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IRRIGATION OF FRUIT TREES AND VINES

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Effects of tree size on water use of peach (*Prunus persica* L. Batsch)

Abstract A short-term experiment was conducted to determine the effects of reducing tree size on peach tree water use (TWU). Tree size was progressively reduced by de-branching an individual isolated tree over a 15-day period. TWU was measured at 15-min intervals using heat pulse sap flow sensors located at eight positions in the trunk sapwood. Measures of TWU were compared with estimates derived from reference crop evapotranspiration (ET_o) and the area of shade cast by the tree on the soil surface (A_{SH}). A_{SH} was estimated prior to each de-branching event using a combination of photographs of the tree taken from the direction of the sun, and measures of fractional radiation interception in the area of shade cast by the tree. TWU and ET_o averaged 39.5 l/day and 4.7 mm/day, respectively, in the 6-day period prior to de-branching. Effective canopy cover (ECC; estimated as A_{SH} measured at solar noon) was 5.8 m^2 in that period. Five de-branching events reduced TWU and ECC by >95%. To account for the daytime variation in A_{SH}, we used effective area of shade (EAS), calculated from estimates of A_{SH} at solar noon and 3 h each side of solar noon. K_{cb}, the basal crop coefficient defined by Allen et al. [Crop evapotranspiration: guidelines for computing crop water requirements (FAO irrigation and drainage paper 56). Food and Agriculture Organisation of the United Nations, Rome, 1998], was related to EAS by K_{cb} = 1.05 EAS. These data for an isolated tree suggest that the transpiration component of orchard water use may be related to ET_o using estimates of effective fraction of shade on the soil surface.

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Introduction

The peach-growing districts in Northern Victoria, Australia are under continual change as new varieties are introduced and trees are increasingly subjected to novel trellising and pruning techniques. As a result, differences in tree size (and canopy architecture) are common depending on tree age, the distance between trees, tree training method, the degree of pruning, and the amount of annual shoot growth during the season. There is a need for generic estimates of peach tree water use (TWU) in order to estimate the transpirational water requirement of trees under the range of conditions experienced by the industry.

Micro-irrigation provides the opportunity to match water supply and TWU producing minimal water losses from the understorey (soil evaporation and cover crop transpiration). It is therefore necessary to distinguish TWU from understorey evapotranspiration (ET_e) in order to estimate and minimise irrigation requirements in orchards. Allen et al. (1998) considered the independent contributions of soil evaporation and crop transpiration by splitting the crop coefficient (K_c) into two separate coefficients; K_e, a soil evaporation coefficient and K_{cb}, a crop transpiration coefficient (referred to as the basal crop coefficient). By this formulation, crop water requirement (ET_c) = (K_{cb} + K_e) ET_o where ET_o is reference crop evapotranspiration. The approach was originally developed to improve daily estimates of water use for irrigated row crops (Wright 1982), but it can equally be applied to orchards under conditions where TWU represents crop transpiration (TWU = K_{cb} ET_o) and ET_e is approximated with soil evaporation (ET_e = K_e ET_o). The approach of Allen et al. is a simplification of a complex physical system whereby water use of discontinuous canopies is considered in terms of two distinct independent sources. Shuttleworth and Wallace (1985) provided a formal analysis of the water use of coupled two-source systems.

Reported values of K_{cb} in peach orchards vary spatially and temporally (Mitchell et al. 1991; Boland et al. 1993; Ferreira et al. 1996; Valancogne et al. 2000; Ayars et al. 2003). Transpiration is directly related to net radiation absorption and hence solar radiation interception by the foliage (Thorpe 1978; Johnson and Lakso 1991; Green 1993). K_{cb} is therefore expected to be strongly influenced by tree size and foliage display. Allen et al. (1998) recommended K_{cb} could be adjusted for differences in foliage cover. Allen et al. suggested that adjustment be made in terms of canopy cover (CC), the proportion of the soil surface covered by foliage when observed from the zenith, or effective canopy cover (ECC), the proportion of the soil surface shaded by foliage at solar noon. Fereres and Goldhamer (1990) provided an empirical relation between ECC and percentage of full ET used by developing almond canopies. Concepts of CC and ECC, which are equally applicable to orchards and isolated trees, provide potentially simple methods to account for the effects of complex changes in leaf area density and tree size on TWU.

