up of soils and related ecological problems (Li, 2001; Chen *et al.*, 2007, 2008), jujube could provide a sustainable cultivation strategy in semi-arid environments. It is therefore beneficial to study water consumption mechanism of jujube forest especially in mountainous regions corresponding to fragile semi-arid environments. The accurate prediction of evaporation and transpiration, collectively known as evapotranspiration (ET), is necessary for developing viable water-saving management strategies that support high water use efficiency (WUE) and economic benefit.

As recommended by FAO-56, the Penman-Monteith (PM) model is amongst the most familiar model to estimate both actual ET (ET) and potential ET (PET) (Allen *et al.*, 1998). The PM-model assumes the entire canopy as being a "big leaf" while ignoring evaporation from beneath, which only holds true under dense forest/crop conditions. When evaporation is a significant fraction of ET (as in sparse forest/crop conditions), the PM-model could greatly underestimate ET (Shuttleworth and Wallace, 1985). In the Loess Plateau, due to water shortage, jujube forests are usually cultivated sparsely with low canopy cover (<40%), which increases the soil evaporation contribution to the forest water balance. Building on the PM-model, Shuttleworth and Wallace (1985) derived the SW-model, which is actually a coupled canopy and soil surface model. The SW-model can separately simulate evaporation and transpiration. Lafleur and Rouse (1990) also noted that the SW-model was in excellent agreement with hourly and daytime measurements of ET. Further, Federer *et al.* (1996) compared the SW, PM, Priestley-Taylor (PT) and McNaughton-Black (MB) models for potential ET in three different land cover types and concluded that potential ET in all the land cover types was best estimated by the SW-model. For potential ET in a forest ecosystem, Fisher *et al.* (2005) confirmed Federer *et al.* (1996) results.

The SW model has been used over vineyards (Zhang *et al.*, 2008; Ortega-Farias *et al.*, 2010) and some row crops such as maize, wheat and cotton (Anadranistakis *et al.*, 2000; Kato *et al.*, 2004), but very little studies report its

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applicability over orchard conditions. Kato *et al.* (2004) noted that most previous simulations involving the SW-model were for a few days or within a narrow range of leaf area index (LAI). Although Kato *et al.* (2004) ran the SW-model during a two months period, the accuracy of the estimation was not analyzed under different spatio-temporal and climatic conditions. Further, the SW-model has mostly validated on data from the eddy covariance (Sene, 1994; Fisher *et al.*, 2005; Zhu *et al.*, 2012) or Bowen ratio methods (Ortega-Farias *et al.*, 2007; Zhang *et al.*, 2008; Ortega-Farias *et al.*, 2010). Although the two methods are widely acceptable for ET measurement, they are not able to separate the vegetation and soil contributions. Further validation is therefore still needed via field observed transpiration or evaporation.

Thermal diffuse probe (TDP) is a widely accepted device used in measuring sap-flux directly in the field. Estimation of transpiration from sap-flux is relatively easy to implement at high precision with ready availability at a stand-alone or site scale (Granier *et al.*, 1996; Čermák *et al.*, 2004; Williams *et al.*, 2004). In this study, TDP-measured transpiration was used to validate the estimated transpiration at hourly and daily time scales while ET computed with the water balance method was used to evaluate the SW model-estimated ET. The sap-flux was monitored under different climatic, LAI and soil moisture conditions for one growth season involving 24 jujube trees over the period from May 10 to October 9, 2012. The performances of the SW-model were evaluated at hourly and daily time scales under a range of climatic conditions. The overall objective of the study was to provide comprehensive performances and validation of the SW-model in the semi-arid fragile environment. The study also builds additional insight into the water consumption of the local jujube forests.

Materials and Methods

Experimental Site and Measured Data

Experimental site: Field measurements were conducted in Mengcha village of Shaanxi Province, China (38° 11´N, 109° 28´E) for the period from May 10 to October 9 2012 corresponding to the jujube (*Ziziphus jujuba* Mill.) growth season. This is a typical semi-arid, hilly ravine of the Loess Plateau. The 9-year jujube trees with average canopy heights of ≈2 m at the time of the study were cultivated on the 40-degree east-facing slope terrace (Fig. 1). Because of economic constraints and lack of suitable irrigation techniques, the jujube fields were usually under rain-fed conditions. Moreover, due to the semi-arid conditions along with timely weed control, soils under the jujube plants were nearly bare.

