

Estimating Actual Transpiration of Apple Trees Based on Infrared Thermometry

Y. Osroosh¹; R. T. Peters²; and C. S. Campbell³

Abstract: A method was developed based on the radiative properties and energy budget of a single apple leaf to calculate the actual transpiration (T) of apple trees. The model uses canopy temperature (T_c), air temperature (T_a) measured in the orchard, and other meteorological data from a local weather station as inputs. The model was applied to two scenarios, as follows: (1) well-watered, young Fuji apple trees in the 2007 and 2008 growing seasons; and (2) older apple trees, bearing little fruit in the 2013 growing season. Simulated transpiration rates at both scenarios were compared with Penman-Monteith (PM) model predictions corrected by regionally adjusted crop coefficients, i.e., values of ET_c . In 2007 and 2008, a linear regression analysis of the relationship between daily mean transpiration (T_{avg}) and ET_c revealed that they better agreed on warm and dry days (correlation coefficient $R^2 = 0.57$, slope = 1.16, and intercept = 0.4) than during cold and humid periods ($R^2 = 0.48$, slope = 0.69, and intercept = 2.3). Combining the results of the 2007 and 2008 seasons, T_{avg} and ET_c presented a fairly good agreement, with the relationships R^2 , slope, and intercept of 0.77, 1.0, and 1.08, respectively. In 2013, the actual water use calculated by a soil water budget approach (ET_{WB}) was considerably less than ET_c while there was no significant difference between the total simulated transpiration (ΣT_{avg}) and ET_{WB} . In 2013, a linear regression analysis of the relationship between midday T (T_{mid}), T_{avg} , and midday stem water potential (Ψ_{stem}) showed they were highly correlated (T_{mid} , $R^2 = 0.85$; T_{avg} , $R^2 = 0.87$). The experiments presented varied results on the linear relationship between air vapor pressure deficit (D_a) and T_{avg} from year to year. On the other hand, canopy and air temperature difference (ΔT_m) was linearly related to T_{avg} in all of the seasons. According to the model for the actual transpiration (i.e., the T-model), the apple trees had an intense transpiration in the morning and then there was a decline around solar noon. The transpiration increased again late in the afternoon. Real-time estimations of water use using the T-model can provide a basis for a fully automated system of irrigating apple orchards. DOI: 10.1061/(ASCE)IR.1943-4774.0000860. © 2014 American Society of Civil Engineers.

Author keywords: Infrared thermometry; Energy budget; Stem water potential; Crop coefficient; Evapotranspiration.

Introduction

To maximize irrigation efficiency, applied water has to be precisely adjusted to the crop water use (Casadesús et al. 2011). The water use of apple trees (ET_c) is often estimated using the reference Penman-Monteith (PM) evapotranspiration (ET), ET_r (Allen et al. 1998), and corrected by a crop-specific coefficient (K_c ; Lakso 2003). Due to various approximations and assumptions in the determination of K_c , ET_c estimations can be inaccurate (Auzmendi et al. 2011). To eliminate the need for using a crop coefficient, some researchers have related the transpiration of apple trees to the field measurements of daily or midday radiation interception (Auzmendi et al. 2011; Girona et al. 2011; Casadesús et al. 2011). However, these relationships are empirical and site-specific data are most often required (Pereira et al. 2006).

Apple trees fall into the category of tall, discontinuous horticultural crops with well-coupled leaves to the atmosphere (Jarvis 1985).

The transpiration of apple trees is controlled by stomatal conductance, net radiation, and an air vapor pressure deficit (Lakso 2003; Dragoni et al. 2005). In addition to responding to environmental factors such as solar radiation and vapor pressure deficit (Jarvis 1985; Lakso 2003), the stomatal conductance of apple leaves reacts to changes in crop loads (Palmer et al. 1997). The latter is not directly accounted for in available models for estimating conductance (Jarvis 1976; Thorpe et al. 1980); thus, satisfactory estimations are dependent upon local adjustments and empirical coefficients.

It is well-known that stomata close in the face of water deficit to decrease the tree water loss through transpiration. This in return leads to an elevated canopy temperature (Blonquist et al. 2009). As an alternative approach, the empirical models of stomatal conductance can be possibly replaced with canopy temperature measurements by infrared thermometers (IRTs) or thermal pictures of canopies. Rather than being a relative indicator of water stress, the canopy temperature along with an energy budget equation may be then used to estimate the transpiration of apple trees.

There is fairly good literature available on the applications of infrared thermometry in ET estimations of homogenous row crops. Jackson et al. (1981) proposed a method based on infrared thermometry to calculate crop ET indirectly from the crop water stress index (CWSI) measurements. In accordance with the same approach, Taghvaeian et al. (2012) used CWSI values to estimate maize transpiration. Ben-Asher et al. (1989) used infrared thermometry to estimate aerodynamic and canopy resistance required for the computation of transpiration from a Penman ET equation in tomatoes.

However, the nonhomogeneity of the tree canopies poses a big challenge in the use of infrared thermometry and modeling of the

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transpiration process. The high cost of thermal cameras with complicated image processing requirements and inadequate resolution of satellite images make them implausible options (Testi et al. 2008). It might be possible to achieve an optimum accuracy using infrared sensors by choosing proper installation positions and angles, and/or averaging readings from a number of sensors.

Thermal methods in the form of an empirical CWSI have been studied on some fruit trees including pistachios, peaches, olives, and grapevines (Testi et al. 2008; Paltineanu et al. 2013; Berni et al. 2009; Agam et al. 2013; Akkuzu et al. 2013; Wang and Gartung 2010). Tokei and Dunkel (2005) reported a case study on the possible use of canopy temperature in the determination of apple tree transpiration by a theoretical approach. Their study focused primarily on the interactions of canopy temperature and some environmental factors (i.e., radiation and relative humidity) measured in the vicinity of the trees with some specialized instruments.

The goal of this paper was to develop an analytical model for estimating the real-time transpiration of apple trees from the energy budget of a single apple leaf similar to that of the big leaf approach (Monteith 1965; Thorpe 1978; Caspari et al. 1993). The research reported in this paper included a method of estimating net radiation from climatic parameters to avoid a need for net radiation measurements in the field. Estimated transpiration rates were compared with the PM model simulations adjusted by the crop coefficient values for the region.

Modeling of Transpiration

Neglecting metabolic heat production and heat storage, the energy balance model for a single apple leaf under steady-state conditions can be expressed as (Campbell and Norman 1998; Monteith and Unsworth 1990)

$$R_n = R_{abs} - L_{oc} = H + (\lambda E) \quad (1)$$

where R_n = net radiation; R_{abs} = absorbed radiation; λE = latent heat flux; L_{oc} = outgoing emitted radiation; and H = sensible heat flux from the leaf (all terms are in Wm^{-2}). R_{abs} is the sum of absorbed shortwave and longwave radiations.

In the research reported in this paper, the IRTs were installed above the trees where they could only see the upper half of canopy (Fig. 1). The top tree leaves were then categorized into two main groups based on their exposure to longwave and shortwave radiation sources at solar noon, as follows: (1) one side exposed to the

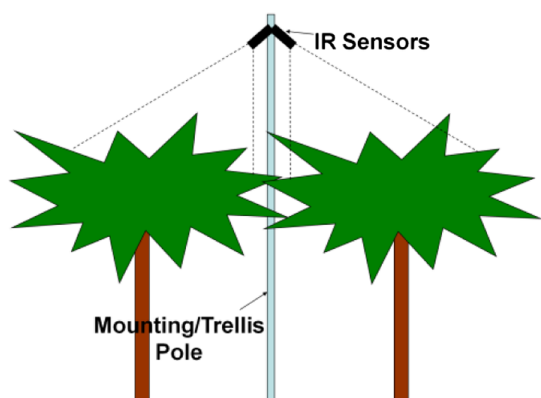


Fig. 1. Infrared thermometer sensors setup in the field; in 2007 and 2008, the sensors were pointed downwards at approximately 45° angles at both the north and south sides of a tree

sky and the other side exposed to the foliage (top leaves), and (2) both sides mostly exposed to the foliage within the canopy (middle or inner leaves). The modeling was based on the assumption that the upper half can be treated as a single leaf bearing all the characteristics of both leaf types. The contribution of the lower canopy was summarized into a longwave energy component (L_c) radiated to the upper half. The temperature at the border of the two halves was assumed to be the same as the canopy temperature (T_c) measured by an IRT.