Direct studies on the effects of tree size on TWU are limited. Mitchell et al. (1991) found that TWU increased threefold with rapid increases in tree size during the first and second year of growth. In mature trees, Boland et al. (1993) reported a fourfold within-season increase in TWU but attributed only part of this increase to tree size. In contrast, Ayars et al. (2003) attributed a fivefold within-season increase in TWU to increases in leaf area density and tree size.

In mature peach orchards, estimates of CC and/or ECC have been reported in association with measures of water use or TWU (Klein 1983; Worthington et al. 1984; Natalie et al. 1985; Ferreira et al. 1996; Snyder et al. 2000; Valancogne et al. 2000; Ayars et al. 2003). Single values of CC and ECC have commonly been reported. Natali et al. (1985), however, attempted to adjust estimates of orchard water use for changes in CC, while Ayars et al. (2003) measured ECC (the fraction of midday photosynthetically active radiation (PAR) intercepted over the planting square) every 3–4 weeks during a season and showed a linear relationship between ECC and K_{cb}.

This study describes the diurnal behaviour of TWU and the effects of modifying tree size on TWU by progressively de-branching an isolated tree. Diurnal changes in TWU were investigated in terms of associated dynamic changes in the area of shade cast by the foliage of the tree on the soil surface (A_{SH}). The data were used to test the hypothesis that effects of tree size on daily TWU can be accounted for in terms of CC and ECC. CC was estimated from measures of horizontal foliage extent. A_{SH} and ECC were estimated from a combination of photographs of the tree taken from the direction of the sun, and measures of fractional radiation interception in the area of shade cast by the tree.

Materials and methods

The experiment was carried out at Tatura in Northern Victoria, Australia (36° 26′S, 146° 15′E). Measurements of sap flow and foliage radiation interception were made on an isolated peach tree subjected to progressive de-branching in the period, 2–17 March 2001. The tree was sufficiently removed from neighbours to experience full sunlight between 0700 and 1700 h. Tree height was approximately 4 m and tree extent was adequately described as an ellipsoid truncated in the lower hemisphere. The tree was drip irrigated during the experiment at a rate of 96 l/day. Fruit was removed from the tree prior to the experiment.

De-branching

De-branching was achieved by pruning lower branches on 9, 13, 14, 15 and 17 March (days 7, 11, 12, 13 and 15 of the experiment). Approximately one fifth of the leaf area was removed at each occasion. Complete defoliation was achieved on day 15. Leaf area removed at each pruning was measured with a planimeter (LI-3100 Area Meter; LI-COR Incorporated, Lincoln, NE, USA). Total leaf area during the experiment was reconstructed according to the area of foliage removed during de-branching.

Peach tree water use

Tree water use was determined from measures of sap flow using the compensation heat pulse technique described by Smith and Allen (1996). Eight sap flow sensors (SF100; Greenspan Technology, Warwick, QLD, Australia) were used in this experiment. Sensors were installed on day 0 (2 March) at equal intervals on the perimeter of the trunk (i.e. N, NE, E, SE, S, SW, W and NW). The N, S, E and W sensors were installed at 0.35 m and the remainder were installed 0.45 m above the soil surface. Strips of fibreglass were packed between the sensors and the trunk was wrapped in aluminium foil for thermal insulation.

Heat pulse velocity (HPV) was calculated from measurements of the time taken to achieve thermal equilibrium after the heat pulse. HPV was determined at intervals of 15 min using a heat pulse of 2 s duration. HPV was corrected for the effect of wounding by the numerical solution of Swanson and Whitfield (1981) on the assumption, wound diameter = 2.2 mm. Sap velocity was estimated from the wound-corrected HPV and the fractions of wood and water within the sapwood (Edwards and Warwick 1984). The fractions of wood and water in the sapwood were determined gravimetrically from core samples taken from nearby peach trees (volumetric wood fraction = 0.40 and volumetric water fraction = 0.41).

The radial profile of sap velocity in the sapwood was determined during the installation of each sensor. The resulting depth distribution of sap velocity was described by a sensor-specific least squares polynomial, which was subsequently used to convert measures of sap velocity taken at depths of approximately 10 and 15 mm in the sapwood to sap flow. To account for heat transfer due to diffusion when convection was negligible, sap flow was retrospectively set to zero when the time for thermal equilibration exceeded 130 s (based on measures of sap flow after complete defoliation of the experimental tree).