The range of annual precipitation in the past decade is 432-510 mm, with a mean of 451 mm. The precipitation mainly occurs from July through September with a high inter-annual variability (Huang *et al.*, 2008). The annual mean temperature is 8.8°C and cumulative temperature ≥10°C is 3 470°C. Also long-term annual solar radiation in the study area is 580.5 kJ cm^{-2}. The soil type is typically loess, with a uniform texture and moderate permeability.

Measured data: Twenty four replicates of the sap-flux experiment were set up in the field using the same aged trees with similar trunk diameters and canopy structures (Fig. 1). A TDP was inserted into each tree connected to a data logger recording measurements every 10-min time steps. Following the methods proposed by Granier (1987) and Lu *et al.* (2004), the probe signals were converted into sap-flux. The rest of the calculations regarding transpiration were done after the recommendations given by Williams *et al.* (2004).

A neutron probe was used to measure soil moisture every 10 days in the 20–300 cm soil layer by 20 cm intervals (Fig. 1). A small weather station was installed nearby the experimental site to record the climate variables required by the SW and water balance models: precipitation (P, mm), net radiation (R, W m^{-2}), wind speed (W, m s^{-1}), relative humidity (H %) and temperature (T °C) in 10-min time steps. Because of the limited precipitation and small LAI during the jujube growth season, canopy interception, runoff and deep percolation contributions to the local water budget were neglected. Thus ET was computed from the local water balance as follows:

$$ET_i = P_i + V_i^o - V_i \tag{1}$$

Where, ET_i is the evapotranspiration at the i^{th} time step; V_i^o and V_i are soil water storage at the initial and end periods of the i^{th} time step, respectively. The soil water storage was calculated as the sum of water storage in each layer in a given time step.

The LI-6200 (USA) photosynthetic system was applied to monitor stomatal conductance, photosynthetic active radiation (PAR) and vapor pressure deficit (VPD) of jujube leaf for 10 sunny days during the growth season. The measurements were taken at the hourly time step between 07:00 and 19:00 local time. These data were used to fit the stomatal resistance model proposed by Winkel and Rambal (1990), given as:

$$r_l = \frac{r_{l\min}}{g(Q)g(D)} \tag{2}$$

$$g(Q) = 1 - \exp\left(\frac{-Q}{K_1}\right) \tag{3}$$

$$g(D) = 1 - \exp(-K_2 D) \tag{4}$$

Where, $r_{l\min}$ is the minimum stomatal resistance (s m^{-1}); Q and D represent PAR (μmol m^{-2} s^{-1}) and VPD (kPa), respectively; K_1 and K_2 are the minimum PAR value required for a nearly maximum stomatal aperture (μmol m^{-2} s^{-1}) and the canopy specified parameters (kPa^{-1}).

LAI was also obtained using the Winscanopy Regent (Canada) commercial canopy analysis equipment. LAI was analyzed each 10 days from germination until the stable state at fruit ripening stage. The time series data for LAI were fitted with growth function as follows:

$$LAI = 1.90 + \frac{-1.09}{1 + \exp((DOY - 157.49)/4.41)} \quad (5).$$

Where, DOY represents the day of year. The jujube growth season in 2012 lasted 153 days, from 131 DOY (May 10) to 283 DOY (October 9).

Model Description

Building on the PM-model, Shuttleworth and Wallace (1985) derived a combined dual-factor limit (bare soil and closed canopy ET) as follows:

$$ET = C_c PM_c + C_s PM_s \quad (6).$$

Where, C_c and C_s are model coefficients; PM_c and PM_s are the combined equation for the dual-factor limits of full canopy and bare soil in the PM-model. For the sake of brevity, we did not derive the S-W model here and refer readers to Shuttleworth and Wallace (1985).

After deriving ET, evaporation (E, mm) and transpiration (T, mm) could be separately computed as follows (Shuttleworth and Wallace, 1985):

$$E = \frac{\Delta R_{ns} + \rho c_p D_o / r_a^s}{\Delta + \gamma(1 + r_s^s / r_a^s)} \quad (7)$$

$$T = \frac{\Delta(R_n - R_{ns}) + \rho c_p D_o / r_a^c}{\Delta + \gamma(1 + r_s^c / r_a^c)} \quad (8).$$

Where, ρ is the air density (g mm^{-3}); γ is the psychrometric constant (kPa°C^{-1}); Δ is the saturated pressure slope (kPa°C^{-1}); c_p is the specific heat at constant pressure (MJ kg^{-1}°C^{-1}); D_o is the vapor pressure at transpiring height (kPa); R_{ns} is the solar radiation (W m^{-2}); The additional parameters are explained in Fig. 2.

