Estimating Potential Transpiration of Apple Trees Using Theoretical Non-Water-Stressed Baselines

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Abstract: To maximize irrigation efficiency, applied water has to be precisely adjusted to the crop water use. This study develops a method based on the energy balance of a single apple leaf to calculate potential transpiration (E_p) for the whole apple tree. The E_p model was based on two main submodels predicting canopy temperature (T_c) and total canopy conductance (g_T). The g_T model was derived by simplifying the energy budget to rely on only climatic data and an empirical coefficient. These submodels were evaluated using the canopy temperature data collected in a Fuji apple orchard during the 2007, 2008, and 2013 growing seasons. The applicability of the E_p model was examined on (1) well-watered, young Fuji apple trees, and (2) well-irrigated, older apple trees bearing little fruit. Predicted potential transpiration rates at both scenarios were compared with those predicted by the ASCE standardized Penman–Monteith values for alfalfa (ET_r). Daily average weather data collected during the three growing seasons provided the inputs to the E_p model and its components. With the exception of air temperature measured in the orchard, the rest of the meteorological data were obtained from a local weather station. The canopy temperatures of the fully watered trees were predicted during midseason with mean absolute errors (MAEs) of about 0.41, 0.33, and 0.23°C in 2007, 2008, and 2013, respectively. These MAEs were better than the individual IRT accuracy of ±0.6°C. The coefficient of variation (CV) of the predictions averaged 2% over the experiment plots/years, being better than that of the measurements (CV = 4.8%) with the exception of one plot in 2007 with little difference (3% versus 2%). E_p was fairly correlated with ET_r on warm and dry days ($R^2 = 0.58$, $p < 0.001$) with slope and intercept values of close to 1.0 and 0.0, respectively. The model was able to reflect the high degree of coupling between the apple trees and the humidity of the surrounding air during cold and humid periods as E_p resulted in significantly lower values. The overall results of the experiments with Fuji apple trees showed that the non-water-stressed baselines and potential transpiration of Fuji apple trees can be estimated using the proposed approach. **DOI: [10.1061/(ASCE)IR.1943-4774.0000877](#).** *© 2015 American Society of Civil Engineers.*

Author keywords: Infrared thermometry; Canopy conductance; Reference evapotranspiration; Potential transpiration; Non-water-stressed baselines.

Introduction

Currently, the Penman–Monteith (PM) equation (Allen et al. 1998) corrected by a crop-specific coefficient (K_c) is used as the model of transpiration for tree canopies like apples. The PM model commonly referred to as reference ET (ET_r) is primarily developed for estimating transpiration from dense grass or alfalfa canopies. Apple tree leaves, however, are highly coupled to the atmosphere. As a result of this coupling, the water consumption of apple trees is controlled by stomatal regulations, radiation, and vapor pressure deficit (Jarvis 1985) compared to the transpiration of grass and alfalfa, which are mainly driven by net radiation (Lakso 2003). Dragoni et al. (2005) concluded a short dense crop cannot be a proper model for apple trees' transpiration leading to an overestimation of ET during humid and cold periods. They suggested that the PM model be modified to suit different conditions of tall discontinuous apple trees including stomatal and boundary layer conductances, as well as the bulk air effect on transpiration.

Canopy conductance has been an important part of several modeling efforts for estimating transpiration of tree canopies (Pereira et al. 2006; Green et al. 2003b). It has been directly measured in the field (Green et al. 2003a), alternatively estimated by empirical models (Jarvis 1976; Thorpe et al. 1980), or as in the original approach of the PM model, assumed constant (Pereira et al. 2006). Apparently, stomatal conductance of apple trees cannot be assumed constant because of its relationship with relative humidity (Dragoni et al. 2005) as a result of high coupling between the trees and surrounding bulk air (Jarvis 1985). The available empirical equations usually demand site-specific data on stomatal conductance and microclimate to determine required calibration coefficients. However, measurement of stomatal conductance itself most often is not a feasible option as a large number of field readings are usually required to well represent the tree canopies. If stomata close in response to the water deficit, the tree transpiration decreases and canopy temperature increases (Blonquist et al. 2009). Direct measurement of stomatal conductance can be replaced with a theoretical approach based on an energy budget equation, canopy temperature, and measurements of meteorological factors affecting conductance. As an alternative approach to the direct measurement, canopy conductance can be therefore dealt with indirectly through the measurement of canopy temperature by infrared thermometry.

A common method of indirect estimation of ET proposed by Jackson et al. (1981) relies on the crop water stress index (CWSI) (Ben-Asher et al. 1989; Taghvaeian et al. 2012). The computation of the CWSI requires two empirically or theoretically determined

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baselines: the non-water-stressed baseline (NWSBL) or lower boundary (potential) canopy and temperature difference (ΔT_P) representing a fully irrigated crop ideally transpiring at maximum stomatal conductance, and the non-transpiring baseline (NTBL). A CWSI value of zero corresponds with a well-watered condition. A CWSI based on empirical baselines was first introduced by Idso et al. (1981) and a theoretical CWSI was first defined by Jackson et al. (1988). The base for derivation of the theoretical baselines has been the PM ET model (Alves and Pereira 2000) and the empirical CWSI based on a linear relationship between ΔT and air vapor pressure deficit (Idso et al. 1981). Empirical NWSBLs are climate-dependent, site-specific, and might change from year to year (Idso et al. 1990; Alves and Pereira 2000). Thus, a theoretical approach not requiring costly, time-consuming field experiments will be more desirable.

As discussed before, the grass/alfalfa-based ET is not a suitable model for apple tree transpiration. The estimation of the potential transpiration of apple trees requires only NWSBLs, which must be developed specifically for apple tree conditions. However, the non-homogeneity of apple tree canopies and highly variable thermal distribution of their surfaces pose a big challenge in the modeling and required measurements. It might be possible to improve the required canopy temperature as input by trying different installation positions and angles of infrared temperature sensors (IRTs) and averaging readings from a number of sensors to achieve an optimum accuracy.

The goal here was to develop an analytical model for estimating potential transpiration of whole apple tree from the energy balance of a single leaf. The effort included (1) development of a theoretical NWSBL model, (2) a method of estimating net radiation, and (3) a simple model of canopy conductance not relying on field measurements of stomatal conductance. Predicted canopy temperatures and potential transpiration rates were compared with measured ΔT values and ET calculated using the PM approach, respectively.

Modeling of Transpiration

Apple tree leaves were categorized into four main types based on their exposure to long-wave and short-wave radiation sources at midday (Fig. 1): (1) one side exposed to the sky and the other side exposed to the foliage (top leaves), (2) both sides mostly exposed to the radiation from the foliage within the canopy (middle or inner leaves), (3) one side exposed to radiation from other leaves within the canopy and the other side exposed to the ground surface (bottom leaves), and (4) one side exposed to the sky and the other side exposed to the ground surface (side leaves). The top and middle leaves form the upper canopy, and the side and bottom leaves make the lower canopy.

Leaves falling into the lower half category receive long-wave (L_g) and reflected short-wave (S_{rg}) radiations from the ground surface under the trees. To estimate the net radiation for the lower half of the canopy, L_g must be calculated. The challenge is that L_g is a function of the ground surface temperature (T_g), which is unknown. In addition, the ground surface ranges from bare to completely covered (by grass), can be shaded or sunlit, and soil surface layer moisture can be highly variable depending on the irrigation system and time. This variability introduces another approximation in estimations of L_g as well as the less important S_{rg} component. Therefore, measurements/estimations of the lower half net radiation would be associated with a high degree of uncertainty.

This study assumed that an infrared sensor (IRT) can only see the upper half of the canopy, thus only leaves falling into the categories 1 and 2 were of importance. The modeling was based on the
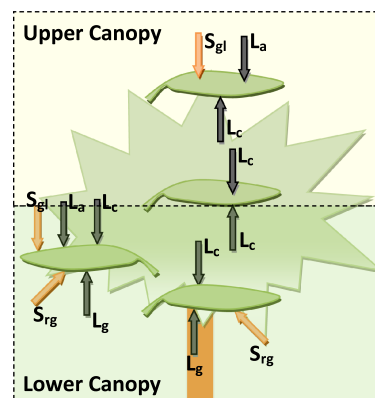
Fig. 1. Various types of leaves exposure to the long-wave (L_a, L_c, L_g) and short-wave (S_{gl}, S_{rg}) radiation sources (i.e., incoming and outgoing) at solar noon; L_a, L_c, and L_g are the long-wave flux densities from the atmosphere, apple tree canopies, and ground surface under the trees, respectively; S_{rg} and S_{gl} are reflected shortwave radiation from the ground surface under the trees and global solar irradiance (sum of direct beam and diffused: $S_{gl} = S_b + S_d$), respectively

assumption that the upper half can be treated as a single leaf bearing the characteristics of both upper canopy leaf types. This is similar to that of the *big-leaf* approach in the literature (Monteith 1965; Thorpe 1978; Caspari et al. 1993) and assumes a representative leaf embraces all of the properties of the whole tree canopy (Jarvis 1995). Using the first law of thermodynamics (i.e., the principle of conservation of energy), the energy balance model for a single apple leaf can be expressed as