Tree water use was related to measures of sap flow by calibration using the cut-tree method described by Green and Clothier (1988). The relationship between TWU and sap flow (SF) of a similarly instrumented excised peach tree with its trunk immersed in water was: TWU = 1.35 (±0.04) SF; $R^2 = 0.90$, $n = 32$.

Canopy cover

Foliage depth (measured from the top of the tree) and horizontal extent in east-west (x_{EW}) and north-south (x_{NS}) aspects was measured before each de-branching event. The mean horizontal extent, x, was taken as:

$$x = \frac{x_{\mathrm{EW}} + x_{\mathrm{NS}}}{2}. \tag{1}$$

Canopy cover was estimated as the vertical projected circular area of the horizontal foliage extent:

$$\mathrm{CC} = \pi \left(\frac{x}{2}\right)^2 \tag{2}$$

Area of shade on the soil surface

A_{SH} was calculated as:

$$A_{\mathrm{SH}} = fA_{\mathrm{SE}}, \tag{3}$$

where A_{SE} was the area within the shadow envelope cast by the tree on the soil surface and f was the fraction of shade within the shadow envelope. A_{SE} was estimated as:

$$A_{\mathrm{SE}} = \frac{A_{\mathrm{FE}}}{\cos\theta} \tag{4}$$

where A_{FE} was the area within the foliage envelope projected in the direction of the sun and θ was the solar zenith angle calculated according to USDC (2003) (Fig. 1).

A_{FE} was estimated using photographs of the tree taken from the direction of the sun. Direct photographic estimates of A_{SE} were precluded by distortions introduced by the camera lens and the obstructions caused by the foliage. A digital colour camera (DC120 Zoom Digital Camera; Eastman Kodak Company, New York, USA) was interposed between the sun and the tree such that the camera viewed sunlit foliage elements as seen on the plane normal to the direction of the solar beam. Photographs were taken at approximately hourly intervals from 0700 to 1700 h on day 5 (before de-branching) and on days 7, 11, 12 and 13 after de-branching events. Each digital photographic image of the delineated foliage extent was outlined. A_{SE} was taken as the area within the outline of the foliage, scaled to actual dimensions based on measures of x_{EW} and x_{NS} above. Image analysis was performed using ARCVIEW software (ArcView GIS 3.2a; Environmental Systems Research Institute, Redlands, USA).

f was estimated as the fraction of PAR intercepted in the shadow envelope at the time when photos were taken using a sunfleck ceptometer (Sunfleck Ceptometer; Decagon, Pullman, USA).

Effective canopy cover, effective area of shade

Measures of A_{SH} were related to solar time using a quadratic polynomial. ECC was estimated as the value of A_{SH} at solar noon. Effective area of shade (EAS) was estimated as the mean value of A_{SH} at solar noon, solar noon −3 h and solar noon + 3 h.

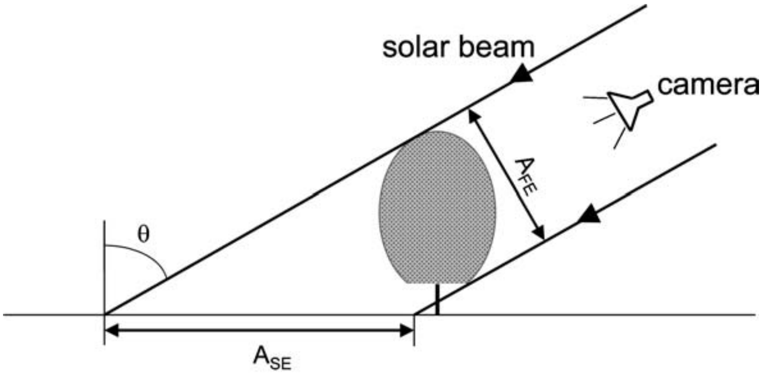

Fig. 1 Schematic representation of the area within the foliage envelope projected in the direction of the sun (A_{FE}) and the corresponding area of shadow envelope cast by the foliage of the tree on the soil surface (A_{SE}). *Arrows* indicate the direction of the solar beam. The position of the digital camera to measure A_{FE} is shown. θ is the solar zenith angle