The SW-model has been noted to be insensitive to the change in the coefficient of net radiation extinction over tree canopies (C). While change in ET was less than 1% for C range of 0.5–0.9 under different LAI values, the corresponding change in transpiration was 5–10%. Hence following the procedure described by Zhou *et al.* (2006), C was set to 0.5. Soil heat flux was also assumed to have a negligible effect on the simulation (Zhou *et al.*, 2006).

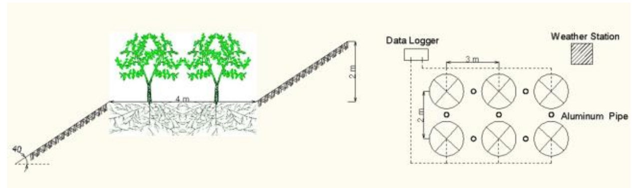

Fig. 1: Experimental layout and neutron probe pipe system in the soil at 3-m length and planted midway between every neighboring jujube trees for representative soil moisture in the study area

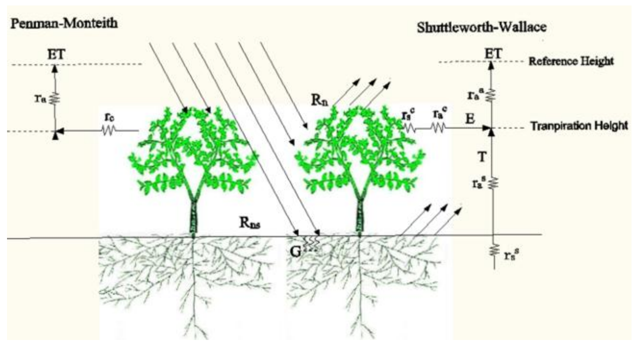

Fig. 2: Graphical depiction of the Penman-Monteith (PM) and Shuttleworth-Wallace (SW) models. ET is the evapotranspiration, which is the total evaporation (E) from soil surface and the transpiration (T) from plant canopy (mm); R_n and R_{ns} are respectively the net radiation above canopy and just above the soil surface (W m^{-2}); r_a is the aerodynamic resistance to transpiration from reference height (s m^{-1}); r_a^a is the aerodynamic resistance to transpiration from soil surface (s m^{-1}); r_c is the bulk resistance to canopy stomatal (s m^{-1}); r_s^c and r_s^s are respectively the canopy boundary layer and the soil surface resistances (s m^{-1})

The specific details regarding the calculations of the canopy surface resistances (r_a^c and r_s^c), aerodynamic resistances (r_a^s and r_a^a) have been well documented in the past (Shuttleworth and Wallace, 1985; Shuttleworth and Gurney, 1990; Zhou *et al.*, 2006; Zhu *et al.*, 2012). Soil resistance (r_s^s) was set to 1200 m s^{-1} in this study and is discussed later.

Model Evaluation

To assess the validity of the SW-model, the estimated values were compared with measured transpiration by TDP and the ET derived from the water balance method.

Following Annandale *et al.* (2004), three statistical parameters were used for the assessment: (1) mean absolute error (MAE, %); (2) coefficient of determination (R^2); and (3) Willmott index of agreement (D) — see Willmott (1982). According to De Jager (1994), the recommended model reliability criteria for R^2 and D is >0.8 and for MAE is <20%.

$$MAE = \frac{(1/n)\sum_{i=1}^{n}|Pi - Oi|}{O} \times 100 \quad (9)$$

$$D = 1 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(|Pi - Oi| + |Oi - O|)^2} \quad (10)$$

$$R^2 = \frac{\sum_{i=1}^{n}(Pi - O)^2}{\sum_{i=1}^{n}(Oi - O)^2} \quad (11).$$

Where, Pi and Qi are respectively the i^{th} predictions and observations (mm); n is the number of samples; O is the average observation (mm).

Results

Hourly Transpiration

Daytime hourly transpiration: The daytime hourly transpiration was estimated from processing hourly average values for the jujube growth season spanning from 131–283 DOY. Results for period 157–165 DOY (Fig. 3) showed that daytime transpiration followed similar daily dynamics, with maxima at noon and minima at daybreak/nightfall. The estimated average daytime hourly values were in good agreement with the observed values (R^2 = 0.88, D = 0.90 and MAE = 20%).