Apple trees have discontinuous, sparse canopies. They can have various forms of architecture and their leaves are of different shapes, sizes, and orientations. In addition, a tree canopy is comprised of an unknown number of shaded (inner) and sunlit (top) leaves, and shoot growth constantly changes the light interception pattern. On the other hand, it is very probable that during day all types of leaves finally become sunlit for about half of daylight hours. Thus, it is not far-fetched to assume equal numbers of leaves in each category. Thus, R_{abs} of a representative leaf can be expressed as

$$R_{abs} = (0.5R_{top}) + (0.5R_{inner}) \quad (2)$$

The total absorbed radiation (Watts per square meter) for the top and middle leaves were estimated using Eqs. (3) and (4), respectively, as per Campbell and Norman (1998)

$$R_{top} = [\alpha_S(F_{gl}S_{gl})] + \{\alpha_L[(F_aL_a) + (F_cL_c)]\} \quad (3)$$

$$R_{inner} = [\alpha_S(F_{tr}S_{tr})] + [\alpha_L(2F_cL_c)] \quad (4)$$

where S_{gl} = global solar irradiance (sum of direct beam and dif-fused, $S_{gl} = S_b + S_d$); S_{tr} = transmitted shortwave radiation through apple leaves ($S_{tr} = \tau S_{gl}$); L_a and L_c = longwave flux density from the atmosphere and apple tree canopies, respectively, computed using the Stefan-Boltzmann equation; F_{gl} (= 0.5), F_{tr} (= 0.5), F_a (= 0.5), and F_c (= 0.5) are view factors between the leaf surface and the various sources of radiation (namely global and transmitted solar radiation, and atmospheric and apple tree canopy thermal radiation, respectively); τ , α_S , and α_L = green leaf transmittance ($\tau = 0.06$), absorptivity in the short waveband ($\alpha_S = 0.85$), and the absorptivity in the thermal waveband ($\alpha_L = 0.95$), respectively. The view factors were calculated according to Campbell and Norman (1998), and the values of apple leaf and ground optical properties were adapted from Green et al. (2003). The outgoing longwave radiation from the leaf/canopy (L_{oc}) was calculated using the Stefan-Boltzmann relationship

$$L_{oc} = F_e \varepsilon_s \sigma T_c^4 \quad (5)$$

where ε_s = thermal emissivity of apple leaf ($\varepsilon_s = \alpha_L$); σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$); T_c = canopy temperature (K); and F_e is the view factor between the entire surface of the leaf and the complete sphere of view ($F_e = 1.0$). The emissivity of the sky [$\varepsilon_a(c)$] required to compute the emitted radiation from the atmosphere [$L_a = \varepsilon_a(c)\sigma T_a^4$, T_a in K] was calculated as per Monteith and Unsworth (1990)

$$\varepsilon_a(c) = [(1 - 0.84c)\varepsilon_{ac}] + (0.84c) \quad (6)$$

where c = fraction of the sky covered by clouds. The value of c was calculated by comparing the daylight average of measured global radiation ($\overline{S_{gl}}$, Wm^{-2}) with the potential extraterrestrial incoming solar radiation for the same day (R_{ap} , Wm^{-2})

$$c = \begin{cases} \left(1 - \frac{\overline{S_{gl}}}{R_{ap}}\right) & \text{if } \overline{S_{gl}} \leq R_{ap} \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

R_{ap} was calculated according to FAO-56 (Allen et al. 1998). The emissivity of a clear sky (ε_{ac}) was estimated using the subsequent empirical relationship [Eq. (8)] as per Brutsaert (1984)

$$\varepsilon_{ac} = 1.72 \left(\frac{e_a}{T_a}\right)^{1/7} \quad (8)$$

where e_a = vapor pressure (kPa) at air temperature (T_a , K).

Another component of the energy balance equation is the sensible heat flux (H). The term H is expressed as (Campbell and Norman 1998)

$$H = g_H C_P \Delta T_m \quad (9)$$

where C_P = heat capacity of air ($29.17 \text{ J} \cdot \text{mol}^{-1} \cdot \text{C}^{-1}$); ΔT_m = measured canopy and air temperature difference ($\Delta T_m = T_c - T_a$); T_c = leaf temperature ($^{\circ}\text{C}$); T_a = air temperature ($^{\circ}\text{C}$); and g_H = boundary layer conductance to heat ($\text{mol m}^{-2} \text{ s}^{-1}$).

In the research reported in this paper, in accordance with Campbell and Norman (1998) and Blonquist et al. (2009), conductance was preferred over the traditional use of resistance in the calculations. The boundary layer conductance of air to heat for laminar forced convection (g_{Hf}) was calculated using the subsequent empirical formula [Eq. (10)] as per Campbell and Norman (1998)

$$g_{Hf} = (1.4)0.135 \sqrt{\frac{u}{d}} \quad (10)$$

where u = wind speed (at 2-m high above the ground); and d = characteristic dimension defined as 0.72 times the leaf width ($w_l = 5 \text{ cm}$, measured in the field). Considering the fact that apple leaves are hypostomatous, water loss occurs mostly through the abaxial side of leaf but sensible heat exchange from both sides ($H = H_{ab} + H_{ad}$). Assuming equal conductance for both abaxial and adaxial sides, the combined air conductance to heat is $g_H = 2g_{Hf}$. Reorganizing Eq. (1) to solve for $E (=T)$ yields

$$T = 1,555.2 \frac{R_n - g_H C_P \Delta T_m}{\lambda} \quad (11)$$

where T = actual transpiration (mm day^{-1}) and the factor 1,555.2 ($0.018 \text{ kg mol}^{-1} \times 24 \text{ h} \times 3,600 \text{ s h}^{-1}$) converts $\text{mol m}^{-2} \text{ s}^{-1}$ to mm day^{-1} . Assuming a linear relationship between T and ΔT_m ($T = c + b\Delta T_m$), the slope b and intercept c of the line can be described by reorganizing Eq. (11)

$$T = \frac{Q}{\lambda} - \left\{ \left[\frac{(g_H C_P) - n}{\lambda} \right] \Delta T_m \right\} \quad (12)$$

where $R_n = Q + n\Delta T_m$; and Q and n are defined by Eqs. (13) and (14), respectively

$$Q = 0.25\{(\alpha_S S_{gl}) + (\alpha_S S_{nl}) + [4(\alpha_L - 1)L_a]\} \quad (13)$$

$$n = [(3\alpha_L) - 4]\varepsilon_a(c)\sigma T_a^3 \quad (14)$$

Application of T-Model

Experimental Site

The field experiments were conducted in a Fuji apple orchard on the Roza Farm of the Washington State University Irrigated Agriculture Research and Extension Center near Prosser, Washington. The site was located at the coordinates of latitude 46.26° N, longitude 119.74° W, and 360-m above sea level in a semiarid zone with almost no summer rain, and an average annual precipitation of 217 mm. The site's soil was a shallow Warden silt loam soil (web soil survey) of more than 90-cm deep (field observation).

Using three dielectric soil moisture sensors (10HS, Decagon Devices, Pullman, Washington), soil moisture readings were taken during and after an irrigation event at a depth of 45 cm at different locations in the orchard. The irrigation continued until soil moisture reached a steady state (saturation). To determine soil water content at field capacity (θ_{FC}), the soil was then allowed to drain freely for a few days. Based on this method, the θ_{FC} was found to be 32.5% (volumetric water content).

Plot Design

Two scenarios [i.e., (1) Scenario A, and (2) Scenario B] were examined to support the application of this model. The T-model was initially applied to field investigations (Scenario A) in 2007 and 2008 where young, well-developed apple trees were fully irrigated to a depth of 90 cm throughout the growing seasons. Once the model had been evaluated and optimized, it was applied to another case (Scenario B) in 2013 where the same apple trees were older bearing little or no fruit. During the 2007 and 2008 growing seasons, two plots of apple trees named N and S (42 trees/plot) were marked for conducting the experiment. The trees were spaced 4 m (row spacing) \times 2.5 m (tree spacing) apart in the orchard and irrigated by a pressure compensated microsprinkler irrigation system (Hurricane, NaanDanJain Irrigation, Post Naan, Israel) with water emitters of 27.0 Lh^{-1} spaced at 2.5-m intervals (in-row between each tree). The transpiration of apple trees was estimated for the two fully irrigated plots for the two fully irrigated plots (i.e., N and S).

During the 2013 growing period, the same orchard was irrigated by two lines of drip tubing laterals (pressure compensating) of in-line 2.0 Lh^{-1} drippers (BlueLine PC, Toro Company, El Cajon, California), spaced at 91.4-cm intervals along laterals. This time, three plots, each consisting of 48 trees (three subplots of 6×3 trees/plot), were marked for conducting the experiment. In addition to N and S, a new plot was assigned to be irrigated using a neutron probe (NP) soil moisture meter (503DR Hydroprobe, Campbell Pacific Nuclear, Concord, California). Manual irrigation was scheduled in the plots of the NP treatment based on weekly readings of the soil water content. These readings were also used to calculate apple trees water use (ET_{NP}) under the NP treatment. Throughout the growing season, the quantity of applied irrigation water was cautiously controlled to keep the soil water depletion within the 50% maximum allowed depletion (MAD = 96 cm) for apple trees (Allen et al. 1998). This was assured by taking weekly soil water content readings using a neutron probe in all of the plots.