Meteorological data

Solar radiation (R_s), air temperature (T), relative humidity (RH) and wind speed (u) were measured in an automatic weather station located within 50 m of the experimental site. R_s was measured using a silicon pyranometer (SRA-01; Monitor Sensors, Caboolture, Australia). T and RH were measured at 1.5 m height using a combination platinum RTD and capacitive sensor probe (HP102A; Rotronic Instrument Corporation, Huntington, USA) mounted in a cylindrical white aluminium screen. u was measured using a 3-cup anemometer at 2-m height (AND-02; Monitor Sensors, Caboolture, Australia). Measurements were taken every 5 s and the average calculated and stored at 15-min intervals in a data logger (6004B STARLOG Portable Data Logger; Unidata, O'Connor, Australia).

Reference crop evapotranspiration and basal crop coefficients

$\mathrm{ET_o}$ was calculated every 15-min using the FAO standardised Penman-Monteith equation (grass height = 0.12 m, surface resistance = 70 s/m, albedo = 0.23; Allen et al. 1998):

$$\mathrm{ET_o} = \frac{0.408\Delta(R_n - G) + \gamma 37.5u(e_s - e_a)/(T + 273)}{\Delta + \gamma(1 + 0.34u_2)} \tag{5}$$

Here, $\mathrm{ET_o}$ was reference evapotranspiration (mm/h), R_n was net radiation at the crop surface (MJ/m^2/h), G was soil heat flux density (MJ/m^2/h), T was air temperature at 1.5 m height (°C), u_2 was wind speed at 2 m height (m/s), $e_s - e_a$ was saturation vapour pressure deficit (kPa), Δ was the slope of the vapour pressure curve (kPa/°C) and γ was the psychrometric constant (kPa). R_n, G, $e_s - e_a$, Δ and γ were computed according to functions described by Allen et al. (1998).

Values of K_{cb} were derived from relationships between TWU and $\mathrm{ET_o}$ after appropriate adjustment of units.

Statistical analysis

Genstat 6.1.0.200 (VSN International Limited, Oxford, UK) was used for all statistical procedures.

Results

Diurnal changes in TWU

Diurnal changes in TWU, R_s, $e_s - e_a$ and $\mathrm{ET_o}$ for a clear-sky day (day 4) are shown in Fig. 2. The pattern of TWU showed a flattened sinusoid during the day. TWU increased rapidly after dawn until the maximum was reached at 1,100 h. Maximum TWU was maintained for approximately 6 h, after which TWU declined rapidly in the late afternoon and continued for approximately 1 h after sunset. TWU was approximately zero during the night.

Maximum TWU persisted over an extended period compared with the maxima in R_s and $\mathrm{ET_o}$. In contrast, $e_s - e_a$ achieved a maximum in the late afternoon as TWU declined. Instantaneous values of TWU were compared with $\mathrm{ET_o}$ for five cloudless days (days 1, 2, 4, 5 and 6) (Fig. 3). Data were unavailable for day 3. TWU showed a consistent curvilinear relationship with $\mathrm{ET_o}$. However, TWU varied at low values of $\mathrm{ET_o}$ ($\mathrm{ET_o} <$ 0.2 mm/h) depending on time of day: at low values of $\mathrm{ET_o}$, afternoon TWU exceeded corresponding values in the morning.

Diurnal changes in A_{SH}

Diurnal changes in A_{SH} on day 5 are shown in Fig. 4. A_{SH} decreased rapidly after sunrise and showed a clear minimum near solar noon. A quadratic polynomial adequately described changes in A_{SH} on day 5:

$$A_{SH} = 0.44(\pm 0.03)t^2 + 0.12(\pm 0.08)t + 5.79(\pm 0.33); \quad R^2 = 0.96, n = 10 \tag{6}$$

where t was solar time (h) relative to solar noon.

Effects of de-branching on diurnal TWU

De-branching had a major effect on the maximum values of TWU and a less marked effect on the duration of maximum TWU (Fig. 5). The mean maximum value of TWU recorded between 1,000 and 1,600 h ($\mathrm{TWU_{max}}$) decreased from 3.80 l/h before de-branching (day 4) to 3.46, 2.33 and 1.99 l/h on days 7, 11, and 12, respectively. Positive values of TWU extended over 15 h in the early part of the experiment and declined to a period of 12.5 h on day 13.