However, the comparison between the measured and estimated transpiration for specific hours shows some apparent discrepancies. Specifically, the simulated transpiration were higher than the observed values at noon and lower in the morning. This was especially significant on DOY 161 and 164. For the other hours, the mismatch between the simulated and observed transpiration was relatively small. Based on the criteria, the evaluation results for the different daytime hours show that the SW-model appeared to perform poorly at daybreak, noon and nightfall (Fig. 4).

Nighttime hourly transpiration: The lack of radiation during nighttime limits the SW-model in accurately estimating diurnal hourly transpiration. This implies that the SW-model simulated transpiration is invalid for nighttime hours, i.e., for the period 1900–0700 h. The observed nighttime transpiration plotted in Fig. 3 appears to follow a U-shaped curve, with minima at midnight and maxima just before daybreak or just after nightfall. The boxplot in Fig. 5 depicts an asymmetrical distribution of nighttime transpiration that was skewed for low or high values.

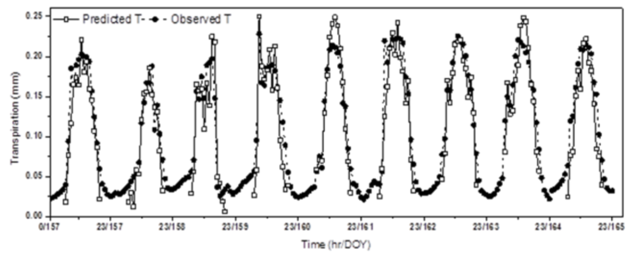

Fig. 3: Plot of average observed versus estimated hourly daytime transpiration (T) for the 157–165 DOY of 2012 in the Mengcha village study area

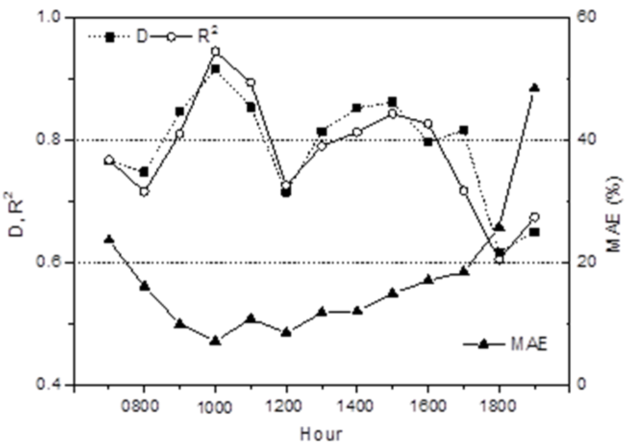

Fig. 4: Plot of tested model results for daytime hour (0700–1900 h). The two horizontal dash lines (0.8-40% and 0.6-20%) are the reliability criteria lines for D/R^2 and MAE, respectively. For each hour, 153 samples are used

Also the scatter was significantly larger during stages I and IV. During stages I and II, the average hourly nighttime transpiration was almost constant (0.027 mm/h). Then from the start of stage III, the transpiration rate steadily increased up to the peak value of 0.078 mm/h observed at the end of stage III. After that, the transpiration rate slightly decreased down to 0.05 mm/h (Fig. 5).

Daily Transpiration

Average daily transpiration for the studied jujube growth season was 2.17 mm/d. The observed transpiration rapidly increased from 1.11 to 2.67 mm/d in stage I, slightly increased in stages II and III, reaching the maximum of 3.56 mm/d at the end of stage III, and decreased through stage IV to 1.13 mm/d (Fig. 6).

The estimated and observed transpiration matched fairly well at the daily scale with R^2 = 0.87, D = 0.87 and MAE = 10.86% (Fig. 6 and Fig. 7). The transpiration estimated by the SW-model was further tested after grouping in terms of rain and non-rain weather conditions.

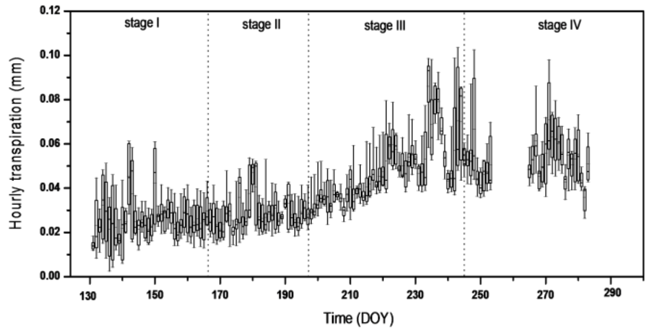

Fig. 5: Boxplot of nighttime transpiration of jujube plants. Note that outliers are omitted in the plot. The three vertical dash-lines divide the growth period into four stages (I–IV); respectively denoting germination to leaflet stage (131–167), flowering to fruit-setting stage (168–197), fruit enlargement stage (198–244), and fruit ripening stage (245–283). Due to instrument failure between DOY 258 and 265, no measurements are available for these days