$$R_n = R_{abs} - L_{oe} = H + \lambda E + C + M + S \tag{1}$$

where R_n = net radiation; R_{abs} = absorbed radiation; L_{oe} = outgoing emitted radiation; λE = latent heat flux; H = sensible heat flux; C = leaf conductive heat loss (through stem); M = net rate of heat storage in metabolic reactions (e.g., photosynthesis or respiration); and S = net rate of physical heat storage (all terms in W m^{-2}). Considering the conductive heat loss, metabolic heat production, and heat storage are fairly small (Knoerr and Gay 1965; Blonquist et al. 2009; Okajima et al. 2012) and assuming steady state (Campbell and Norman 1998; Monteith and Unsworth 1990), C, M, and S were assumed negligible ($C = M = S = 0$). Absorbed radiation for a leaf is the sum of absorbed short-wave and long-wave radiations. R_n is the difference between this sum and the emitted long-wave radiation from the leaf. The average absorbed radiation for a leaf representative of the upper canopy is then calculated as

$$R_{abs} = a \times R_{top} + b \times R_{inn} \tag{2}$$

where a and b = percentages of each leaves type and $a + b = 1$. Because apple tree canopies are sparse, it is very probable that during the day all types of leaves finally become sunlit for about half the daylight hours. This leads to an assumption of equal numbers of leaves in each category. Therefore, for daily mean values, R_{abs} of the representative leaf can be expressed as

$$R_{abs} = (R_{top} + R_{inn})/2 \tag{3}$$

The lower canopy will be still influential by radiating long-wave energy at a temperature of T_c (canopy temperature at the border of the two halves) to the upper half. As a simplification, this temperature was assumed to be the same as the canopy temperature

measured by the IRT. Total absorbed radiations (long and short waves) for the top and middle leaves were estimated using the following relationships (Campbell and Norman 1998), respectively

$$R_{top} = \alpha_S(F_{gl}S_{gl}) + \alpha_L(F_aL_a + F_{c1}L_c) \tag{4}$$

$$R_{inn} = \alpha_S(F_{tr}S_{tr}) + \alpha_L(2F_{c1}L_c) \tag{5}$$

where S_{gl} = global solar irradiance (sum of direct beam and diffused: $S_{gl} = S_b + S_d$); and S_{tr} = transmitted short-wave radiation through the apple leaf ($S_{tr} = \tau S_{gl}$). L_a and L_c are the long-wave flux densities from the atmosphere and apple tree canopies, respectively, computed using the Stefan–Boltzmann equation. All radiations are in $W\,m^{-2}$. F_{gl}, F_{tr}, F_a, and F_{c1} are view factors between the leaf surface and the various sources of radiation, namely, global (0.5) and transmitted (0.5) solar radiations, and atmospheric (0.5) and apple tree canopy (0.5) thermal radiations, respectively. The view factors were calculated based on the assumption that only one side of a leaf (50%) could be exposed to a radiation source (Campbell and Norman 1998). τ, α_S, and α_L are green leaf transmittance ($\tau = 0.06$), absorptivity in the short-wave band ($\alpha_S = 0.85$) and absorptivity in the thermal wave band ($\alpha_L = 0.95$), respectively. α_S was calculated as $\alpha_S = 1 - (\tau + \rho)$, where ρ is the albedo ($\rho = 0.09$). The values of apple leaf and ground optical properties were adapted from the available literature (Green et al. 2003b). The outgoing long-wave radiation from the leaf (L_{oe}) was calculated using the Stefan–Boltzmann relationship

$$L_{oe} = F_e\varepsilon_s\sigma\mathbf{T}_c^4 \tag{6}$$

where ε_s = thermal emissivity of apple leaf ($\varepsilon_s = \alpha$); σ = Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,W\,m^{-2}\,K^{-4}$); $\mathbf{T}_c$ = canopy temperature (Kelvin); and F_e = 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 [$L_a = \varepsilon_a(c)\sigma\mathbf{T}_a^4$, $\mathbf{T}_a$ in Kelvin], was calculated by (Monteith and Unsworth 1990)

$$\varepsilon_a(c) = (1 - 0.84c)\varepsilon_{ac} + 0.84c \tag{7}$$

where c is the fraction of the sky covered by cloud. c was calculated by comparing the daylight average of real-time global radiation ($\overline{S_{gl}}$, $W\,m^{-2}$) with potential extraterrestrial incoming solar radiation of the same day (R_{ap}, $W\,m^{-2}$)

$$c = \begin{cases} \left(1 - \dfrac{\overline{S_{gl}}}{R_{ap}}\right) & \text{if } \overline{S_{gl}} \le R_{ap} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

R_{ap} was calculated according to the FAO-56 bulletin (Allen et al. 1998). The emissivity of clear sky (ε_{ac}) was estimated using the following empirical relationship (Brutsaert 1984):

$$\varepsilon_{ac} = 1.72\left(\frac{e_a}{\mathbf{T}_a}\right)^{1/7} \tag{9}$$

where e_a = vapor pressure (kPa) at air temperature ($\mathbf{T}_a$, K).

The term H of the energy balance equation is expressed as (Campbell and Norman 1998)

$$H = g_HC_P(T_c - T_a) \tag{10}$$

where C_P = heat capacity of air ($29.17\,J\,mol^{-1}\,C^{-1}$); T_c = leaf temperature (°C); T_a = air temperature (°C); and g_H = boundary layer conductance to heat ($mol\,m^{-2}\,s^{-1}$). The term H is comprised of two components, H_{ab} and H_{ad}, which are sensible heat fluxes from the abaxial and adaxial sides of apple leaf, respectively. This refers to

the fact that apple leaves are hypostomatous transpiring mostly through the abaxial side and that there is sensible heat exchange from both sides of the leaf.

The errors in conductance are normally distributed. Conductance is also directly related to the water flux from the leaf, which makes it more suitable than resistance (Campbell and Norman 1998; Blonquist et al. 2009). In this study, 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 following empirical formula (Campbell and Norman 1998):

$$g_{Hf} = (1.4)0.135\sqrt{\frac{u}{d}} \tag{11}$$

where u = wind speed; and d = characteristic dimension defined as 0.72 times the leaf width ($d = 0.72w_l$, $w_l = 5$ cm: measured in the field). The factor of 1.4 in Eq. (13) is to account for turbulence (Campbell and Norman 1998). Assuming equal conductance for both abaxial and adaxial sides of leaf, the combined air conductance to heat is $g_H = 2g_{Hf}$. Rearranging Eq. (1) to solve for E, the following equation was derived for estimating potential transpiration:

$$E_p = 1{,}555.2\frac{R_n - \Delta T_p g_H C_P}{\lambda} \tag{12}$$

where E_p = canopy potential transpiration ($mm\,day^{-1}$); ΔT_p = potential canopy and air temperature difference ($\Delta T_p = T_c - T_a$), and factor 1,555.2 ($0.018\,kg\,mol^{-1} \times 24\,h \times 3{,}600\,s\,h^{-1}$) converts $mol\,m^{-2}\,s^{-1}$ to $mm\,day^{-1}$. To estimate E_p, ΔT_p must be determined.

The ΔT_p of well-watered apple tree canopies was predicted by the following procedure. First, the latent heat flux (λE) was calculated as (Campbell and Norman 1998)

$$\lambda E = g_T\lambda\left(\frac{D_c}{P_a}\right) \tag{13}$$

where P_a = atmospheric pressure (kPa); λ = latent heat of vaporization ($J\,mol^{-1}$); and g_T = total conductance to water vapor ($mol\,m^{-2}\,s^{-1}$) defined by a series combination of boundary layer conductance (g_v, $mol\,m^{-2}\,s^{-1}$) and stomatal conductance to water vapor (g_s, $mol\,m^{-2}\,s^{-1}$) (Blonquist et al. 2009). D_c is the canopy-to-air vapor pressure deficit expressed by $D_c = e_s(T_c) - e_a$, where $e_s(T_c)$ is the saturated vapor pressure (kPa) at canopy temperature (T_c, °C) and e_a is the vapor pressure (kPa) at air temperature (T_a, °C). Substituting Eqs. (12) and (13) in Eq. (1) and rearranging to solve for ΔT_p yields

$$\Delta T_p = \frac{P_aR_n - g_T\lambda D_c}{g_HC_PP_a} \tag{14}$$

In this equation, R_n and D_c are functions of canopy temperature. D_c was linearized as $D_c = \Delta \times \Delta T_p + D_a$, where Δ is the slope of the relationship between saturation vapor pressure (e_s, kPa) and air temperature (T_a, °C). The air vapor pressure deficit (D_a) was calculated as $D_a = e_s - e_a$ (Idso et al. 1981), where e_s is the saturated vapor pressure at the air temperature (T_a) and e_a is the actual vapor pressure of air. To eliminate ΔT_p from the right side of Eq. (14), it was then rewritten as

$$\Delta T_p = \frac{P_aQ - g_T\lambda D_a}{g_HC_PP_a - nP_a + \lambda g_T\Delta} \tag{15}$$

where $R_n = Q + n\Delta T$. Q and n are defined by the following equations, respectively

$$Q = 0.25[\alpha_S S_{gl} + \alpha_S S_{t1} + 4(\alpha_L - 1)L_a] \quad (16)$$

and

$$n = (3\alpha_L - 4)\varepsilon_a(c)\sigma \mathbf{T}_a^3 \quad (17)$$

By arranging Eq. (15), ΔT_P is linearized in the form $\Delta T_P = a - bD_a$

$$\Delta T_p = \left(\frac{Q}{g_H C_P - n + \lambda g_T s}\right) - \left(\frac{g_T \lambda / P_a}{g_H C_P - n + \lambda g_T s}\right)D_a \quad (18)$$

where $s = \Delta/P_a$. To avoid more sources of uncertainty, g_s and g_v were not analyzed separately, but were dealt with indirectly in form of g_T. Rearranging Eq. (14) to solve for g_T yields

$$g_T = \frac{P_a[R_n - g_H C_P \Delta T_m]}{\lambda D_c} \quad (19)$$

where ΔT_m is the measured canopy and air temperature difference. D_c and R_n are also computed using measured canopy temperatures. A g_T function independent of canopy temperature was also derived after analyzing the field data.