Meteorological Measurements

Canopy temperature (T_c) along with meteorological data including relative humidity (RH), solar radiation (S_{gl}), wind speed (u), and air temperature (T_a) were required inputs to the model of actual transpiration. The real-time meteorological data of the 2007, 2008, and 2013 growing seasons were obtained (every 15 min)

from two electronic weather stations close to the apple orchard [i.e., (1) Roza, and (2) Station WSU HQ, Washington Agricultural Weather Network]. In 2007 and 2008, air temperature was recorded in the orchard using the embedded temperature sensor of a Campbell CR21X datalogger (Campbell Scientific, Logan, Utah). In addition to these data, in 2013 air temperature was measured using three shielded air temperature sensors (Model 109-L, Campbell Scientific, Logan, Utah) installed at a height of 2 m (in-line with the trees) at three locations distant from each other in the orchard. These air temperature sensors were wired to Campbell CR10X dataloggers (Campbell Scientific, Logan, Utah). Air temperature was calculated by averaging readings from the three sensors. Air vapor pressure deficit was calculated using Eq. (15) as per Idso et al. (1981)

$$D_a = [e_s(T_a)] - e_a \quad (15)$$

where $e_s(T_a)$ = saturated vapor pressure at T_a ; and e_a = actual vapor pressure of air estimated as the product of RH and saturated vapor pressure, i.e., $e_a = e_s(T_a)(RH)$.

Measurement of Canopy Temperature

To monitor canopy temperature in 2007 and 2008, a total of 12 IRTs (IRT/c.03, Type T, Exergen, Watertown, Massachusetts) in six pairs were mounted above the trees in the rows. The IRTs were pointed downwards at approximately 45° angles at both the north and south sides of a tree (Fig. 1). The sensors were calibrated using a blackbody calibrator (BB701, Omega Engineering, Inc., Stamford, Connecticut) and wired to a Campbell CR21X datalogger (Campbell Scientific, Logan, Utah). In 2013, canopy temperature was measured using a more accurate model of IRT (IRT/c.2, Type J, Exergen, Watertown, Massachusetts). In a similar setup to those implemented by Sepulcre-Canto et al. (2006) and Testi et al. (2008), in olive and pistachio trees, individual IRTs were installed perpendicularly above a tree pointed straight down and located at the center of the six subplots (three per plot). Considering the field view of this model of IRT (35°), this form of orientation and position will decrease the chance of the ground being seen by the IRT sensor and the number of sensors being used. The IRT sensors were wired to a network of Campbell CR10 and CR10X dataloggers (Campbell Scientific, Logan, Utah) sending out temperature readings to a central computer wirelessly.

Estimation of Water Use

To estimate daily mean transpiration (in units of millimeters per day) of apple trees, two approaches were examined, as follows: (1) daily averages of meteorological and thermal data were used (T_{avg}), and (2) the 15-min time interval transpiration (T_{15}) was calculated and the 24-h total was obtained by accumulation ($T_{acc} = \sum_{i=1}^{96} T_{15}$). Transpiration rates were also estimated using the average values of meteorological data from 11:00 a.m. to 1:00 p.m. (solar noon/midday transpiration, T_{mid}) and from 1:00 p.m. to 3:00 p.m. (noon transpiration, T_{noon}). The relationships between T_{mid} and T_{avg} , as well as T_{noon} and T_{avg} (during the midseason and late-season of 2007, 2008, and 2013) were investigated. The daily mean crop evapotranspiration of Fuji apple trees (ET_c , mm day⁻¹) was computed using the ASCE standardized Penman-Monteith equation (ASCE-EWRI 2005) in combination with the crop coefficient values adjusted for the local climate (Karimi et al. 2013)

$$ET_c = K_c ET_r \quad (16)$$

where ET_r = alfalfa reference evapotranspiration. To estimate daily mean ET_r , the meteorological data including daily received

shortwave solar radiation (MJ m⁻² day⁻¹), maximum and minimum temperatures, RH, and u were obtained from the nearby weather stations. The longwave and net radiations were estimated according to FAO-56 (Allen et al. 1998). The total crop water use of apple trees was calculated by the accumulation of T_{avg} (ΣT_{avg}) and ET_c (ΣET_c). The accumulated transpiration of the N and S plots was also averaged to obtain one ΣT_{avg} value ($\Sigma \bar{T}_{avg}$).

Actual Crop Water Use

A water budget (WB) equation was used to estimate the total irrigation water use by apple trees in 2013 (Evelt 2002)

$$ET_{WB} = P + I + F - \Delta S + (\pm D) - R \quad (17)$$

where ET_{WB} = actual water use (mm); P = precipitation (mm); I = applied irrigation depth (mm); F = lateral flux of water entering the control volume (positive) or exiting it (negative); ΔS = change in soil water content (mm); D = deep percolation (mm); and R = runoff (mm). The terms D and R were assumed to be negligible. In addition, there was no shallow water table below the root zone, thus upward flow was not a concern. The term F was also assumed to be zero because soil moisture readings were taken at the center of the plots, where the effect of horizontal fluxes is negligible. The term ΔS was calculated using the neutron probe readings

$$\Delta S = \theta_f - \theta_i \quad (18)$$

where θ_f = final soil water content (mm) in the end of the measuring period (week or growing season); and θ_i = initial soil water content (mm; week or season).

Measurements of Stem Water Potential

During the growing season of 2013, the stem water potential (Ψ_{stem}) of fully watered trees at solar noon was measured once per week from midsummer to late summer (July 31, 2013, to October 2, 2013). The Ψ_{stem} measurements were taken within a 2-h time window (between 1:00 p.m. and 3:00 p.m.) and on the same day as the neutron probe measurements. For each measurement, six shaded leaves (per plot) from the inner, lower part of tree close to the trunk (where an IRT was mounted) were selected. They were enclosed in aluminum foil covered plastic envelopes, and left attached to the tree for a period of time between 15 and 60 min. After this period of time, the xylem sap pressure of a nontranspiring (enclosed) leaf (Ψ_{leaf}) was expected to equilibrate with the stem water potential (Begg and Turner 1970). The Ψ_{stem} was measured with a pressure bomb (Model 615, PMS Instrument, Albany, Oregon). Up to six Ψ_{stem} readings (per plot per measurement day) were averaged to calculate the Ψ_{stem} of each plot. The Ψ_{stem} measurements were taken under different weather conditions including cold, humid, and overcast days.

Model Assessment

The performance of the model for actual transpiration was evaluated using the model and adjusted PM predictions. The statistical measures used were as follows: (1) relative error (RE) between predicted transpiration (T) and crop ET (ET_c), (2) RMS error, (3) coefficient of variation (CV) of the RMS error, (4) Nash-Sutcliffe coefficient of efficiency (COE; Nash and Sutcliffe 1970), and (5) linear regression between the transpiration model and ET_c . A satisfactory prediction was assumed when the linear regression yielded slopes close to unity, intercepts close to zero, and high correlation ($R^2 = 1$). The COE gives an account of the deviation from unity of the observations variance and the ratio of the mean squared

errors. Therefore, the closer the COE to 1, the better the performance of the model. The total amount of predicted transpiration (D_T) and crop ET (D_{ET}) over a period of time were compared by calculating the relative error (RE)

$$RE = \frac{D_{ET} - D_T}{D_{ET}} \quad (19)$$

The RMS error exploited as a measure of the variance between predicted transpiration and crop ET

$$RMS \text{ error} = \sqrt{\frac{\sum (ET_c - T)^2}{n}} \quad (20)$$

where n = number of measurements. The CV of the RMS error ($CV_{RMS \text{ error}}$) was calculated by dividing the RMS error by the mean of the T-model predictions (\bar{T})

$$CV_{RMS \text{ error}} = \frac{RMS \text{ error}}{\bar{T}} \quad (21)$$

In 2013, the linear relationships between midday Ψ_{stem} , as a widely accepted indicator of apple trees water status (Lakso 2003), and T_{mid} and T_{avg} were investigated. The statistical assessment also included an analysis of variance (at $p = 0.05$) using *SigmaPlot* to conduct multiple comparisons of water use obtained from various methods (i.e., T , ET_c , WB, and NP).

Daily Transpiration

Daily Mean Actual Transpiration and Evapotranspiration

During the midseason, the regionally determined crop coefficients for converting ET_r to ET_c were nearly 1.0 with a peak of 1.06 (Karimi et al. 2013). This is a time when, under dry and warm conditions, the actual transpiration of well-watered apple trees is

expected to be close to the alfalfa reference ET (Dragoni et al. 2005). In addition, canopy temperature measurements early in the season are associated with high uncertainties due to incomplete canopy growth. Therefore, a midseason and late-season time period was used for comparison, but midseason was the focus.

As can be seen in Figs. 2 and 3, there were discrepancies between the fully irrigated plots (i.e., N and S). The statistical analysis showed that there was no significant difference between the plots for the daily mean ($p = 0.699$) and midday ($p = 0.787$) values. There were, however, random occasions when N and S plots exhibited significant disagreement (data not shown), which could be due to field/canopy variability and/or the canopy temperature measurement errors.