Effects of de-branching on daily TWU

Mean daily TWU was 39.5 l/day for days 1–6. De-branching events resulted in a linear decline in mean TWU after day 6 (Fig. 6a). Daily R_s exceeded 20 MJ/m^2/day throughout the experiment, except for days 14 and 15 (Fig. 6b). Daily $\mathrm{ET_o}$ ranged between 3.9 and 5.1 mm/d for days 1–13 but then declined for days 14 and 15 (Fig. 6b).

Effects of de-branching on leaf area, foliage depth and extent, and CC

Total leaf area decreased from 51.9 m^2 in the period before de-branching (day 1–6) to 7.7 m^2 on day 13

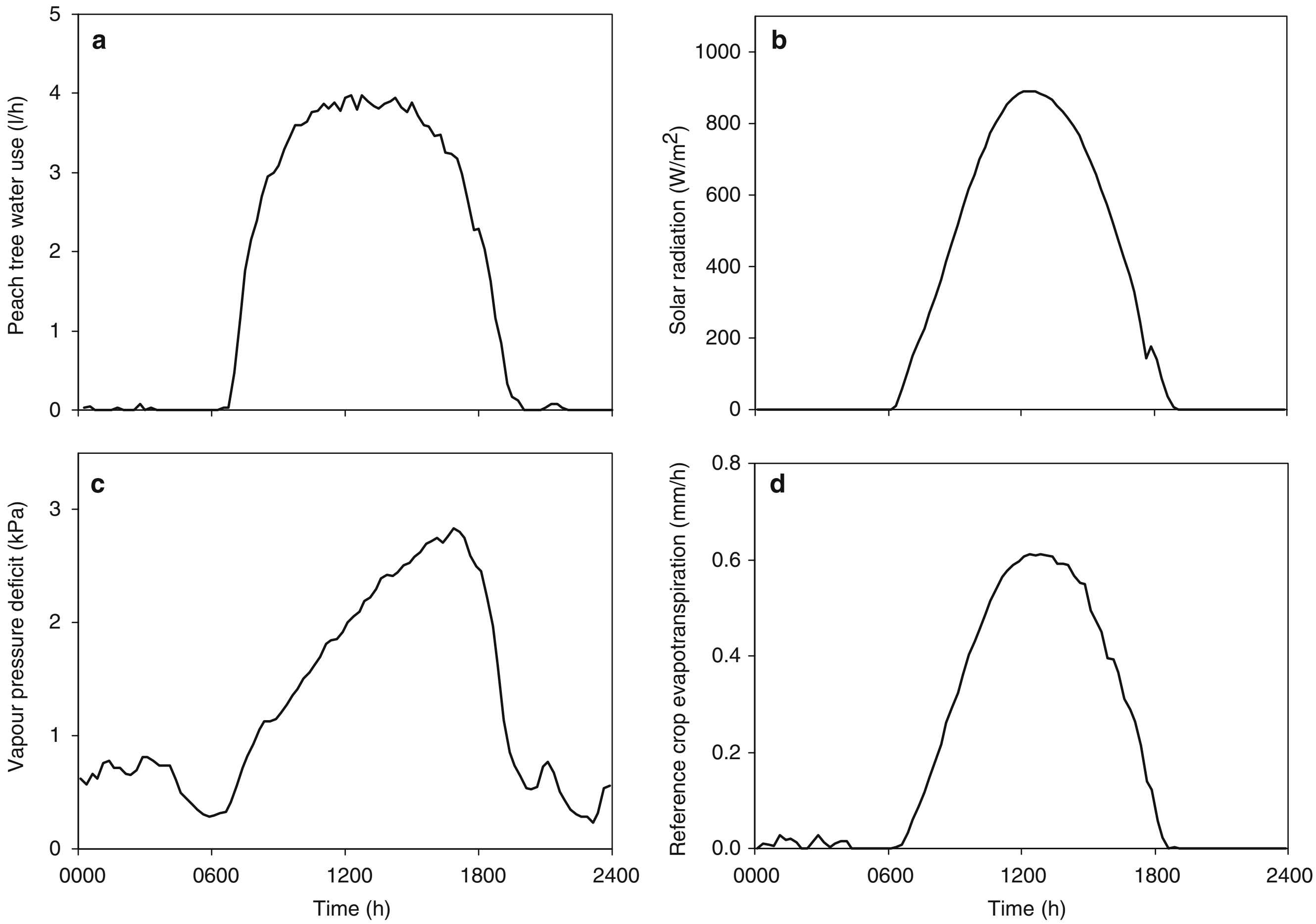

Fig. 2 Diurnal changes before de-branching (day 4) in **a** peach tree water use, **b** solar radiation, **c** vapour pressure deficit and **d** reference crop evapotranspiration