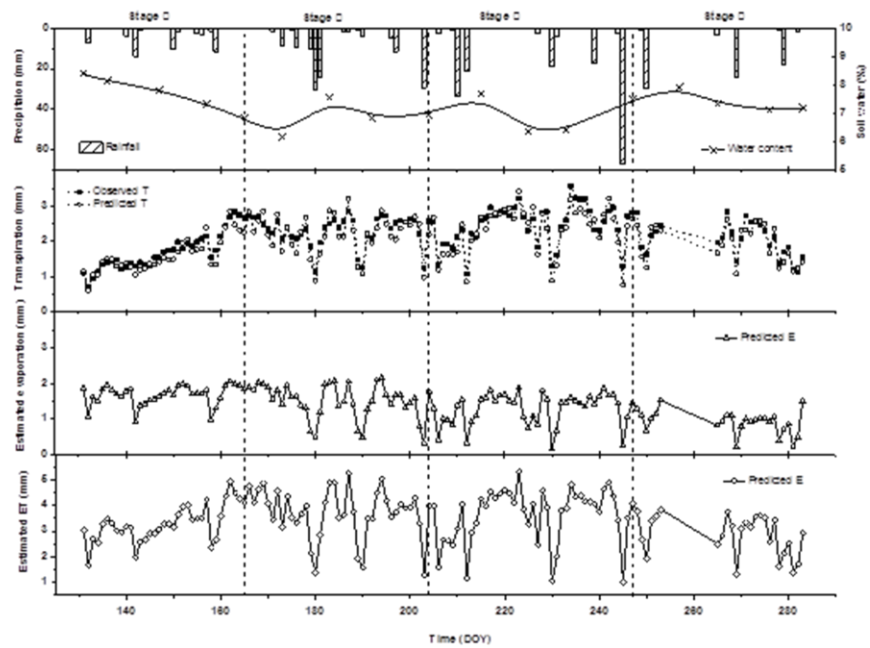

Fig. 6: Plots depicting daily trends of SW-model estimated transpiration and evaporation along with observed transpiration, soil water content and precipitation in the Mengcha village study area

The derived regression function for rain weather conditions was $y = x - 0.22$, where y denotes the SW-model estimated transpiration and x is the measured transpiration. The regression function suggests that estimated transpiration was smaller than the measured value. The SW-model performance in terms of daily transpiration was also within acceptable limits under rain weather conditions, but relatively better under non-rain weather conditions (R^2 = 0.89, D = 0.88 and MAE = 7.46%).

Ten-day Evapotranspiration

The local water balance used to evaluate the SW-model estimated ET at 10-day scale (Table 1) shows that the model was fairly accurate (R^2 = 0.71, D = 0.85 and MAE=12.35%). The average MAE for the estimated ET was 9.71%. Based on the jujube growth season, MAE tended to fall gradually from an average of 14.61% in stage I to 7.75% in stage IV (Table 1).

In this study, no direct measurement of evaporation was made. But since the reliability of both transpiration and evapotranspiration had been validated via field data, the estimated evaporation could still be regarded as acceptable results. The SW-model estimated values combined with other measured variables, presented a vivid insight into the drivers of water budget in jujube forests at different stages in the semi-arid rain-fed conditions.

Table 1: Details of the SW-model estimated evapotranspiration validation analysis at 10-day scale