Application of E_p Model

Experiment Site

The field experiments were conducted in an apple orchard of Fuji in the Roza farm, at the Washington State University, Irrigated Agriculture Research and Extension Center in Prosser, Washington, at the coordinates of latitude 46.26°N, longitude 119.74°W, and 360 m above sea level. The site is located in a semiarid zone with almost no summer rains and an average annual precipitation of 217 mm. The site's soil is a shallow Warden Silt Loam (Web Soil Survey) more than 90 cm deep (field observation).

Plot Design
The E_p model was initially applied to a field investigation (scenario 1) in 2007 and 2008 where young, well-developed apple trees were fully irrigated. To investigate the consistency of the results across the orchard during each growing season, two rows/blocks of apple trees (42 trees per block) as two replications were marked for conducting the experiment. The rows/blocks were named N and S. The trees were spaced 4 m (row spacing) by 2.5 m (tree spacing) apart in the orchard and irrigated by a micro-sprinkler irrigation system with water emitters of $27\,L\,h^{-1}$ spaced at 2.5-m intervals (Hurricane, NaanDanJain Irrigation, Post Naan, Israel). In 2007 and 2008, E_p was estimated for the two fully irrigated blocks of N and S.

After evaluation and optimization of the E_p model, it was applied to another case in 2013 where the same apple trees that while healthy, for various reasons bore little or no fruit. During the 2013 growing period, the orchard was irrigated this time by two lines of drip tubing laterals per row with in-line $2.0\,L\,h^{-1}$ drippers (BlueLine PC, The Toro Company, El Cajon, California), spaced at 91.4-cm intervals along laterals. Six small plots consisting of 18 trees each (6×3) were marked for conducting the experiment. Two treatments of N and S were assigned to these plots (three replications/plots per treatment).

The quantity of irrigation water applied to the trees was controlled to never allow the soil water depletion to exceed the 50% maximum allowed depletion (MAD) for apple trees (Allen et al. 1998). This was assured by taking weekly soil water content readings using a neutron probe (503DR Hydroprobe, Campbell Pacific Nuclear, Concord, California) to a depth of 90 cm (or deeper) in all of the plots.

Meteorological Measurements

The real-time meteorological data of the 2007, 2008, and 2013 growing seasons including relative humidity, solar radiation, wind speed, and air temperature were obtained from two electronic weather stations close to the apple orchard (Roza and WSU HQ, Washington Agricultural Weather Network). During our experiments in the 2007 and 2008 growing seasons, no independent air temperature measurements were taken in the orchard; thus, air temperatures recorded in the field using the embedded temperature sensor of a CR21X datalogger (Campbell Scientific, Logan, Utah) were used. The enclosure was shaded by the foliage at all of the times. 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 about 2 m (in-line with the trees) at three locations distant from each other in the orchard. These air temperature sensors were wired to CR10X dataloggers (Campbell Scientific, Logan, Utah). Air temperature was calculated by averaging the readings from the three sensors.

Measurement of Canopy Temperature

To monitor canopy temperature in 2007 and 2008, a total of 12 IRTs (Exergen model IRt/c.03: Type T, Watertown, Massachusetts) in six pairs were mounted above the trees in Plots N and S [Fig. 2(a)]. The IRTs were pointed downwards at approximately 45° angles at both the north and south sides of a tree. The sensors were calibrated using a blackbody calibrator (BB701, Omega Engineering, Stamford, Connecticut) and wired to a CR21X datalogger.

During the 2013 growing season, canopy temperature was measured in real-time using individual IRTs (Exergen model IRt/c.2: Type J, Watertown, Massachusetts) installed perpendicularly above a tree located at the center of the six plots (small plots of 18 trees) [Fig. 2(b)]. Sepulcre-Canto et al. (2006) and Testi et al. (2008) used similar mountings in olive and pistachio trees, respectively. 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. The IRT sensors were wired to a network of CR10 and CR10X dataloggers sending out temperature readings to a central computer through 900-MHz wireless radios (RF401, Campbell Scientific, Logan, Utah).

Estimation of Reference ET
To estimate alfalfa reference evapotranspiration (ET_r, $mm\,day^{-1}$) of the irrigated Fuji apple orchard, the ASCE standardized Penman–Monteith equation (ASCE-EWRI 2005) was used. The required meteorological data including the daily received solar radiation (in $MJ\,m^{-2}\,day^{-1}$), relative humidity, and wind speed were obtained from the nearby weather stations. Air temperature (maximum and minimum) was provided by the in-field sensors.

Model Assessment
The performance of the E_p model was evaluated using the estimated values of transpiration from the model and those predicted by the PM model. The two submodels ΔT_p and g_T were assessed using the measured ΔT (ΔT_m). The statistical means used comprised (1) the relative error (ε) between predicted transpiration (E_p) and ET_r, (2) the root-mean square error (RMSE), (3) the
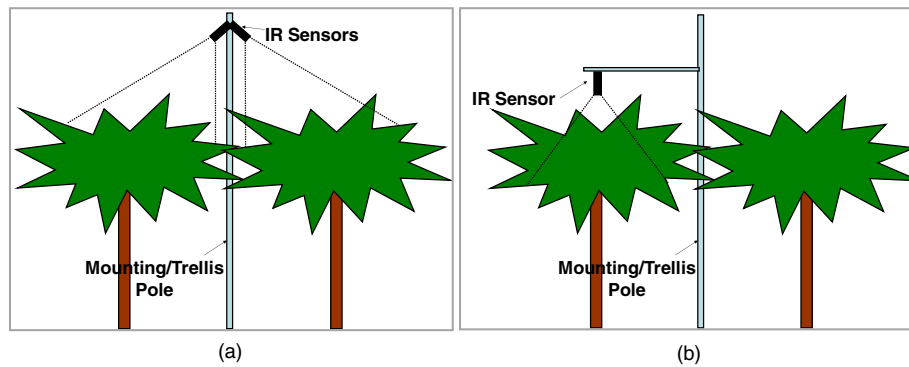
Fig. 2. IRT sensor setup in the field: (a) in 2007 and 2008, the sensors were pointed downwards at approximately 45° angles at both the north and south sides of a tree; (b) in 2013, the sensors were installed at the top of trees closer to the crown to avoid any inclusion of the ground in the view

coefficient of variation of RMSE (CV of RMSE), (4) the mean absolute error (MAE), and (5) a linear regression between predicted and observed values or two sets of predictions. A satisfactory prediction was assumed when the linear regression yielded slopes close to unity, intercepts close to zero, and high correlation (R^2). The accumulated predicted transpiration from the E_p model (D_E) and PM model (D_{PM}) over a period of time were compared by calculating the relative error (ε)

$$\varepsilon = \frac{D_{PM} - D_E}{D_{PM}} \tag{20}$$

The root-mean square error (RMSE) was exploited as a measure of the variance between E_p and ET_r

$$RMSE = \sqrt{\frac{\sum (ET_r - E_p)^2}{n}} \tag{21}$$

and as a measure of the variance between predicted canopy and air temperature difference (ΔT_p) and measured canopy and air temperature difference (ΔT_m)

$$RMSE = \sqrt{\frac{\sum (\Delta T_p - \Delta T_m)^2}{n}} \tag{22}$$

where n = number of measurements. The coefficient of variation (CV) of RMSE was calculated by dividing RMSE by the mean of measurements ($\bar{x}$)

$$CV_{RMSE} = \frac{RMSE}{\bar{x}} \tag{23}$$

Considering the sensitivity of the RMSE to outliers, the mean absolute error (MAE) was also used as a safer measure of the variance between ΔT_p and ΔT_m

$$MAE = \frac{\sum |\Delta T_p - \Delta T_m|}{n} \tag{24}$$

In addition to the aforementioned statistical means, the coefficient of variation of the standard deviation (CV of STD, the ratio of the standard deviation to the mean) was also employed to calculate canopy temperature variations among the apple trees. The RMSE was also used to measure the average difference between two time series.

Microclimatic Considerations
The E_p model, Eq. (12), and its components required microclimatic parameters including relative humidity, solar radiation, wind speed,

and air temperature as inputs. Air temperature measurements in the orchard in the growing seasons of 2007, 2008, and 2013 were compared with those obtained from the nearest weather station. During the experiments in 2007 and 2008, no independent field measurements of air temperature were available; therefore, the air temperature records by the internal sensor of the datalogger were used. Although this method of air temperature measurement was expected to be associated with errors, the analysis showed that these data were far better than that of obtained from a nearby weather station. A sensitivity analysis and preliminary results revealed that using air temperature data from the weather station could lead to substantial errors, making the application of the E_p model impossible.

The two sets of data (i.e., that of obtained from the orchard and nearby weather station) exhibited completely different patterns of air temperature diurnal change in terms of maximum and minimum temperatures and time of their occurrences in the growing seasons of 2007 and 2008 (Fig. 3). Maximum and minimum of air temperatures measured in the orchard occurred with a few hours of delay after the corresponding air temperatures at the weather station. This resulted in up to a 10°C difference between the two time series during some times of day and average difference (RMSE) of 2.8°C in 2007 and 1.9°C in 2008 for daily mean values.