(Fig. 7a). Foliage depth was reduced by < 50% over the same period (Fig. 7b). x_{EW} and x_{NS} decreased from 2.9 and 3.4 m prior to de-branching to 1.3 and 1.7 m on day 13, respectively (Fig. 7c). CC was approximately 7.8 m^2 in the period before de-branching (days 1–6) and declined to 5.7, 5.7, 4.0, 1.8 and 0 m^2 after each

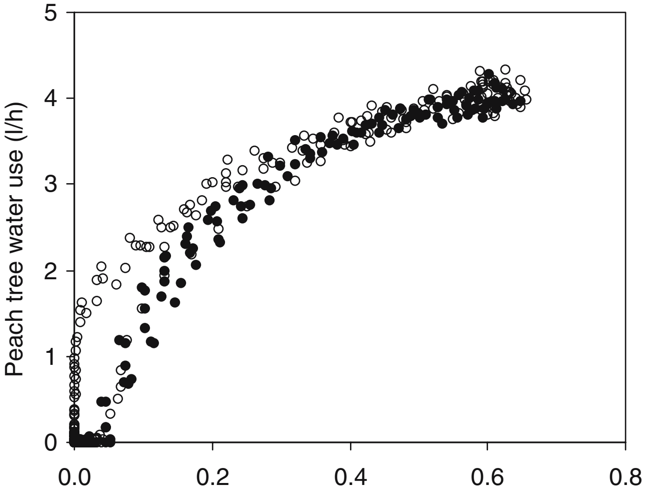

Fig. 3 Peach tree water use in relation to reference crop evapotranspiration before (*filled circle*) and after (*open circle*) solar noon prior to de-branching (days 1, 2, 4, 5 and 6)

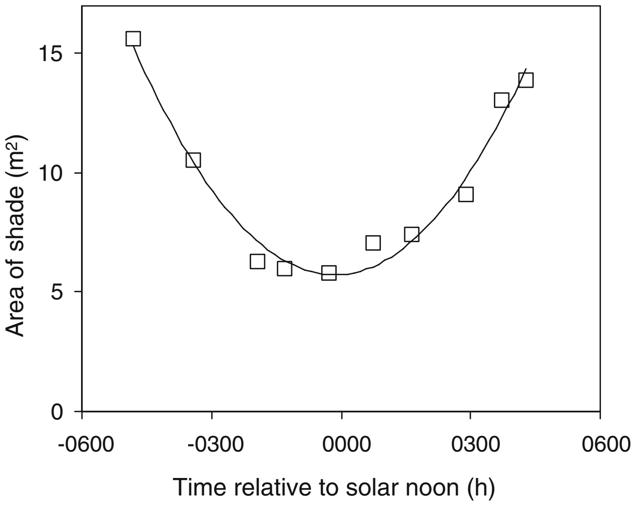

Fig. 4 The area of shade cast by the tree on the soil surface on day 5 before de-branching. A quadratic polynomial was fitted to data (see text for coefficients and standard errors)

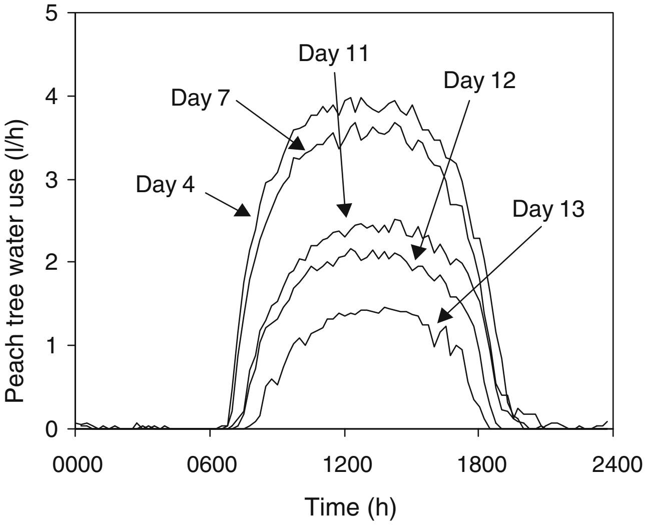

Fig. 5 Diurnal peach tree water use before de-branching (day 4) and after each de-branching event day 7, 11, 12 and 13)