In 2007, the linear regression between T_{avg} and ET_c [midseason and late-seasons, day of year (DOY) = 155–270] yielded slope, intercept, and R^2 of 0.99, 1.07, and 0.72, respectively, for the N plot [Fig. 3(a)]. The slope, intercept, and R^2 of the relationship for the S plot were almost the same with values of 1.05, 1.08, and 0.77, respectively [Fig. 3(b)]. The transpiration was relatively well-predicted, with COEs of 0.86 for the N plot and 0.80 for the S plot; however, T_{avg} for the midseason when the transpiration of apple trees was expected to be almost the same rate as ET_r was overestimated (Table 1; 7.9 and 8.4 mm day⁻¹ by the T-model compared to 6.9 mm by the PM, and RMS errors of 1.6 and 2.0 mm).

The linear regression between T_{avg} and ET_c for the same period in 2008 yielded slope, intercept, and R^2 of 1.0, 1.19, and 0.78 for N plot, and 1.11, -0.02, and 0.69 for S plot, respectively [Figs. 3(c and d)]. Similarly to 2007, the transpiration was relatively well-predicted with COEs of 0.88 for the N plot and 0.83 for the S plot, and midseason T_{avg} was overestimated (Table 1; 8.9 and 8.4 mm day⁻¹ by the T-model compared to 7.8 mm by the PM, and RMS errors of 1.7 and 2.1 mm). The agreement between T_{avg} and ET_c was weaker during the midseasons of 2007 and 2008 (Table 1) compared to midseason and late-seasons, combined in the same years (Fig. 3).

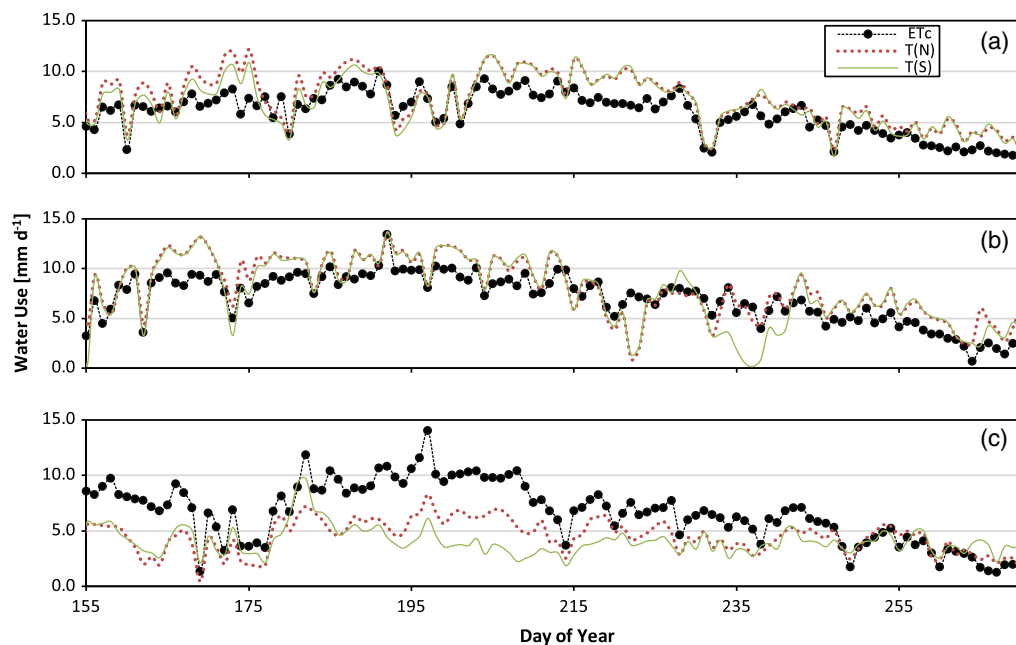


Fig. 2. Comparison of the daily mean water use (mm day⁻¹) estimated by the T-model for plots N [$T(N)$] and S [$T(S)$] and ET_c : (a) growing season of 2007; (b) growing season of 2008; (c) growing season of 2013; ET_c was calculated as the product of ET_r and the crop coefficient values (K_c) adjusted for the local climate (data from Karimi et al. 2013)

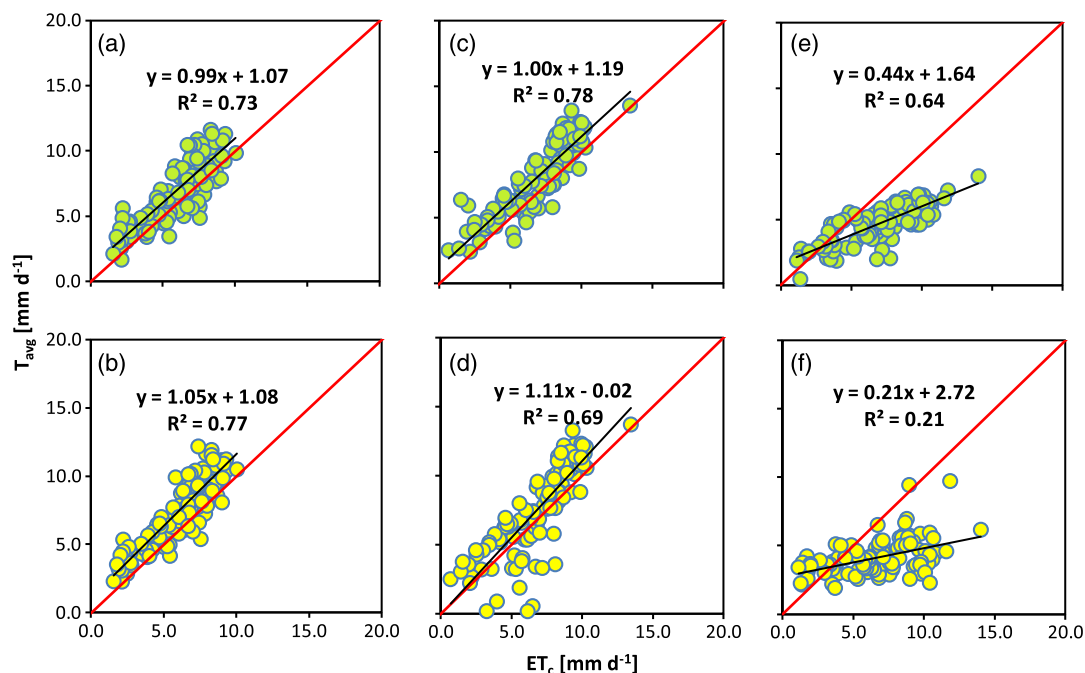


Fig. 3. Comparison of daily mean transpiration (T_{avg} , mm day^{-1}) for plots (N and S) and ET_c : (a and b) 2007 growing season; (c and d) 2008 growing season; (e and f) 2013 growing season (DOY = 155–270)

Table 1. Comparison of Predicted Transpirations from the T-Model and the Regionally Adjusted Crop Coefficient for Midseason of 2007, 2008, and 2013

Year	Plot	R^2	Slope	Intercept	Total (mm)			Average (mm day^{-1})				
					ΣET_c	ΣT_{avg}	Relative error (%)	ET_c	T_{avg}	RMS error	Coefficient of variation of RMS error	Coefficient of efficiency
2007	N	0.59	1.07	0.47	628	716	-14	6.9	7.9	1.6	0.24	0.86
	S	0.63	1.12	0.58	—	758	-22	—	8.4	2.0	0.29	0.80
2008	N	0.73	1.25	-0.96	731	827	-13	7.8	8.9	1.7	0.22	0.88
	S	0.72	1.60	-4.28	—	786	-8	—	8.4	2.1	0.26	0.83
2013	N	0.68	0.55	0.58	702	427	37	7.7	4.8	3.1	0.41	0.84
	S	0.23	0.30	1.93	—	374	45	—	4.2	4.0	0.52	0.75

The transpiration rate remained relatively constant throughout the midseason and late-season of 2013 [Fig. 2(c)]. In 2013, the linear regression analysis between T_{avg} and ET_c yielded determination coefficients of 0.64 ($p < 0.001$) and 0.21 ($p = 0.002$) for the N and S plots, respectively [Figs. 3(e and f)]. In spite of the low R^2 values, the COE values were fairly high (0.85 and 0.75 for the N and S plots, respectively); however, T_{avg} was underestimated (Table 1; 4.8 and 4.2 mm day^{-1} predicted by the T-model compared to 7.7 mm by the PM, and $CV_{RMS\ error} = 41$ and 52%). Considering that the apple trees were in an alternate bearing year, a decrease in transpiration was expected in response to less fruit loads on the trees (Palmer et al. 1997).

Total Water Use

In 2007, ΣT_{avg} was slightly higher than ΣET_c ($\Sigma T_{avg} = 716$ and 758 mm compared to $\Sigma ET_c = 628$ mm) yielding REs of -14 and -22% in the N and S plots, respectively [Table 1; Fig. 4(a)]. In the midseason of 2008, the total transpiration was estimated with relatively small REs of -13 and -8% in the N and S plots, respectively. In 2013, ΣT_{avg} and ΣET_c were also different with estimations of the T-model being significantly smaller with values of 427 mm (N) and 374 mm (S) for ΣT_{avg} , compared to 702 mm for ΣET_c .