Regardless of a relatively good method of air temperature measurement employed in 2013, a similar problem was detected. However, the difference was less pronounced with RMSEa RMSE of only 0.44°C for daily mean values. This was an expected phenomenon because large canopies of apple trees can form a local microclimate. This causes diurnal variations of microclimatological variables such as air temperature to be notably different than those meteorological parameters obtained from a nearby weather station. In 2013, however, the extent of difference in the diurnal changes of air temperature in the field and weather station was less compared to 2007 and 2008, which could be due to lesser degree of canopy growth and consequently lesser impact on the surrounding environment.

ΔT was calculated by averaging over the course of several days for three occasions including early, mid, and late in the season with two different series of air temperature data (two scenarios): (1) measured within the orchard [Figs. 4(b, d, f)] and (2) obtained from the nearby weather station [Figs. 4(a, c, e)]. In scenario a, maximum stomatal activity of apple trees (e.g., maximum ΔT) occurred late in the morning and late in the afternoon with a shift from early in the season to late in the season. Early in the 2008 and 2013 seasons, ΔT started declining in the morning and reached positive values ($\Delta T \geq 0$) at solar noon. Although similar declining patterns could be seen throughout the seasons, its occurrence at this degree might
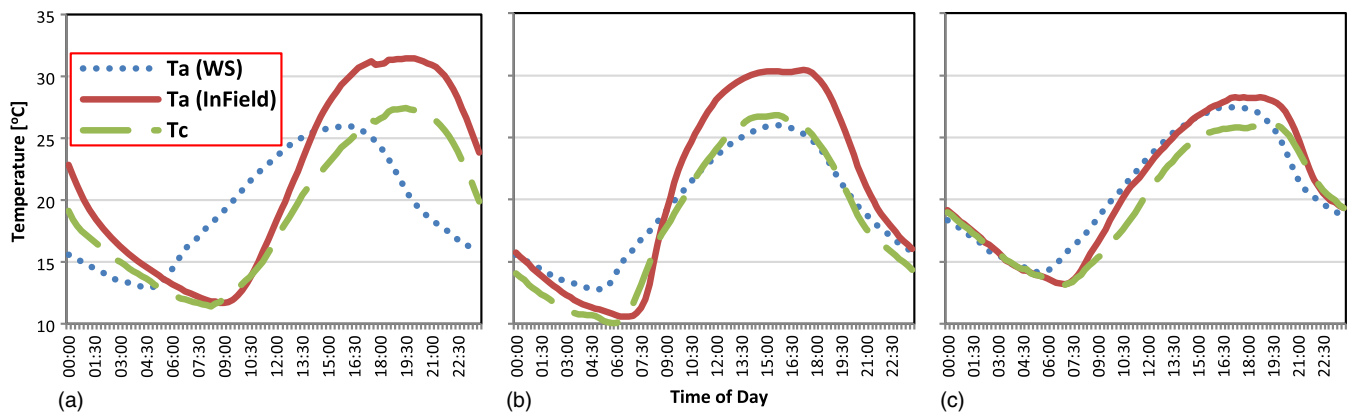
Fig. 3. Comparison of diurnal changes of air temperature (T_a) obtained from the closest weather station and that of measured in the orchard during the growing seasons of (a) 2007; (b) 2008; (c) 2013, all graphs (a–c) represent the average of T_a over 118 successive days (DOY = 152–270) during mid and late season
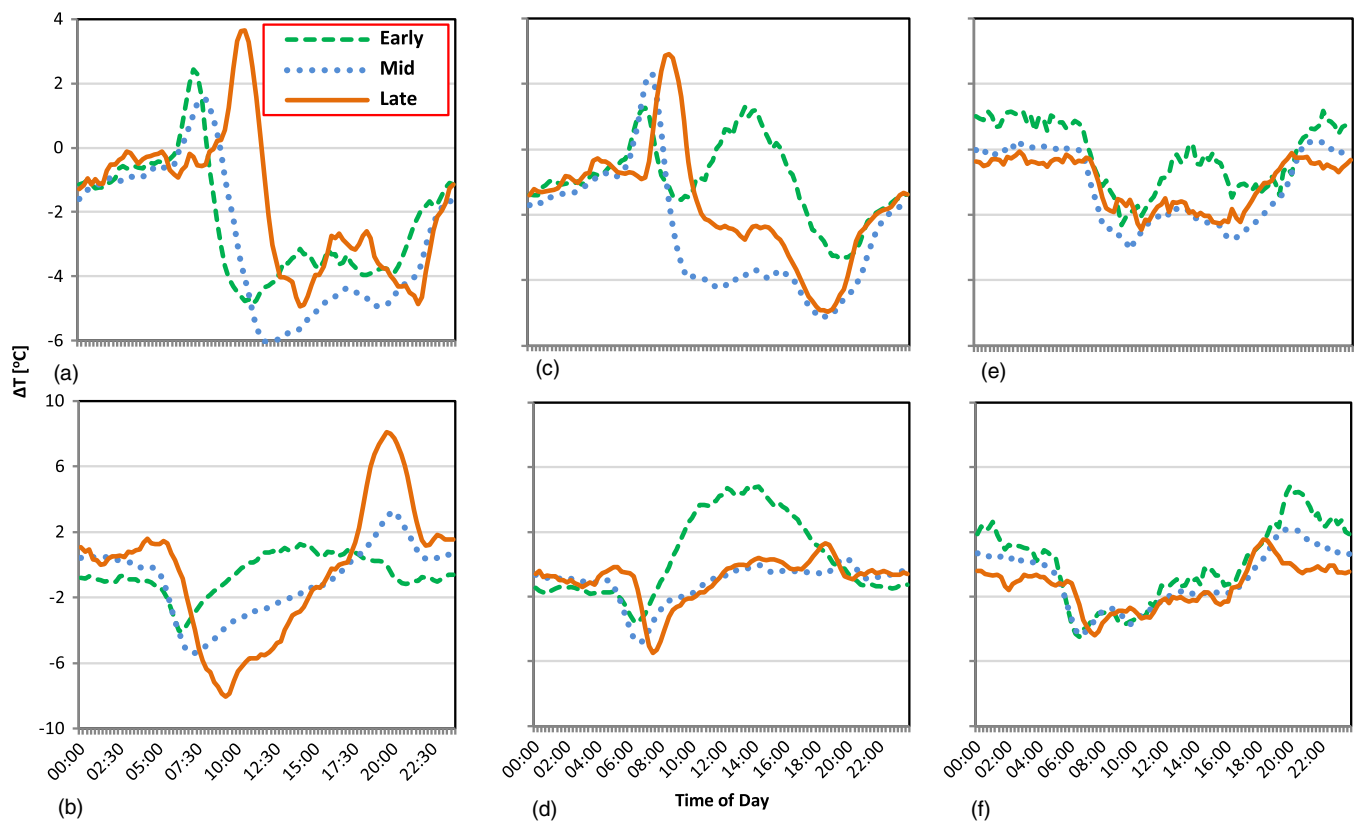
Fig. 4. Average diurnal changes of canopy and air temperature differences (ΔT) during early, mid, and late in the (a and b) 2007; (c and d) 2008; (e and f) 2013 growing seasons; each curve represents the average of ΔT over a few successive days: DOY = 152–160 as early, DOY = 191–200 as mid, and DOY = 260–270 as late in the season; average diurnal variations of ΔT are shown for two situations: air temperature measured (a, c, e) in the orchard and (b, d, f) from the weather station

be partially attributed to the contribution of the ground surface thermal radiation to the canopy temperature. The completion of foliage growth towards the midseason minimized the ground being seen by the IRTs.

A similar pattern of apple trees activity to that of scenario a 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 is controlled by stomatal regulation, which is reflected in a lowered or elevated canopy temperature. 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). This will make it very difficult if not impossible to estimate hourly potential transpiration of apple trees as stomatal conductance is controlled by additional factor(s) not included in the energy budget equation. Daily transpiration, however, relies on daily mean values of canopy temperature where only the overall activity is of importance.

In scenario b, where ΔT was calculated using T_a obtained from the weather station, maximum stomatal activity of apple trees moved to early in the morning with a shift from early in the season to late in the season. This does not comply with the literature as it lacks the activity late in the afternoon reported by Tokei and Dunkel (2005). This analysis showed daily mean ΔT computed using air temperature obtained from a weather station could not reflect trees stomatal activity being positive or small negative values throughout the season with an average of $-0.5°C$ (STD $= 1.2$) in 2007 and $-0.6°C$ (STD $= 1.4$) in 2008. This study thus only used air temperatures measured in the orchard and focused only on predictions of daily potential transpiration rather than over shorter timescales. All of the other required meteorological parameters were obtained from the weather station assuming that those measurements were reliable enough or of less degree of importance.

Potential ΔT (ΔT_p)
During midseason, the crop coefficient for converting alfalfa ET_r to apple trees transpiration is almost 1.0 with a pick of 1.06 (Karimi et al. 2013). This is a time when under normal conditions actual transpiration of well-watered apple trees is expected to be close to the alfalfa reference ET (maximum of 6% discrepancy). To avoid uncertainties of canopy temperature measurements especially during the early season (due to incomplete canopy growth), the midseason (DOY $= 155–243$) period was chosen for the purpose of comparison.