Stage	Period	Precipitation (mm)	3-m depth soil water (mm)		Measured (mm)		Estimated (mm)			ET MAE (%)
			Initial time	Final time	T	ET	T	E	ET	
I	131-136	7.10	252.00±6.13	244.80±5.36	6.68±0.65	14.30	6.87	9.87	16.74	17.03
	137-147	17.60	244.80±5.36	234.80±5.94	15.26±1.28	27.60	14.47	17.26	31.73	14.98
	148-157	16.50	234.80±5.94	219.90±6.05	19.08±1.40	31.40	17.95	18.07	36.03	14.73
	158-165	12.60	219.90±6.05	205.00±6.00	18.88±1.39	27.50	17.01	13.71	30.72	11.72
II	166-173	9.60	205.00±6.00	184.50±6.67	19.88±1.56	30.10	19.14	14.45	33.59	11.60
	174-183	73.80	184.50±6.67	227.00±7.55	21.01±1.78	31.30	19.99	14.27	34.25	9.44
	184-192	7.00	227.00±7.55	204.59±7.06	20.06±1.92	29.41	19.20	12.36	31.55	7.28
III	193-204	45.60	204.59±7.06	208.17±7.01	29.50±2.70	42.02	27.71	18.03	45.74	8.86
	205-215	57.50	208.17±7.01	231.02±8.87	22.08±2.38	34.65	20.79	11.39	32.18	7.15
	216-225	0.00	231.02±8.87	190.91±9.79	27.94±2.73	40.10	27.90	14.95	42.85	6.85
	226-233	24.90	190.91±9.79	192.00±11.36	18.07±2.07	23.81	16.74	9.06	25.80	8.35
	234-247	86.50	192.00±11.36	225.28±8.73	38.29±3.91	53.22	35.47	20.08	55.55	4.38
IV	248-257	41.80	225.28±8.73	238.03±8.28	13.21±1.46	50.08	12.49	18.36	30.85	6.08
	266-276	24.50	220.27±8.28	212.67±5.94	25.23±2.84	31.10	23.92	10.05	33.97	5.81
	277-283	19.80	212.67±5.94	216.31±8.65	11.01±1.39	17.16	10.52	5.26	15.78	2.34

T, E and ET stand for transpiration, evaporation and evapotranspiration, respectively. Mean ± standard deviation. Note that the time intervals are not exactly 10 days because of soil water measurement difficulties due to bad weather conditions. This, however, does not significantly affect the results of the statistical/model analysis, respectively with MAE, D and R^2 for ET at n = 15 of 12.35, 0.85 and 0.71

Total water consumption in the jujube forest was 463 mm, approximately 65% of which was transpiration and 35% evaporation (Table 1). Although soil water content was only 8.4% (about 45% of field capacity) at the start of stage I, it was sufficient enough for this growth stage (Fig. 6). Despite the fact that the 53.8 mm rainfall increased the amount of water in the soil, the high ET (100.8 mm) depleted soil water down to 6.94%. The average daily evaporation and transpiration rates during this stage were similar (≈1.70 mm/d) although showing different patterns. In stage II, average daily transpiration steadily increased to 2.32 mm/d, which was 0.8 mm/d higher than the evaporation rate. Even though total ET increased to 132.83 mm during this stage, soil moisture kept low at 6.95%. This was explained by the higher precipitation received during stage II as compared to stage I.

Jujube consumption was highest (151.79 mm) in stage III, two-thirds of which was transpiration. Concurrently, precipitation was highest (168.90 mm) in stage III corresponding to ≈37% of the annual amount (451 mm). Because of the 63 mm rainstorm on DOY 245, soil water content improved to 7.51% but was still lower than the initial soil moisture during stage I. Both daily evaporation and transpiration rapidly dropped in stage IV, leading to a minimum value at the end of stage IV.

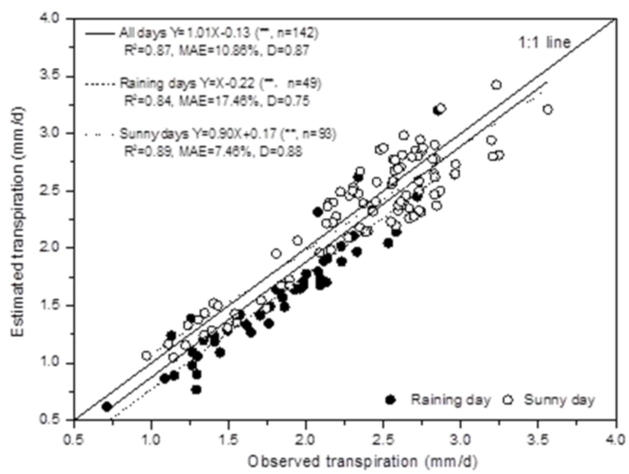

Fig. 7: Correlation plots of SW-model estimated versus observed daily transpiration for rain, non-rain and all weather conditions in the Mengcha village study area

Discussion

This study validated the SW-model for a fruit forest in semi-arid, rain-fed conditions using TDP-measured field data and local water balance. The estimated precisions of the hourly and daily transpiration varied with the weather conditions and the accuracy of ET depended on the growth stage. However, the estimated transpiration and ET always kept close to the actual values. The SW-model therefore proves to perform well for fruit trees in semi-arid, rain-fed conditions.