Overall, the T-model appears to have resulted in significantly lower transpiration rates during the midseason of 2013 (DOY = 155–270) when the apple orchard was older. There was a trivial difference between $\Sigma \bar{T}_{avg}$ and ΣET_c , with $\Sigma \bar{T}_{avg}$ being 18 and 11% more in 2007 and 2008, respectively [Fig. 4(a)], while in 2013, the difference was considerable with $\Sigma \bar{T}_{avg}$ being 47% less than the midseason ΣET_c . In order to determine which method correctly estimated the water use during the 2013 irrigation period, the actual water use of the apple trees (ET_{WB}) was estimated using a water budget approach [Eq. (17)] and compared with $\Sigma \bar{T}_{avg}$ and ΣET_c . A comparison was also made with the accumulated water use of the trees under the NP treatment (ΣET_{NP}) for the same period.

It was expected that the water use of the trees under the NP treatment as well as ET_{WB} would reflect the actual amount of water consumed by well-watered apple trees. On the other hand, ET_c was meant to predict the water use correctly. However, ΣET_c was significantly greater than ΣET_{NP} [Fig. 4(b); $\Sigma ET_c = 787$ mm, versus $\Sigma ET_{NP} = 488 \pm 45$ mm]. There was no significant difference ($p = 0.667$) between the water use calculated by the energy budget equation ($ET_{WB} = 475 \pm 31$ mm) and accumulated \bar{T}_{avg} ($\Sigma \bar{T}_{avg} = 460 \pm 49$ mm). Similarly, the differences in the mean values of the accumulated transpiration from the T-model, water budget, and NP methods were not statistically significant

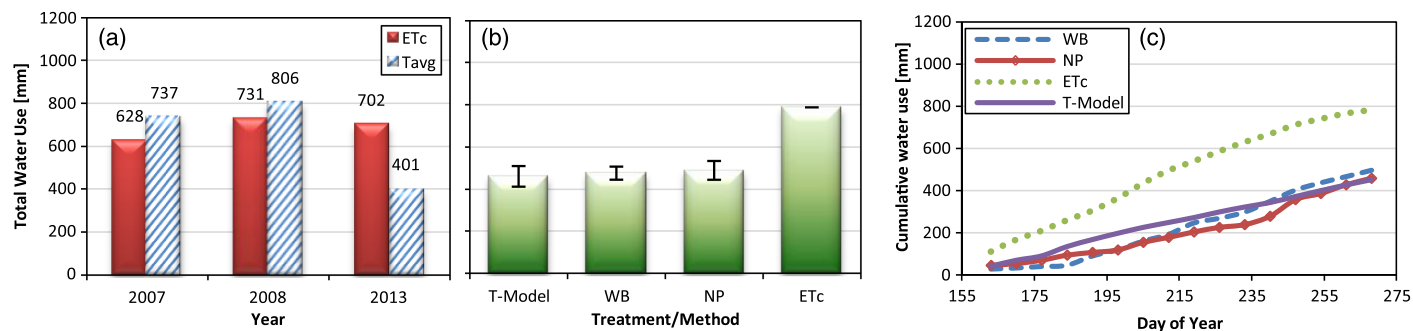


Fig. 4. (a) Accumulated T_{avg} and ET_c in the growing seasons of 2007, 2008, and 2013 (average of N and S plots; only midseason; DOY = 155–240); (b) total water use estimated by the T-model, water budget approach (WB), ET_c , and total water use of fully irrigated trees under the NP treatment during the growing season of 2013 (DOY = 155–270; soil moisture readings at the beginning and end of the season were used to calculate total water use; error bars show the standard error of the mean); (c) cumulative water use estimated by the T-model, WB, ET_c , and NP during the growing season of 2013 (weekly soil moisture readings were used to calculate weekly and cumulative water use)

($p = 0.885$). The cumulative water use of the WB, NP, and ET_c approaches also presented a good agreement [Fig. 4(c)]. Therefore, while ET_c failed to correctly predict the total transpiration of apple trees during the growing season of 2013, the performance of the T-model was quite satisfactory.

Actual Transpiration and Midday Stem Water Potential

In the 2013 growing season, trees within a specific plot (i.e., N or S) did not necessarily receive irrigation water on the same day as the other plot. However, statistical analysis revealed that there was no significant difference among the plots on midday Ψ_{stem} ($p = 0.110$) over the period of measurements (DOY = 212–275). In addition, soil water depletion in the N and S plots never exceeded the 50% MAD recommended for apple trees (Figs. 5 and 6). This implies that the fluctuations of midday Ψ_{stem} and T were not caused by soil water deficit, but by other factors. In addition to a nonlimiting soil water status, the nonstressed midday Ψ_{stem} values were similar to those reported in the literature

for well-watered apple trees (Naor et al. 1997; Naor 2000; Naor and Cohen 2003).

The trees maintained relatively high midday Ψ_{stem} over the period of the experiment with fluctuations mainly driven by the weather conditions. There was an increasing trend in midday Ψ_{stem} towards the end of the season with a minimum of -11.0 bar and maximum of -3.5 bar [Fig. 7(a and b)]. Although the measurements were taken in different weather conditions, both T_{mid} (mm h^{-1}) and T_{avg} (mm day^{-1}) were highly linearly correlated with midday Ψ_{stem} ($\Psi_{stem} = f(T_{mid})$, $R^2 = 0.85$ and $p < 0.001$; $\Psi_{stem} = f(T_{avg})$, $R^2 = 0.87$ and $p < 0.001$). Considering there was no water stress, midday Ψ_{stem} must have been mainly dependent on solar radiation, air temperature, and relative humidity. This means under warmer and drier conditions when the transpiration rate was high, midday Ψ_{stem} was low.

Accumulated Transpiration and Average Transpiration

The value of T_{acc} was highly correlated with T_{avg} in 2007 [Fig. 8(a); $y = 0.93x + 0.19$, $R^2 = 0.93$, and $p < 0.001$], 2008

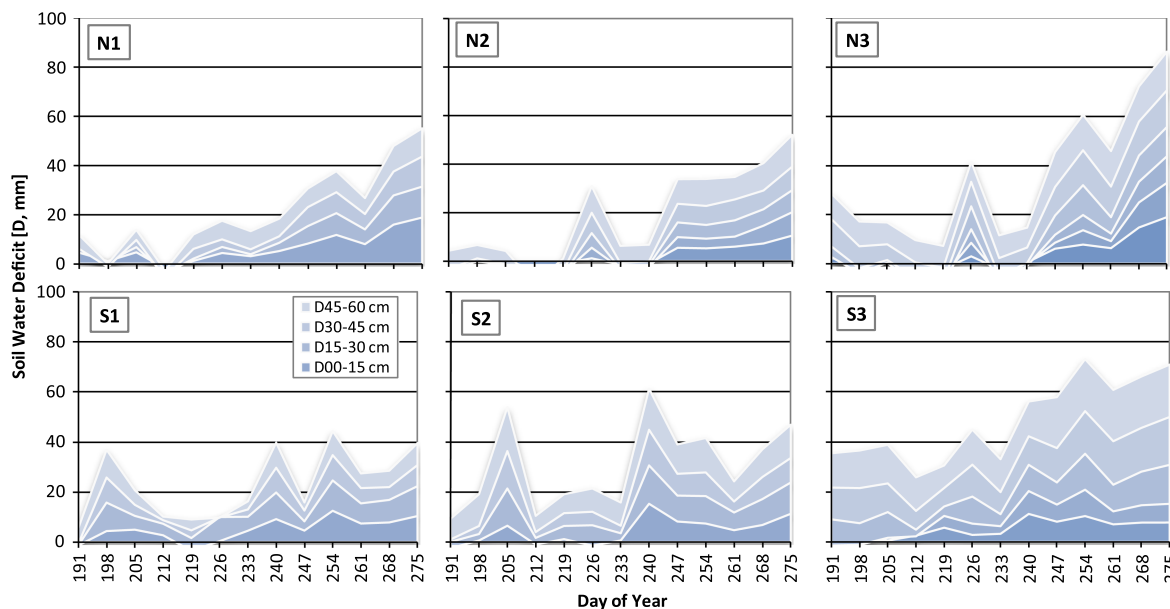


Fig. 5. Soil water deficit (depletion) in 2013 at the root zone down to the depth of 60 cm in the subplots under plots N (N1–N3) and S (S1–S3); soil moisture was monitored using a neutron probe

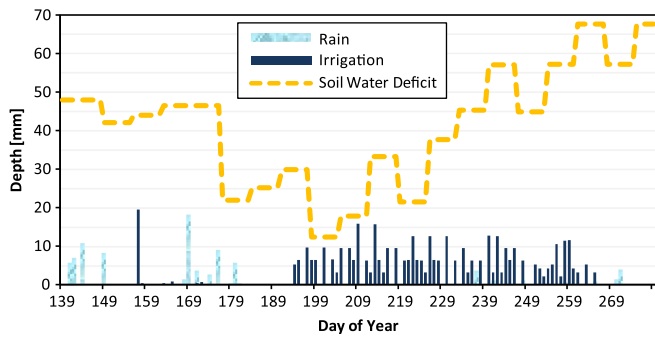


Fig. 6. Plots of average soil water deficit (root depth), irrigation depth, and precipitation (rainfall) in 2013; soil moisture was monitored on a weekly basis using a neutron probe