Total conductance to water vapor (g_T) defined by Eq. (19) is simply a different arrangement of Eq. (18) before linearization and is itself a function of T_c; it thus cannot be directly used to estimate ΔT_p. Considering a high degree of coupling between apple leaves and the surrounding air, daily mean leaf-to-air vapor pressure deficit (D_c) was highly correlated (linearly) with daily air vapor pressure deficit (D_a) during the 2007, 2008, and 2013 growing seasons with R^2 values greater than 0.90 ($p < 0.001$). The slope and intercept of the D_c and D_a relationship curves were slightly

different across the plots and from year to year. The fully irrigated seasons of 2007 and 2008 had the closest values, while the greatest field variability and difference with the rest of the experimental years was seen in 2013 when the apple trees were on an alternate bearing. Considering the good consistency among the field results on the linear relationship between D_c and D_a, further steps were taken to simplify Eq. (19) to make it independent of canopy temperature.

There was very weak correlation between daily mean D_a and ΔT in the experiment years (Fig. 5). To relate D_c to ΔT, D_c was linearized instead as $D_c = \Delta \times \Delta T_p + D_a$. Taking advantage of a linear relationship between D_c and D_a, D_c was replaced with $mD_a + b_1$, where m and b_1 are the slope and intercept of D_c and D_a relationship curve, respectively. After some manipulations, Eq. (19) was rewritten as

$$g_T = \frac{Q\Delta + (n - g_H C_P)(\text{m}'D_a + b_1)}{\lambda(mD_a + b_1)s} \quad (25)$$

where $\text{m}' = m - 1$. g_T was computed using Eq. (25) and the coefficients m and b_1 were obtained by a linear regression between D_a and D_c. These values were then put in Eq. (15) and ΔT_p was estimated for the growing seasons of 2007, 2008, and 2013. The statistical results are presented in Table 1. The correlation was not satisfactory, which could be due to different reasons including field variability, linearization error, and temperature measurement error. The empirical coefficients were determined by fitting the g_T values estimated from Eqs. (25) to (19). The values obtained for coefficient m were very close to unity. The coefficient m was omitted ($m = 1.0$), two new empirical coefficients of b_0 and b_2 were added, and the model was modified to the following form:

$$g_T = b_2\left[\frac{Q\Delta + b_1(n - g_H C_P)}{\lambda(D_a + b_1)s}\right] + b_0 \quad (26)$$
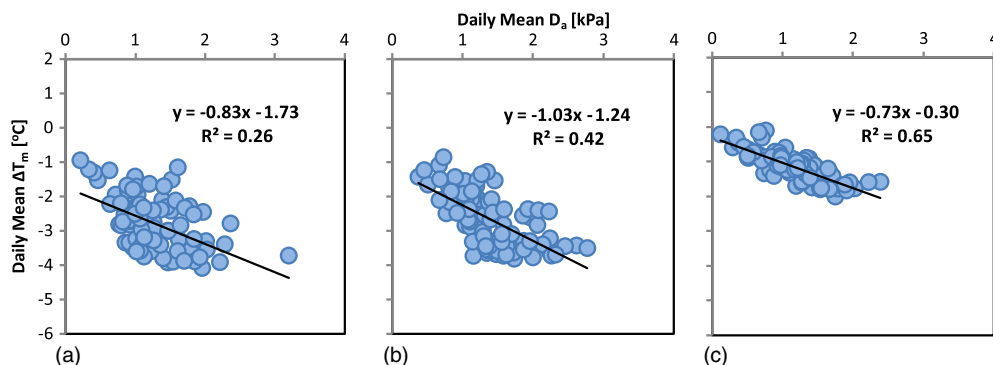
Fig. 5. Relationship between daily mean canopy and air temperature difference (ΔT_m) and air vapor pressure deficit (D_a) in the midseason of (a) 2007; (b) 2008; (c) 2013 ($p < 0.001$)

Table 1. Comparison of Predicted Potential Canopy and Air Temperature Difference ($\Delta\Delta T_P$) and Observed ΔT (ΔT_m)

Year	Plot	b_1	m	R^2	ΔT_m	CV of STD	ΔT_p	MAE (°C)	CV of RMSE	ET_r (mm day^{-1})	E_p (mm day^{-1})
2007	S	0.07	0.69	0.39	-3.00	0.04	-1.91	1.12	0.07	6.7	5.4
	N	0.07	0.71	0.33	-2.80	0.02	-1.73	1.11	0.06	—	5.7
2008	S	0.01	0.64	0.56	-2.77	0.07	-3.15	0.52	0.03	7.8	8.5
	N	0.02	0.69	0.55	-2.69	0.03	-2.56	0.46	0.03	—	10.0
2013	S	0.06	0.92	0.14	-1.06	0.08	-0.23	0.89	0.05	7.4	4.8
	N	0.00	0.84	0.43	-1.18	0.05	-1.20	0.24	0.02	—	1.9

Note: The coefficients are obtained by linear regression between D_a and D_c ($b_0 = 0.0$ and $b_2 = 1.0$).

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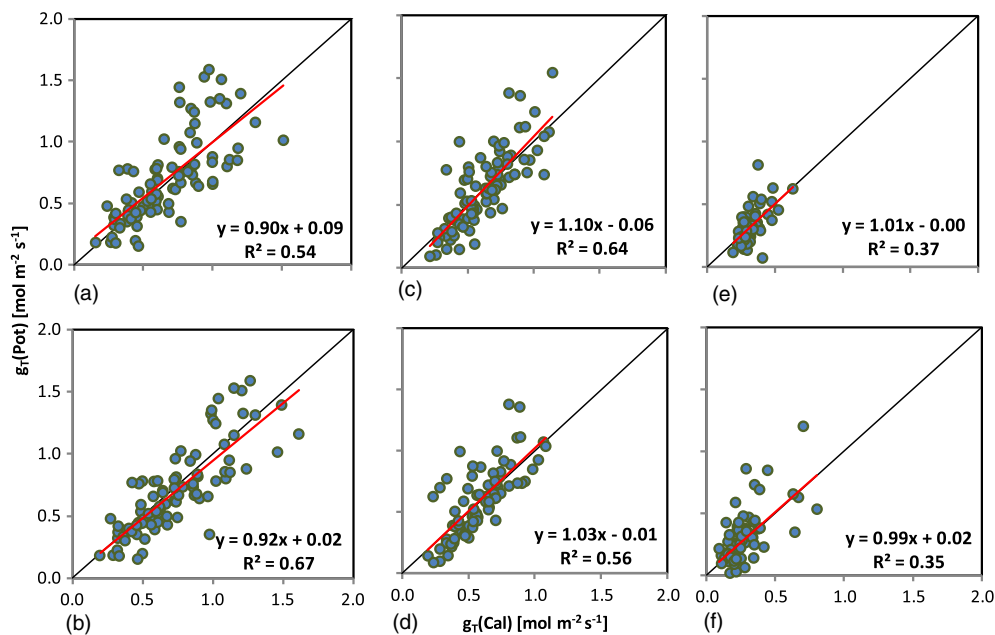
Fig. 6. Correlation between the daily mean potential conductance [g_T(Pot), mol m^{-2} s^{-1}] from Eq. (27), and that of calculated by Eq. (19) [g_T(Cal), mol m^{-2} s^{-1}] ($p < 0.001$) in (a, c, d) Plot N and (b, d, f) Plot S

Among the remaining coefficients, b_1 had the least effect on predictions. Therefore, Eq. (26) was further modified to obtain the following equation:

$$g_T = b_2 \left[\frac{P_a Q}{\lambda D_a} \right] + b_0 \qquad (27)$$

Eq. (27), without the calibration coefficients, is very similar to the inverse of the climatic resistance defined by Rana et al. (2005). Eq. (27) is only dependent on air vapor pressure deficit and QQ, which is a function of global radiation (S_{gl}) and air temperature.

By fitting the daily mean potential conductance estimated by Eq. (27) to that calculated by Eq. (19) (linear regression), the values of b_2 for the 2007 and 2008 seasons were obtained as 11.5 and 9.5, respectively. For the same period, b_0 values were found to be -0.30 and -0.15, respectively. Due to a high degree of nonuniformity in the canopies in 2013, the coefficients calculated for Plots N and S were quite different with $b_2 = 4.3$ and $b_0 = -0.05$ for Plot N and $b_2 = 8.0$ and $b_0 = -0.4$ for Plot S. The results of linear regression between the simplified g_T model [Eq. (27)] and the original model [Eq. (19)] for Plots N and S are illustrated in Figs. 6(a–c). The average of b_2 and b_{o0} in 2007 and 2008 ($\overline{b_2} = 10.5$, $\overline{b_0} = -0.23$) were applied to both years to investigate the repeatability of the results. The linear regression yielded slopes of close to unity and intercepts near zero in 2007, 2008, and 2013. However, the R^2 value in 2013 ($R^2 = 0.38$, $p < 0.001$) was less desirable compared to 2007 ($R^2 = 0.67$, $p < 0.001$) and 2008 ($R^2 = 0.64$, $p < 0.001$).

The values of the empirical coefficients were determined separately for each season by minimizing the MAE MAE between the simulated ΔT (ΔT_p) and measured values of ΔT (ΔT_m). The results of optimization once all of the parameters (b_0, b_1, b_2, and m) were included and Eq. (27) was used to estimate g_T ($b_1 = 0.0$ and $m = 1.0$) as found in Tables 2 and 3, respectively. From the very small difference between the MAE and R^2 values calculated under the two scenarios, it can be inferred that the optimized g_T model [Eq. (27)] minimally compromised the accuracy of ΔT predictions. Thus Eq. (27) was used, relying on just two empirical coefficients, for the rest of total canopy conductance estimations required for determining NWSBLs.