However, the SW-model is essentially derived from the PM-model and both are based on the K-theory. The models use the gradient diffusion theory that is normally violated at canopy water transport (Federer *et al.*, 1996). New theories and models, e.g. the Lagrangian turbulent diffusion theory, explain counter-gradient transport (Raupach, 1988, 1989). However, the use of high computational time by Lagrangian models makes them unfit for applications at large spatial and temporal scales (Dolman and Wallace, 1991). Moreover, detailed measurements of canopy structure formation are too demanding for field applications (Van den Hurk and McNaughton, 1995). Jujube has special deciduous branches bearing shoots (Liu, 2010), adding much difficulty to describe the canopy structure. Moreover, comparisons of Lagrangian and K-theory models (Dolman and Wallace, 1991) reveal minimal differences in estimated ET over low density crops.

Table 2: Correlation coefficients and multiple linear functions for nighttime hourly transpiration (T) in relation to the meteorological factors of relative humidity (RH), Temperature (Temp) and vapor pressure deficit (VPD)

	RH	Temp	VPD	Linear function
T	0.664**	-0.483**	-0.676**	$T = (33.4 + 0.614RH - 1.39T + 7.86VPD) \times 10^{-3}$

The asterisks (**) denote that a value is significant at $p < 0.01$. The R^2 for the linear function is 0.548 at the 1327 degrees of freedom, which is also significant

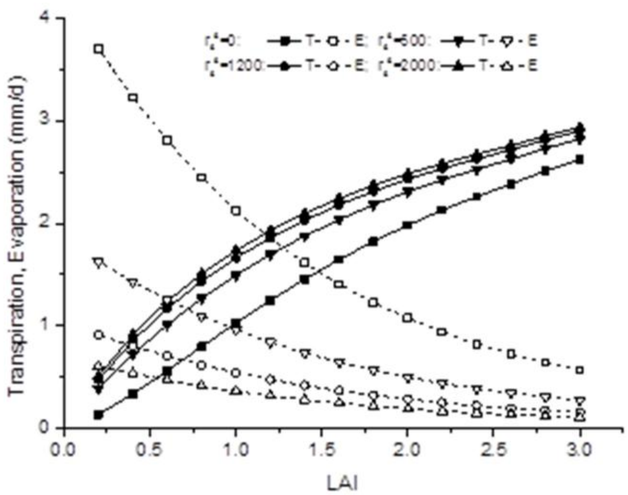

Fig. 8: Plots of the SW-model estimated transpiration (T) and evaporation (E) response to soil surface resistance (r_s^s). Note that this is under constant climatic conditions with daily average relative humidity of 45%, daily maximum temperature of 30°C, daily minimum temperature of 14°C, wind speed of 0.8 m s^{-1}, and solar radiation of 23 W m^{-2}

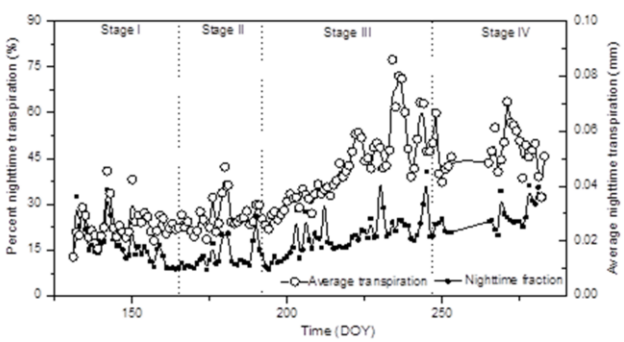

Fig. 9: Dynamics of average daily nighttime transpiration along with nighttime fraction of the average for the jujube growth season in the Mengcha village study area

A 10-min climate data were used to obtained hourly and daily maximum and minimum temperature, daily average wind, total radiation and average relative humidity. FAO-56 recommends the use of maximum and minimum temperature against average temperature as input for estimating the PM-type daily potential ET. This is because if daily average values are used, underestimation of ET could occur due to non-linear relationship between saturation vapor pressure and temperature (Allen *et al.*, 1998). Also 5-day or monthly input examination by Federer *et al.* (1996) noted no significant degradation effects on simulated results. This property makes the SW-model very reliable for simulating evaporation and transpiration at large spatial and temporal scales (Zhou *et al.*, 2006).