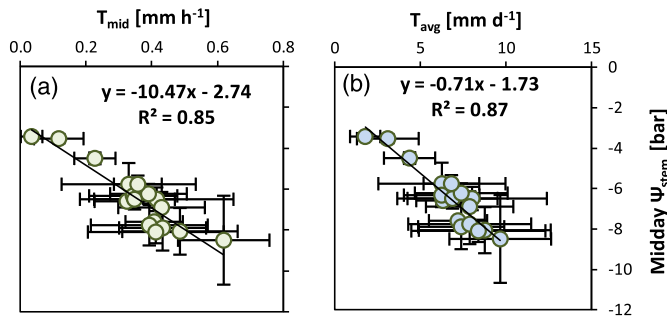


Fig. 7. (a) Linear relationship between midday ψ_{stem} and T_{mid} (mm h^{-1}) in 2013; and (b) linear relationship between midday ψ_{stem} and T_{avg} (mm day^{-1}) in 2013; each value represents the average of up to six measurements per plot; error bars show the standard error of the mean

[Fig. 8(b); $y = 102x + 0.53$, $R^2 = 0.95$, and $p < 0.001$], and 2013 [Fig. 8(c); $y = 0.95x + 0.15$, $R^2 = 0.92$, and $p < 0.001$]. Compared with the use of average meteorological data, T_{acc} did not show any significant advantage in estimations of daily transpiration.

Diurnal Changes of Transpiration

In all of the seasons, transpiration rates at both noon (T_{noon}) and solar noon (T_{mid}) were highly linearly correlated with T_{avg} . In 2007, the linear regression resulted in the R^2 values of 0.82 and

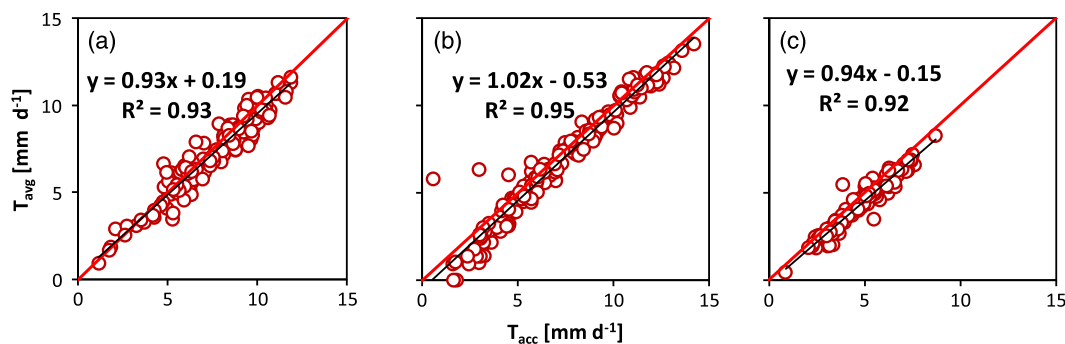


Fig. 8. Relationship between daily transpiration estimated by accumulation of 15-min transpiration over 24 h (T_{acc} , mm day^{-1}) and by using daily average of meteorological data (T_{avg} , mm day^{-1})

0.74, for noon and solar noon, respectively. The R^2 values of 0.84 and 0.83 were obtained, for noon and midday, respectively, in 2008, and a similar value of 0.74 for both noon and solar noon in 2013 (Fig. 9). A relationship established between T_{avg} and estimations of transpiration at other times of day (i.e., before 11:00 a.m. or after 3:00 p.m.) resulted in significantly lower R^2 values (data not shown). The slopes of the relationships indicated a higher rate of T_{noon} than T_{mid} in 2007 and 2008, with values of about $3.1 \times$ and $2.1 \times T_{\text{avg}}$, respectively, for T_{noon} compared to $2.0 \times$ and $1.6 \times T_{\text{avg}}$, respectively, for T_{mid} . In 2013, the slope at noon and solar noon were the same, with a value of 1.70 exhibiting no decrease from noon to solar noon as observed in 2007 and 2008.

Considering $T_{\text{noon}} \geq T_{\text{mid}}$, the maximum transpiration rate must have occurred at a time other than solar noon. To further elucidate this we explored the diurnal pattern of transpiration predicted by the model for the actual evapotranspiration. Transpiration rates for 15-min time intervals (i.e., values of T_{15}) were calculated and averaged over the course of several successive days (mostly sunny) during the early season (DOY = 152–160), midseason (DOY = 191–200), and late season (DOY = 260–270) of 2007, 2008, and 2013 (Fig. 10). Hourly ET_r and S_{gl} were also calculated and averaged over the same period of time (Fig. 11).

The transpiration was intense in the morning, and next was a drop around solar noon. It increased again in the afternoon. The time of a peak in T_{15} coincided with a peak in canopy and air temperature difference (ΔT_m). A similar diurnal pattern of transpiration for apple trees was previously reported by Tokei and Dunkel (2005). This can be explained by the fact that, in addition to R_n , the transpiration of apple trees was controlled by stomatal regulations reflected in a lowered or elevated canopy temperature. On the other hand, the peak of ET_r [Figs. 11(a, c, and e)] coincided with a peak in incoming solar radiation [Figs. 11(b, d, and f)]. The observed behavior of the apple trees was different from row crops where the transpiration is mainly driven by net radiation (Lakso 2003) and is reduced drastically in response to low solar radiation levels (Wanjura and Upchurch 1997).

Transpiration and Humidity

The relationship between the whole canopy transpiration of apple trees and air vapor pressure deficit (D_a) was previously studied by Dragoni et al. (2005) and Auzmendi et al. (2011). Dragoni et al. (2005) demonstrated that the transpiration was highly related to D_a in a humid climate. Auzmendi et al. (2011) also showed that T was dependent on D_a at different weather conditions. The transpiration of apple trees was expected to be mainly driven by net

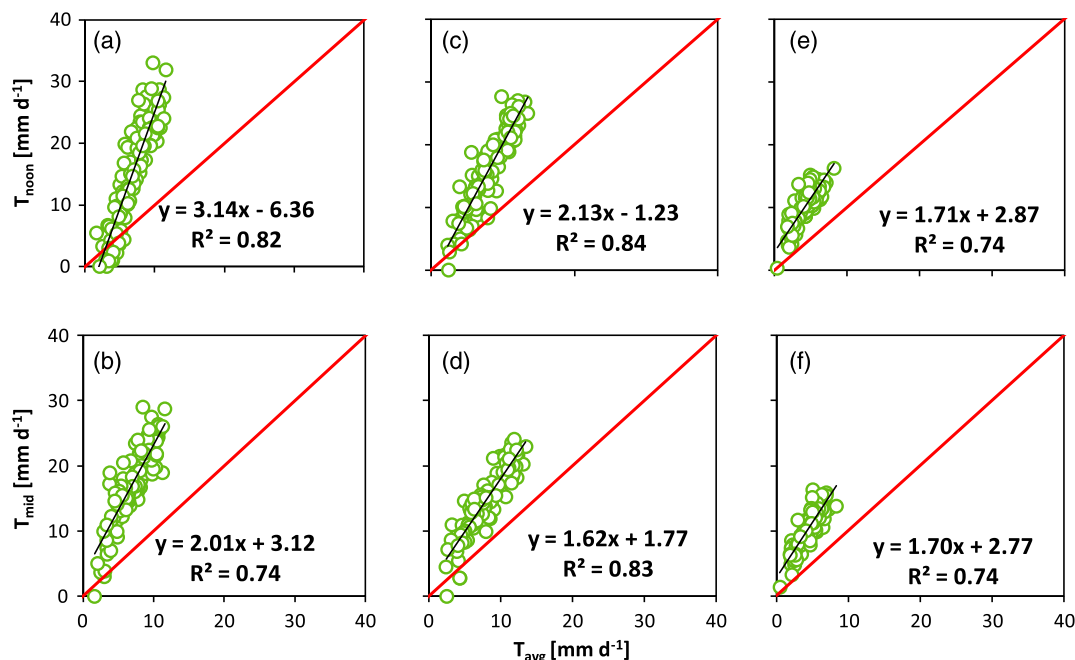


Fig. 9. (a) Relationship between transpiration at noon (T_{noon} , mm day^{-1}) and daily mean transpiration (T_{avg} , mm day^{-1}), 2007; (b) relationship between transpiration at solar noon (T_{mid} , mm day^{-1}) and T_{avg} , 2007; (c) relationship between transpiration at noon (T_{noon} , mm day^{-1}) and daily mean transpiration (T_{avg} , mm day^{-1}), 2008; (d) relationship between transpiration at solar noon (T_{mid} , mm day^{-1}) and T_{avg} , 2008; (e) relationship between transpiration at noon (T_{noon} , mm day^{-1}) and daily mean transpiration (T_{avg} , mm day^{-1}), 2013; (f) relationship between transpiration at solar noon (T_{mid} , mm day^{-1}) and T_{avg} , 2013