In the latter scenario (Table 3), the values of b_2 in 2007 and 2008, and for Plots N and S were almost the same, and b_0 was zero. In 2013, on the other hand, the coefficients were different from the rest of the years. In 2013, the field also showed a high degree of nonuniformity among the tree canopies of Plots N and S, which is reflected in the statistical results in Table 3. The difference between $g_T(N)$ and $g_T(S)$ arose from a difference in the measured canopy temperatures, which was itself due to the nonuniformity of the apple tree canopies (Fig. 7).

The weak correlation between g_T(Pot) and g_T(Cal) in 2013 can be explained by the fact that the apples trees were on an alternate bearing. This means that although variations of stomatal conductance were dependent on weather conditions, the average level of stomatal conductance was maintained low in response to the small

Table 2. Comparison of Predicted Potential Canopy and Air Temperature Difference (ΔT_P) and Observed ΔT (ΔT_m)

| Year	Plot	b_0	b_1	b_2	m	R^2	ΔT_m	CV of STD	ΔT_p	MAE (°C)	CV of RMSE	ET$_r$ (mm day^{-1})	E_p (mm day^{-1})
2007	S	−0.05	−0.01	8.76	1.00	0.67	−3.00	0.04	−3.01	0.37	0.02	6.7	8.2
	N	−0.15	0.00	5.67	0.94	0.50	−2.80	0.02	−2.84	0.43	0.03		7.8
2008	S	−0.16	0.05	7.26	0.94	0.76	−2.77	0.07	−2.74	0.29	0.02	7.8	8.5
	N	−0.28	0.03	6.78	0.93	0.71	−2.69	0.03	−2.67	0.33	0.02		8.9
2013	S	0.20	−0.08	1.17	1.08	0.24	−1.07	0.08	−1.03	0.28	0.02	7.4	4.3
	N	0.25	0.00	0.67	1.00	0.75	−1.18	0.05	−1.14	0.18	0.01		4.6

Note: Values of the coefficients (b_0, b_1, b_2, and m) were obtained by minimizing the MAE between ΔT_P and ΔT_m.

Table 3. Comparison of Predicted Potential ΔT (ΔT_p) and Observed ΔT (ΔT_m)

Year	Plot	b_0	b_2	R^2	ΔT_m	CV of STD	ΔT_p	MAE (°C)	CV of RMSE	ET_r (mm day^{-1})	E_p (mm day^{-1})
2007	S	0.00	8.47	0.67	−3.00	0.04	−2.98	0.38	0.02	6.7	8.1
	N	0.00	7.63	0.53	−2.80	0.02	−2.77	0.43	0.03	—	7.6
2008	S	0.00	8.12	0.76	−2.77	0.07	−2.80	0.34	0.02	7.8	8.9
	N	0.00	8.14	0.76	−2.69	0.03	−2.71	0.32	0.02	—	8.9
2013	S	0.16	1.58	0.25	−1.07	0.08	−1.09	0.27	0.02	7.4	4.5
	N	0.22	1.06	0.74	−1.18	0.05	−1.16	0.18	0.01	—	4.7

Note: The values of b_0 and b_2 were calculated by minimizing the MAE after assuming $b_1 = 0.0$ and $m = 1.0$.
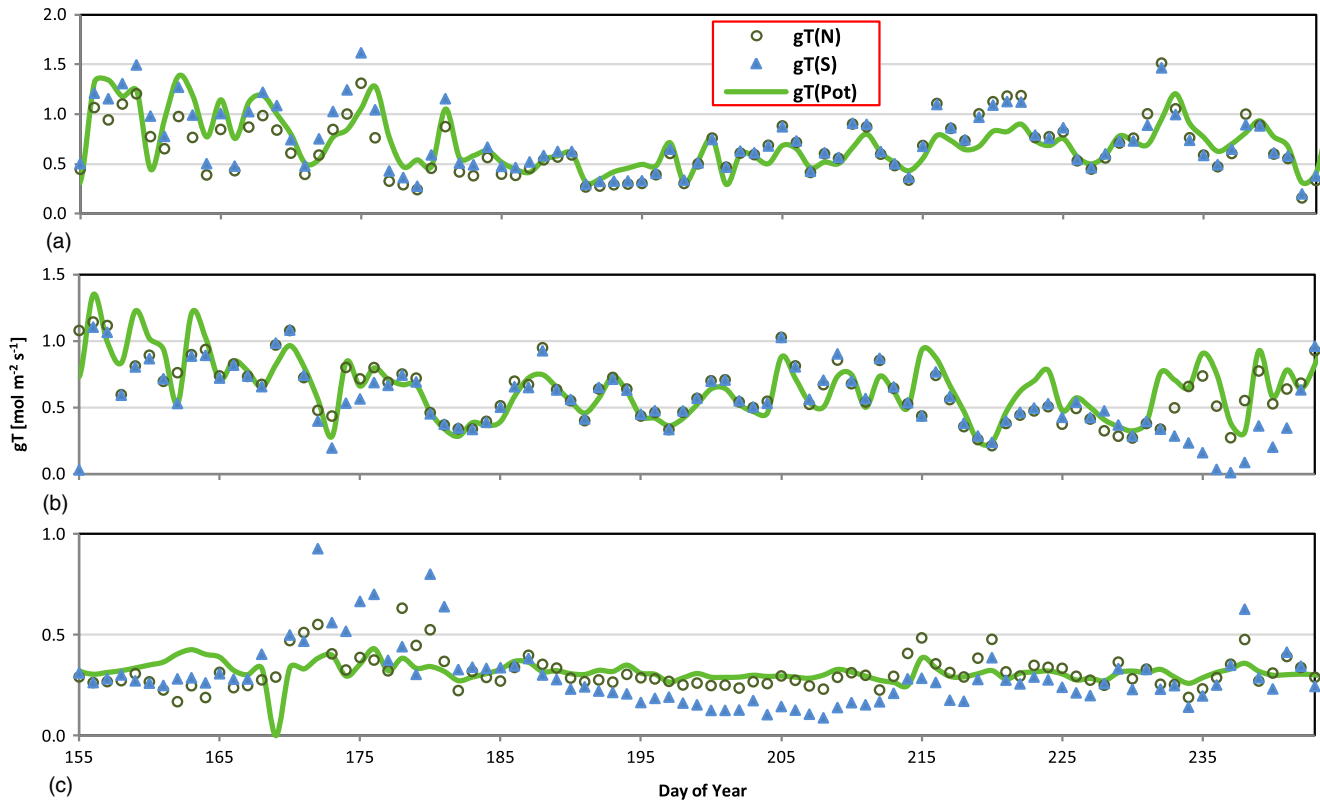
Fig. 7. Comparison of the daily mean potential conductance [g_T(Pot), mol m^{-2} s^{-1}] from Eq. (27) and Eq. (19) [g_T(Cal), mol m^{-2} s^{-1}] for Plots N and S (a) in 2007 ($b_0 = 0.0$ and $b_2 = 8.0$); (b) in 2008 ($b_0 = 0.0$ and $b_2 = 8.0$); (c) in 2013 ($b_0 = 0.22$ and $b_2 = 1.06$)

fruits on them (Palmer et al. 1997). In 2013, the trees played the main role in controlling the average canopy conductance rather than climatic factors, while in 2007 and 2008 stomatal regulations were more affected by radiation and vapor pressure deficit.

Measured and predicted canopy and air temperature differences (daily average) for the 3 years of field investigations are depicted in Fig. 8. Linear regression between ΔT_P and ΔT_m using the data of midseason 2007 yielded a slope, intercept, and R^2 of 0.92, −0.26, and 0.67 for Plot S [Fig. 9(a)] and 0.83, −0.49, and 0.53 for Plot N, respectively. For the same period in 2008, a linear regression between ΔT_P and ΔT_m resulted in a slope, intercept, and R^2 of 1.19, 0.56, and 0.76 for Plot S and 1.05, 0.15, and 0.76 for Plot N [Fig. 9(b)], respectively.

In 2013, the results from Plots N and S were quite different with no correlation between ΔT_P and ΔT_m in Plot S with a slope, intercept, and R^2 of 0.56, −0.45, and 0.25, respectively, and a relatively high correlation between the predicted and measured ΔT in Plot N with a slope, intercept, and R^2 of 0.85, −0.19, and 0.74 [Fig. 9(c)], respectively. The ΔT predictions were all satisfactory in the experimental years with average MAEs of 0.41, 0.33,

and 0.23°C in 2007, 2008, and 2013, respectively. Moreover, variation of predictions (CV of RMSE) in all of the experiment plots/years was better than that of measurements (CV of STD) with the exception of Plot N in 2007, which had a small difference (3% vs. 2%).

The variation of canopy temperature measurements among the plots and from year to year was about 4.8%. This small variation indicates that the number of IRT sensors used per plot and canopy surface viewed by the IRTs were sufficient. In addition, this could be an indication that, as planned, all of the trees were well irrigated (Testi et al. 2008). As the linear regression resulted in good correlations and ΔT was accurately predicted (Table 3), as well as similar results in Plots N and S, it was concluded that the performance of the ΔT_P model was satisfactory.