The application of the SW-model therefore is considered reliable and operational for the sparse jujube plantations in the study area. Because of hilly semi-arid terrain, natural or cultivated forests in the Loess Plateau occur in sparse and low density with small LAI. Such crop stand is well captured by the SW-model, due to its structure and input variables. This is useful for applying and developing sustainable agricultural water management strategies in the fragile semi-arid region.

The accuracy of the SW-model mainly depends on how closely the stomatal resistance and LAI reflect reality: as a matter of facts, the tree water dynamics are most significantly driven by these factors. Also Ortega-Farias *et al.* (2007) reported that the SW-model was sensitive to errors of ±30% in LAI and mean stomatal resistance, while was not affected by errors in the estimation of aerodynamics resistances. Furthermore, LAI is a dynamic variable with major impact on the tree water balance. LAI was measured here using commercial equipment that operates on the gap fraction theory (Welles and Cohen, 1996). However, LAI retrieval may be largely impacted by the embedded assumptions regarding the spatial distribution of the leaves, the presence of non-photosynthetic elements as well as difficulties in images classifications (Jonckheere *et al.*, 2004; Weiss *et al.*, 2004). When LAI is low, the impact of LAI error on ET becomes significant. This could explain why the best performances were observed with the higher LAI values (Table 1).

Moreover, stomatal behavior is driven both by the climatic/weather conditions and by soil-plant water conditions mainly governed by the soil water availability. As mentioned above, a simple stomatal model (Winkel and Rambal, 1990) that uses only climatic factors, PAR and VPD was adopted in this study. Although the model requires less parameters and observations, it could not be less accurate than any complex stomatal model given the soil water variability in hilly study area. For the jujube growth season under rain-fed conditions, the average fluctuation in observed soil moisture within the 3-m soil layer was less than 10% (Fig. 6). This suggests that jujube crops in the study area were under a fairly fixed range of persistent water stress. The analysis also shows that the use of the simplified stomatal model had no significant degradation effect on the simulated values. Visible discrepancies only appeared at extreme times of the day like at noon, daybreak and nightfall hours (Fig. 4), and in rainy day conditions (Fig. 7).

In this study, soil surface resistance was the only fixed resistance (r_s^s). The response of estimated daily evaporation and transpiration was analyzed at four levels of r_s^s, 0, 500, 1200 and 2000 s m^{-1}, respectively denoting very wet, wet, dry and very dry soil moisture conditions (Shuttleworth and Wallace, 1985; Zhou *et al.*, 2006). The large evaporation and transpiration gaps at r_s^s of 0 and 500 (Fig. 8) suggest that the SW-model is sensitive to this factor within r_s^s range of 0–500. As r_s^s increases beyond 500, the model becomes increasingly insensitive to this factor. As discussed above, the soil moisture was low and relatively constant during the growth season (Fig. 6). The performance of SW-model indicates that the fixed r_s^s (1200 m s^{-1}) adopted in this study could well reflect the reality of soil resistance during the jujube growth season.

The atmospheric water transport which accounts for a significant fraction of plant daily water consumption, is a continuous process. While nighttime evaporation is often ignored, the TDP instrument instead measures even nighttime transpiration. Correlation analysis shows nighttime hourly transpiration in the study area is significantly driven by the meteorological factors of VPD, relative humidity and temperature (Table 2), which is consistent with the findings of Buckley *et al.* (2011). Further, as stomatal processes during night time are not very clear, a statistical multi-linear model could simulate nighttime transpiration (Table 2). Future investigations of this empirical model would allow furthering exploring the dynamics of hourly daytime and nighttime transpiration.

For the jujube growth season, nighttime transpiration (which was 19% of average daily transpiration) was positively related with average daily transpiration (Fig. 9). This observation was different from that reported by Buckley *et al.* (2011), Daley and Phillips (2006) and Phillips *et al.* (2010), where 6–10% variation was noted. The discrepancy could be due to differences in tree species and site conditions.

The study shows that ET was heavily driven by transpiration in the region, especially daytime transpiration. Based on the analysis, annual ET in the study area exceeds average annual precipitation, suggesting a water stress condition during jujube growth season. While transpiration accounted for some 65% of the ET, daytime transpiration was 81% of the total transpiration. As a major cash crop in the region, the results could be useful in devising more efficient water management strategies to improve water use efficiency and jujube yields. The successful application of the SW-model in the study area also laid the foundation for replications in other semi-arid regions across the globe.

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