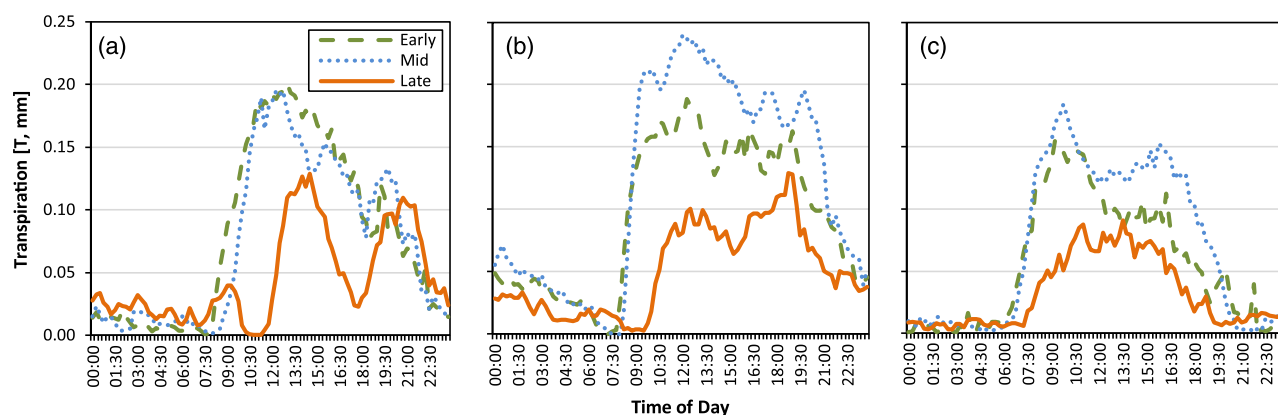


Fig. 10. Diurnal changes of transpiration estimated by the T-model: (a) during the 2007 growing season; (b) during the 2008 growing season; and (c) during the 2013 growing season; each curve represents the average of T over a few successive days (DOY = 152–160 as early, DOY = 191–200 as mid, and DOY = 260–270 as late in the season)

radiation during warm and dry days similar to that of the reference alfalfa/grass (Dragoni et al. 2005).

To compare the behaviors of T and ET_c on different days, two arbitrarily defined conditions [i.e., (1) warm and dry ($D_a > 1.5$ kPa and $S_{gl} > 320$ Wm^{-2}), and (2) cold and humid ($D_a < 1.0$ kPa and $S_{gl} < 230$ Wm^{-2})] were assumed. The predicted values of transpiration by the two models were then classified and separately fitted by a linear regression. As anticipated, T better agreed with ET_c on Condition 1 days ($R^2 = 0.57$ and $p < 0.001$) with a relationship slope and intercept of 1.16 and 0.42, respectively [Fig. 12(a)]. Because of a high coupling between the apple trees and the humidity of the surrounding air (Jarvis 1985), T resulted in lower values than ET_c during Condition 2 periods [Fig. 12(b); $R^2 = 0.48$, slope = 0.69, intercept = 2.32, and $p < 0.001$]. Combining the

values from the growing seasons of 2007 and 2008 (all days included), T and ET_c yielded a fairly good agreement ($R^2 = 0.77$ and $p < 0.001$), with a slope of 1.00 and intercept of 1.08 [Fig. 12(c)]. The overall results confirmed the idea that the transpiration of the apple trees changed significantly in response to the air vapor pressure deficit.

While the relationship between solar radiation and T is theoretically established in Eq. (12), D_a is not explicitly available in Eq. (12). How D_a relates to T can be explained through its impact on stomata (Rana et al. 2005; Dragoni et al. 2005) and consequently ΔT_m , as any change in stomatal conductance has a direct effect on canopy temperature (Blonquist et al. 2009). Thus, D_a is expected to have been integrated into the canopy temperature component of the T-model.

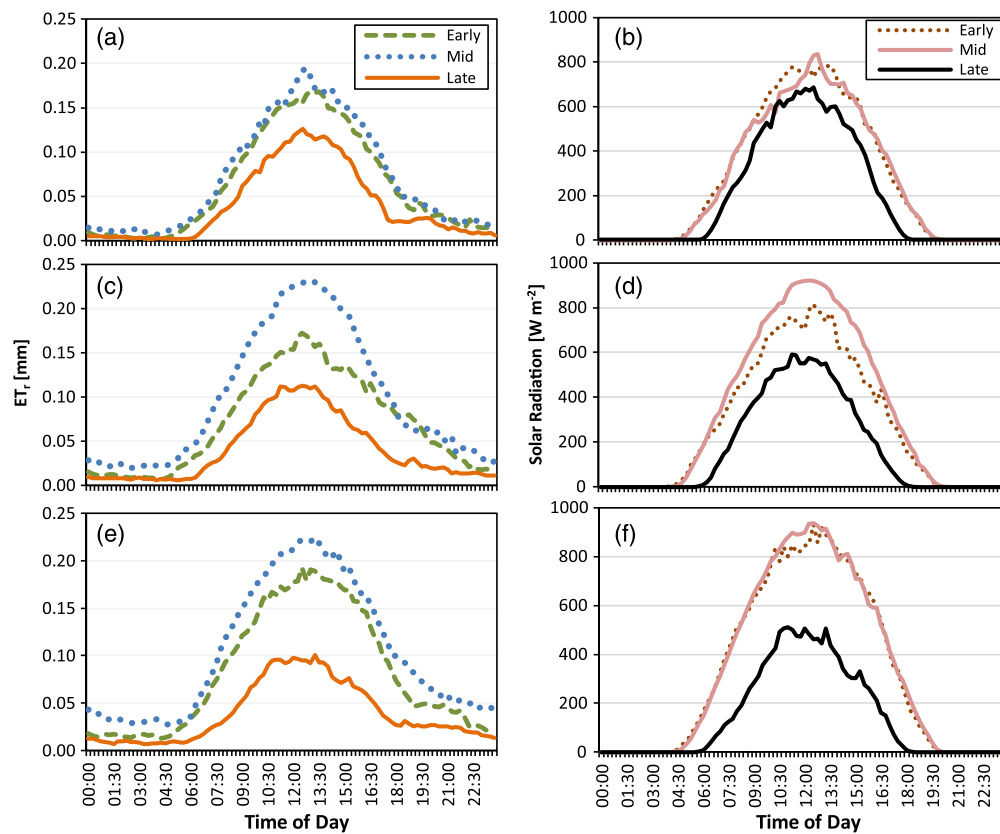


Fig. 11. (a) Hourly changes of ET_r ; (b) hourly changes in global solar radiation; (c) hourly changes of ET_r ; (d) hourly changes in global solar radiation; (e) hourly changes of ET_r ; (f) hourly changes in global solar radiation; averaged over the course of several successive days during early (DOY = 152–160), mid (DOY = 191–200), and late (DOY = 260–270) growing seasons of 2007, 2008, and 2013

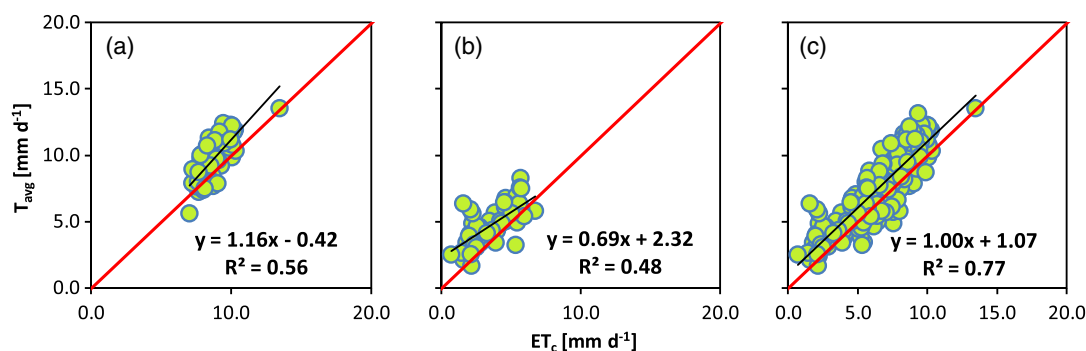


Fig. 12. (a) Correlation between T_{avg} and ET_c during warm and dry periods ($p < 0.001$); (b) during cold and humid days ($p < 0.001$); (c) for all of the days during the growing seasons of 2007 and 2008