Potential Transpiration (E_p)

In all 3 years, E_p showed a good correlation with ET_r, with E_p being overall more than the PM reference ET [Figs. 10(a, c, e)]. As presented in Table 3, the best fit between the predicted and
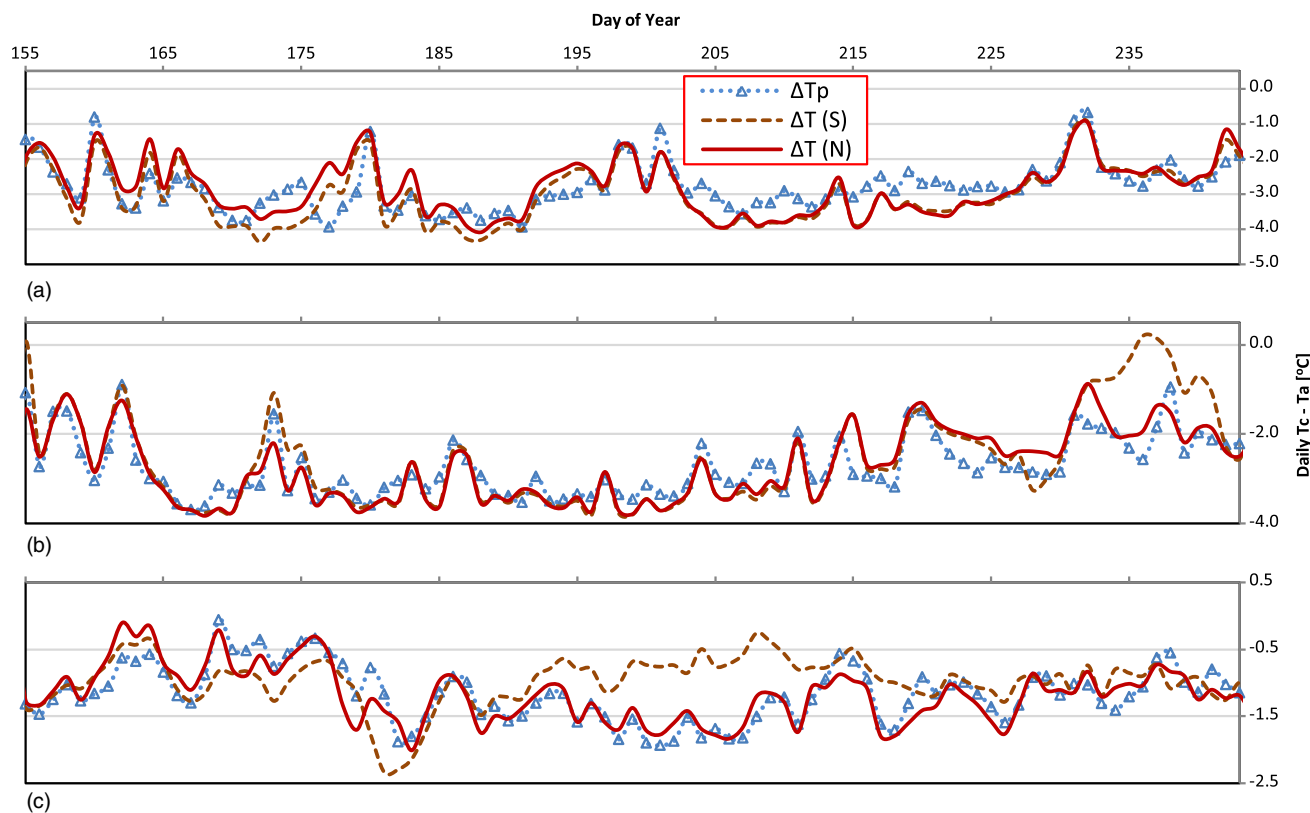
Fig. 8. Comparison of the measured [$\Delta T(S)$ and $\Delta T(N)$] and predicted (ΔT_p) canopy and air temperature differences (daily mean) in Plots N and S during midseason in (a) 2007; (b) 2008; (c) 2013
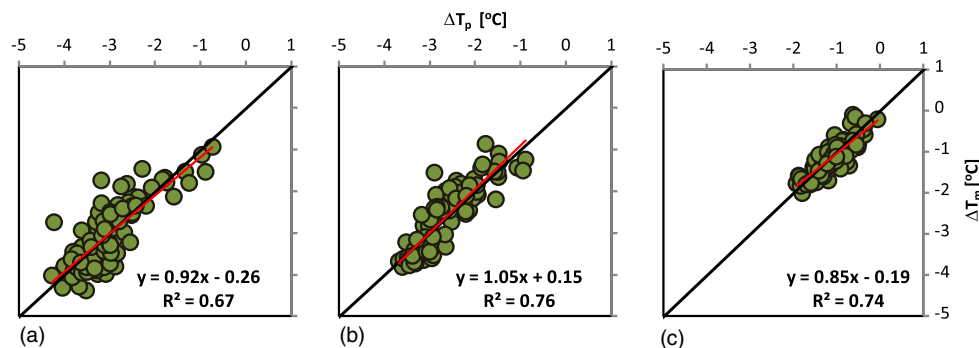

Fig. 9. Correlation between the measured (ΔT_m) and predicted (ΔT_p) canopy and air temperature differences (daily mean) for the 3 years of field investigations during midseason in (a) 2007; (b) 2008; (c) 2013

observed ΔT in the 2007 and 2008 growing seasons was achieved by only adjusting b_2 ($b_0 = 0.0$, $b_1 = 0.0$, and $m = 1.0$). The rounded average of b_2 in these years ($b_2 = 8.0$) was used to estimate ΔT_P and potential transpiration rates of the apple trees in 2007, 2008, and 2013. Except for the air temperature, which was measured in the orchard, all of the meteorological parameters required to compute E_p and ET_r were obtained from the weather station.

Linear regression between the daily mean E_p and ET_r [Figs. 10 (a, c, e)] yielded good correlations with R^2 values of 0.84, 0.76, and 0.89 ($p < 0.001$) for midseason in 2007, 2008, and 2013, respectively. However, nonzero intercept values and line slopes of about 0.7 pointed to the fact that the E_p model overestimated transpiration compared to the PM method. Due to this overestimation, total

E_p was higher, yielding relative errors REs of -18%, -0.13% and -0.14% during midseason in 2007, 2008, and 2013, respectively (Table 4).

For the purpose of comparing the E_p and ET_r behaviors, two boundary conditions of warm and dry ($D_a > 1.4$ kPa, $S_{gl} = 330 \pm 30$), as well as cold and humid ($D_a < 0.4$ kPa, $S_{gl} = 150 \pm 50$) were assumed. E_p was fitted to ET_r to minimize their difference [Figs. 10(b, d, f)]. This resulted in b_2 values of 6.13, 6.51, and 6.50 ($b_0 = 0.0$) for the 2007, 2008, and 2013 seasons, respectively. No significant change in the R^2 values occurred as E_p estimations were already fairly close to the ET_r estimations. The transpiration of apple trees was expected to be mainly driven by net radiation during warm and dry days, similar to that of the reference alfalfa/grass (Dragoni et al. 2005). As it was anticipated,
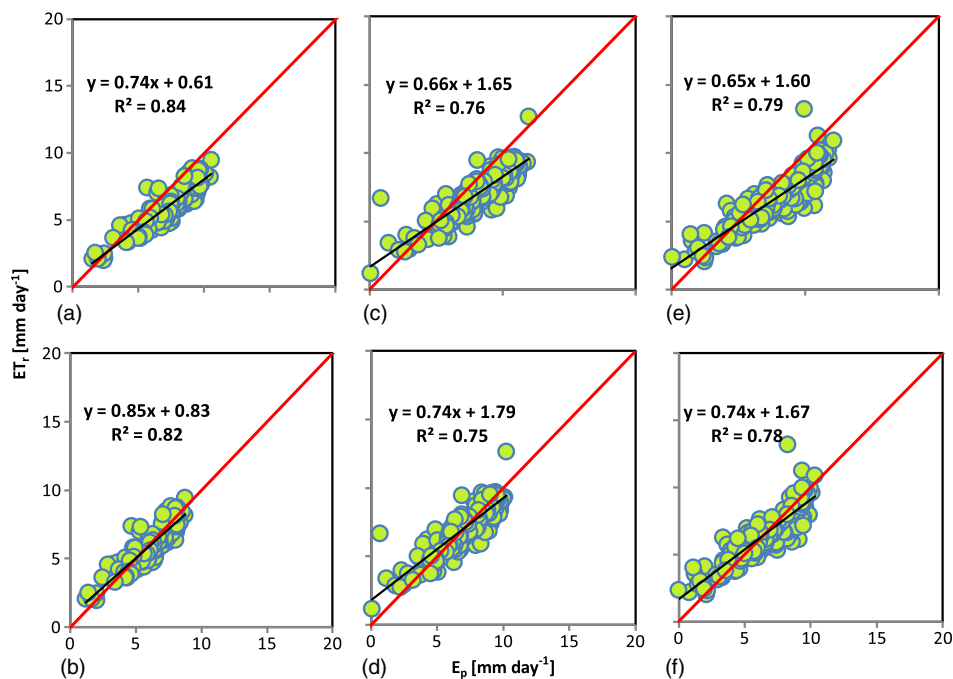
Fig. 10. Correlation of the daily mean potential transpiration (mm day^{-1}) estimated by the E_p model with that of predicted by the PM model (ET$_r$) for (a, c, e) Plot N and (b, d, f) Plot S during the (a and b) 2007; (c and d) 2008; (e and f) 2013 growing seasons ($p < 0.001$)

Table 4. Comparison of the Total (mm) and Average (mm day^{-1}) Predicted Potential Transpiration by the PM Model (ET$_r$) and the E_p Model in the Growing Seasons of 2007, 2008, and 2013 ($b_0 = 0.0$, $b_1 = 0.0$, $b_2 = 8.0$, and $m = 1.0$)

| Year | R^2 | Total ET (mm) | | | Average ET (mm day^{-1}) | | |
		ET$_r$	E_P model	RE (%)	ET$_r$	E_P model	RMSE (mm)
2007	0.78	600	706	−18	6.7	7.8	1.5
2008	0.70	699	794	−13	7.8	8.8	1.6
2013	0.81	669	762	−14	7.4	8.5	1.5

the estimated E_p was well correlated with ET$_r$ ($R^2 = 0.58$, $p < 0.001$) on warm and dry days with a slope close to unity (≈ 0.99) and intercept close to zero (≈ 0.10) [Fig. 11(a)]. However, because of a high coupling between the apple trees and the

humidity of the surrounding air (Jarvis 1985), E_p resulted in significantly lower values [Fig. 11(b)] during cold and humid period,s showing a very week correlation with ET$_r$ ($R^2 = 0.42$, $p < 0.001$).