An empirical linear relationship between D_a and ΔT_m was first established by Idso et al. (1981) in row crops. Testi et al. (2008) were also able to develop a similar empirical relationship in pistachio trees. However, such a relationship has not been properly established in apple trees. In this paper, in accordance with the same principals as in the original approach of Jackson et al. (1981), it was attempted to theoretically relate D_a to ΔT_m , and consequently transpiration. Using the latent heat flux formula (Campbell and Norman 1998), T ($\text{mol m}^{-2} \text{s}^{-1}$) is defined as

$$T = g_T \left(\frac{VPD}{P_a} \right) \quad (22)$$

where g_T = canopy conductance (a series combination of boundary layer conductance to water vapor, g_v , and stomatal conductance, g_s , all in $\text{mol m}^{-2} \text{s}^{-1}$); and VPD = canopy to air vapor pressure deficit (kPa). Linearizing VPD ($VPD = \Delta \cdot \Delta T_m + D_a$, where Δ is in $\text{kPa } ^\circ\text{C}^{-1}$, is the slope of the relationship between VPD and T_a) and substituting it in Eq. (22), T can then be expressed as a function of ΔT_m and D_a

$$T = [(g_T s) \Delta T_m] + \left[\left(\frac{g_T}{P_a} \right) D_a \right] \quad (23)$$

where $s = \Delta / P_a$ ($^\circ\text{C}^{-1}$). Combining Eqs. (12) and (22) and rearranging them in the form $\Delta T_m = a - m D_a$ gives

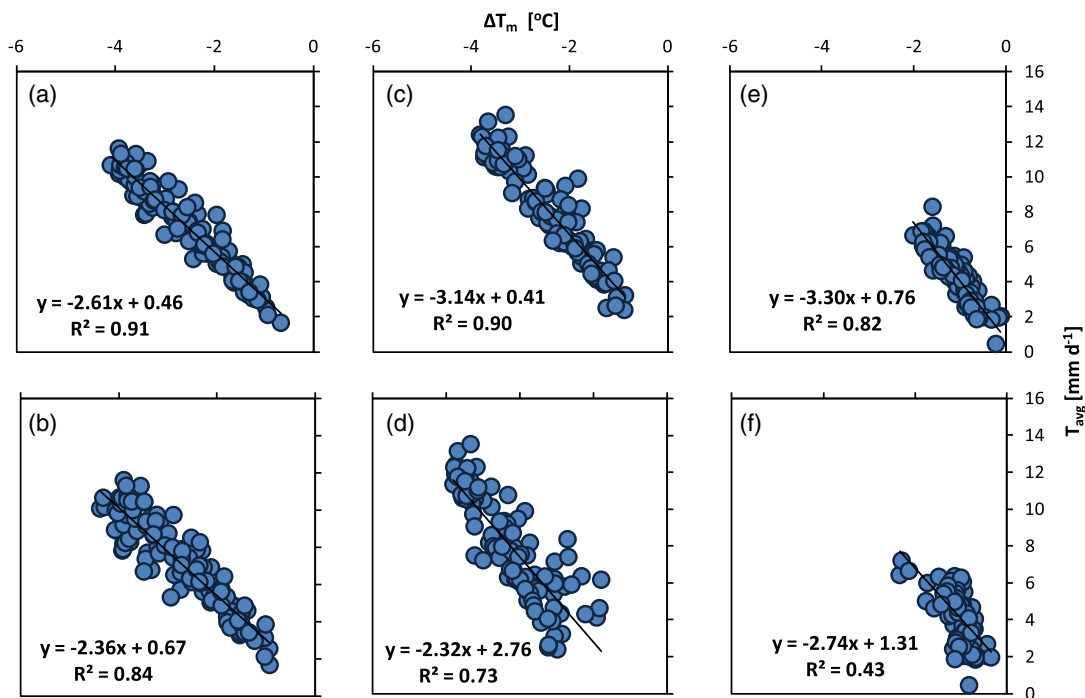


Fig. 13. Daily mean transpiration (T_{avg}) versus daily mean canopy and air temperature difference (ΔT_m): (a and b) growing season of 2007; (c and d) growing season of 2008; (e and f) growing season of 2013

$$\Delta T_m = \left[\left(\frac{1}{\gamma^* + s} \right) Q \right] - \left[\left(\frac{1}{P_a} \right) \left(\frac{1}{\gamma^* + s} \right) D_a \right] \quad (24)$$

where $\gamma^* = [(g_H C_p) - n]/(\lambda g_T)$; that is, γ^* is similar to the psychrometric constant defined by Campbell and Norman (1998). Having ΔT_m from Eq. (24), substituting it in Eq. (12) and doing some mathematical manipulations, T can be reorganized in the form $T = a + (b D_a)$

$$T = \left(\frac{1 - \beta}{\lambda} Q \right) + \left(\frac{\lambda g_T \beta}{P_a} D_a \right) \quad (25)$$

where $\beta = 1/[1 + (s/\gamma^*)]$. Making an assumption of constant stomatal conductance, a linear relationship between T and D_a will be imaginable, where an increase in D_a leads to an increment in T . This cannot be necessarily a valid assumption as the stomata of apple leaves respond to factors such as bulk air relative humidity (Jarvis 1985; Dragoni et al. 2005) and net radiation (Rana et al. 2005). Thus, γ^* is not constant under normal conditions.

Eq. (25) relates transpiration to D_a and presents a theoretical method for estimating the potential transpiration of apple trees. As previously discussed, canopy/stomatal conductance is not constant and needs to be measured or estimated. The empirical models of Jarvis (1976) and Thorpe et al. (1980) defined the stomatal conductance of apple leaves as a function of D_a and radiation. A reduction in crop loads after harvest or an alternate bearing condition (little fruit) like in the growing period of 2013 can, however, cause stomatal closure and consequently a reduction in transpiration rates (Auzmendi et al. 2011; Girona et al. 2011; Lakso 2003). This makes the use of an empirical model of stomatal conductance very limited.

In the linear version of the T-model [Eq. (12)], the intercept c is a function of net radiation (Q component), while the slope of the T and ΔT_m relationship is mainly controlled by the air conductance to heat (g_H). Being climate-dependent, Q and g_H are functions of

solar radiation and wind speed, respectively, and air temperature affects both. The average values of these variables are considered to be relatively constant in a specific climate zone. This can be seen in Fig. 13 where the relationship between T and ΔT_m demonstrated similar slopes and intercepts across the field, and from year to year. This included the growing season of 2013 when a very low fruit load caused a significant decrease in the transpiration rate of the apple trees. Although peak T dropped from about 14 mm in 2008 to 8 mm in 2013, a similar linear relationship was seen between T and ΔT_m .

Conclusions

During the growing periods of 2007 and 2008, canopy temperatures of apple trees were measured using IRTs pointed downwards at approximately 45° angles at both the north and south sides of a tree. In 2013, IRTs were installed perpendicularly above the trees. A transpiration model along with canopy and air temperatures measured in the orchard, and local meteorological data from a nearby weather station, were used to estimate the transpiration of apple trees. The overall results of the experiments with Fuji apple trees showed that actual canopy transpiration can be reliably estimated using infrared thermometry under real field conditions.

In 2007 and 2008 it was assumed that the apple trees were well-watered (nonlimiting amount of water in the soil), and that the corrected PM model predictions (ET_c) exactly reflected the crop water use of apple trees during the season. The apple trees had a mean crop level of above 100 fruit/tree in 2007. The same assumption was made for 2013; however, as a result of alternate bearing the orchard yielded less than 15 fruits/tree with no fruits on some trees. This provided a good opportunity to evaluate the T-model when the PM model failed to predict the decreased transpiration rate in response to lower crop loads. The effect of stomatal regulations on transpiration was integrated into the canopy temperature

component of the T-model allowing it to account for decreased load in 2013.

Although the overall performance of the T-model was satisfactory, there were some sources of uncertainty in modeling absorbed and net radiations. Net radiation estimations on some days were sometimes small negative values close to zero (data not shown), while net radiation is expected to be positive during the daytime as per FAO-56 (Allen et al. 1998). A source of error was the simplicity of the approach used in the research reported in this paper to calculate cloud cover and sky emissivity. More advanced approaches for estimating incoming longwave radiation can be found in Flerchinger et al. (2009). Moreover, R_{abs} was basically developed for the light and thermal energy interception by an apple leaf at solar noon. This introduced some errors in the calculations of hourly transpiration rates at other times. The thermal radiation across the canopy (i.e., upper and lower halves) was also assumed uniform and occurring at T_c , which introduced another approximation into the model.

One finding of this paper was that the transpiration was intense in the morning and late in the afternoon. Considering this fact, perhaps these hours are more suitable times for detecting the water status of apple trees for the purpose of irrigation scheduling compared to the traditional solar noon. The present model can provide a basis for a fully automated system of irrigating apple orchards. On one hand, real-time water use can be computed in any time scale. On the other hand, the high correlation of T with midday ψ_{stem} can be used for determining when to apply water. The possibility of precision irrigation scheduling of small areas within larger fields or even individual trees is another advantage. There may also be a hope for replacing IRT sensors with satellite IRT pictures for estimating transpiration of larger orchards. The conventional use of a crop-coefficient and reference ET can be then replaced by the present approach. In this paper, the approach of the research reported in this paper was compared against the PM model. Using the noncalibrated T-model for the calculation of crop water use resulted in small errors. Further improvement can be achieved by calibrating the model using lysimeter data (Auzmendi et al. 2011) or sap flow measurements (Dragoni et al. 2005; Nicolasa et al. 2005).

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