Total crop water use predictions from the E_p model and PM approach calculated for midseason in 2007, 2008, and 2013 are depicted in Fig. 12. Although the accumulated E_p values of Plots N and S were very close, their values were averaged to obtain one single value. Calculation of E_p using the coefficients presented in Table 4 ($b_0 = 0.0$ and $b_2 = 8.0$) resulted in a small difference of about 100 mm between the total E_p and ET$_r$ during all of the experimental years [Fig. 12(a)]. Accumulated E_p was also computed by assuming $b_0 = 0.0$ and $b_2 \approx 6.5$ [Fig. 12(b)]. The difference between the predicted values from the two models was very trivial.

According to Dragoni et al. (2005), during warm and dry days the crop coefficients (K_c) are expected to be similar to the published K_c for arid climates like Washington State. Considering
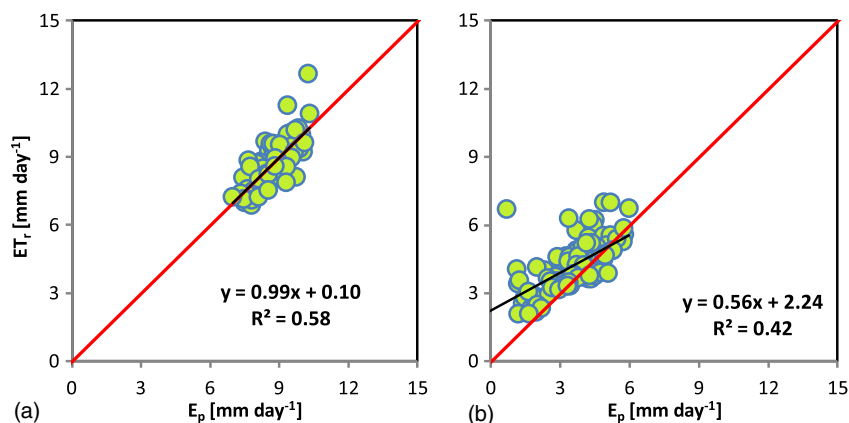
Fig. 11. Correlation between E_p and ET$_r$ for the 2007, 2008, and 2013 growing seasons (combined) during (a) warm and dry periods ($D_a > 1.4$ kPa, $S_{gl} = 330 \pm 30$; $p < 0.001$); (b) cold and humid days ($D_a < 0.4$ kPa, $S_{gl} = 150 \pm 50$; $p < 0.001$)
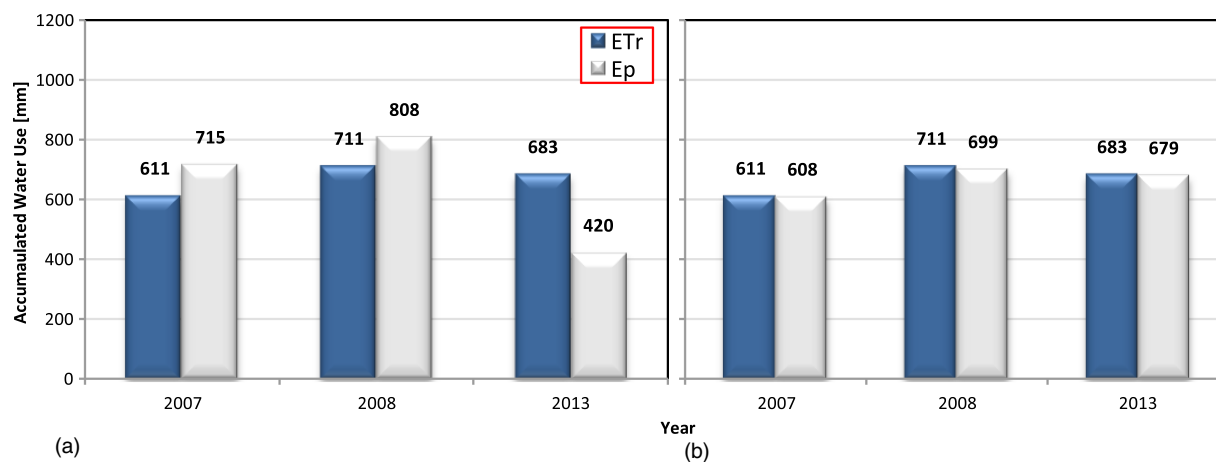
Fig. 12. Accumulated water use predicted by the E_p and ET$_r$ models at midseason in 2007, 2008, and 2013 (averages of Plots N and S); E_p was calculated using (a) the coefficients listed in Table 3; (b) the values of $b_0 = 0.0$ and $b_2 \approx 6.5$

the dominance of dry and warm periods during midseason in eastern Washington and a difference of about 3% (average) between accumulated ET$_r$ and ET$_c$, the total predicted transpirations seemed logical. In the studied area with an arid climate (high D_a), there does not appear to be any advantage in using E_p over the PM model for the estimation of apple trees potential water use. However, in more humid climates (smaller D_a), ET$_r$ seems to be minimally correlated with E_p. In more humid climates, using ET$_r$ is expected to lead to significant overestimation of apple tree transpiration rates.

Conclusions

During the 2007 and 2008 growing seasons, 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 and in 2013 using those installed perpendicularly above a tree, respectively. A transpiration model along with these IR measurements, in-field air temperature sensors, and local meteorological data from a nearby weather station were used to estimate the potential transpiration of apple trees. The E_p model presented here adequately described the potential transpiration of apple trees under real field conditions.

Since alfalfa andgrass mainly respond to net radiation, in the PM approach a constant value of 0.6 mol m^{-2} s^{-1} is assumed for the *big-leaf* stomatal conductance (Allen et al. 1998). In the present approach, a simple model with a theoretical basis dependent merely on radiation and vapor pressure deficit was developed to account for the response of apple leaf stomas to the bulk air relative humidity. Under normal conditions (well-irrigated, young apple trees), this model only requires the determination of one empirical coefficient. In the studied orchard, this empirical coefficient showed to be fairly constant with slight variations from plot to plot and from year to year. In 2013, the average stomatal conductance was maintained low by the trees in response to low fruit loads, which resulted in the empirical coefficients being different than in 2007 and 2008. This has to be accounted for in estimations of transpiration at post-harvest times because a reduction in crop loads can decrease the stomatal conductance and consequently transpiration of apple trees (Auzmendi et al. 2011; Girona et al. 2011). To formulate this phenomenon, the relationship between the conductance and apple fruit loads needs to be established.

The canopy temperatures of the fully watered trees were well predicted, with an average MAE of about 0.32°C. These MAEs were better than the accuracy of an individual IRT indicated in the manual ($\pm$0.6°C). Climatic parameters and canopy conductance (g_T) were the only required inputs to the ΔT_p model. Once used to calculate the CWSI, the present NWSBL model can be a base for fully automating the apple orchards. Considering the response of apple trees to the bulk air relative humidity, the advantages of the NWSBL and E_p models will be more pronounced if used in more humid areas compared to eastern Washington.

The components of the E_p model required microclimatic parameters as their input. Since the early studies on infrared thermometry (Idso et al. 1981; Jackson et al. 1981), it has been known that the measurements of air temperature should ideally take place as close as possible to plant canopies. However, in many cases, the most feasible data are acquired from a weather station in the vicinity of the field. Although apple leaves were well exposed to the air, formation of a microclimate around large tree canopies caused diurnal variations of a meteorological variable like air temperature to be notably different than those obtained from a nearby weather station. All of the other required meteorological parameters were obtained from the weather station assuming those measurements were reliable. Study of the microclimate to find relationships between the measurements taken within and outside the field can probably allow for enhancing the estimations of crop water use from the model.

To improve the estimation of radiation interception by apple canopies, a new methodology was developed based on the characteristics of a single apple leaf rather than using available procedures (Allen et al. 1998; Irmak et al. 2003), which are mainly based on the surface radiance balance. There were, however, some sources of uncertainty in the modeling of light and thermal energy interceptions by apple trees. A tree canopy is comprised of an unknown number of shaded and sunlit leaves, and shoot growth constantly changes light interception patterns. Discontinuous canopies of apple trees can have various forms of architecture and their leaves are of different shapes, sizes, and orientations. Moreover, the model was basically derived for light interception conditions at midday. This introduced some errors in estimations of transpiration when used for times other than solar noon in hourly or smaller timescales. Another approximation was introduced into the model by the temperature across the upper half of the canopy being assumed uniform and equal to the average temperature measured with the IRTs.

This paper compared the presented approach against the PM model. The performance of the E_p model and its components can be further investigated using lysimeter (Auzmendi et al. 2011) or sap flow measurements (Dragoni et al. 2005; Nicolasa et al. 2005).

Acknowledgments

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