de-branching (Fig. 7d). Leaf area was consistently reduced by approximately 11 m^2 at each de-branching, whereas foliage depth and extent, and canopy cover varied depending on the position of branches removed from the tree.

Effects of de-branching on A_{SH}

De-branching caused a major reduction in the minimum value of A_{SH}, with little effect on qualitative changes during the day. A_{SH} was described by quadratic polynomials:

Day 7

$$A_{SH} = 0.29(\pm 0.04)t^2 - 0.06(\pm 0.11)t + 4.08(\pm 0.51); \quad R^2 = 0.85, n = 11 \tag{7a}$$

Day 11

$$A_{SH} = 0.21(\pm 0.04)t^2 + 0.04(\pm 0.11)t + 4.15(\pm 0.50); \quad R^2 = 0.72, n = 11 \tag{7b}$$

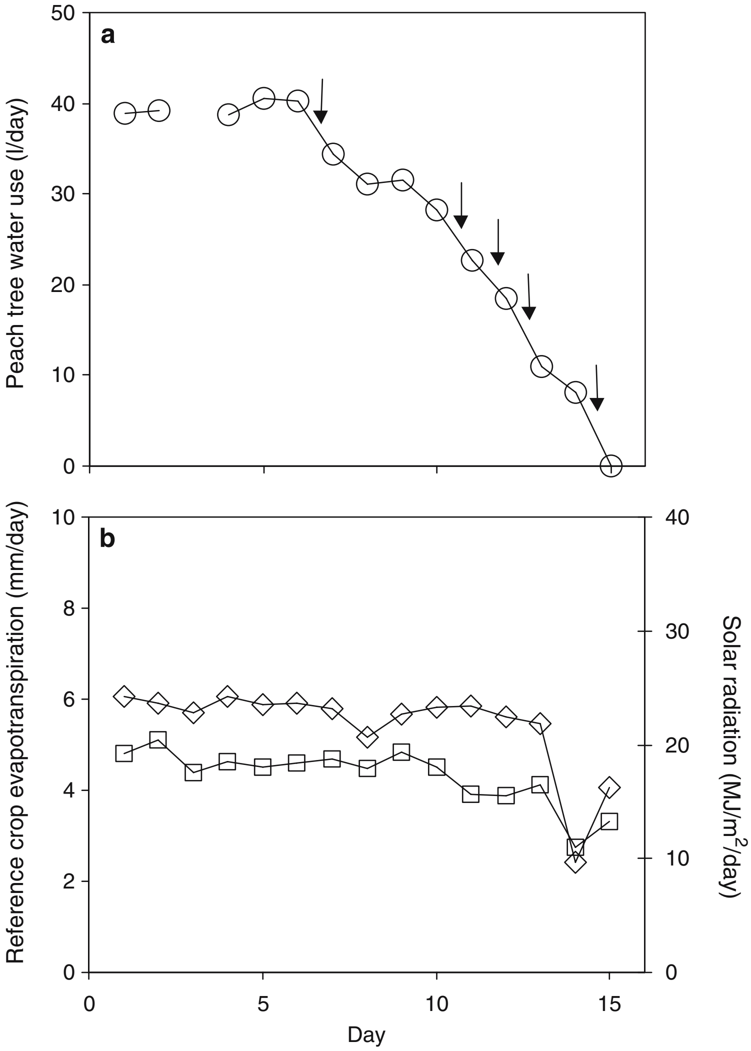

Fig. 6 Changes during the experiment in **a** daily peach tree water use and **b** daily reference crop evapotranspiration (*open square*) and solar radiation (*open diamond*). *Arrows* indicate de-branching events. Instrument malfunction resulted in missing tree water use data on day 3

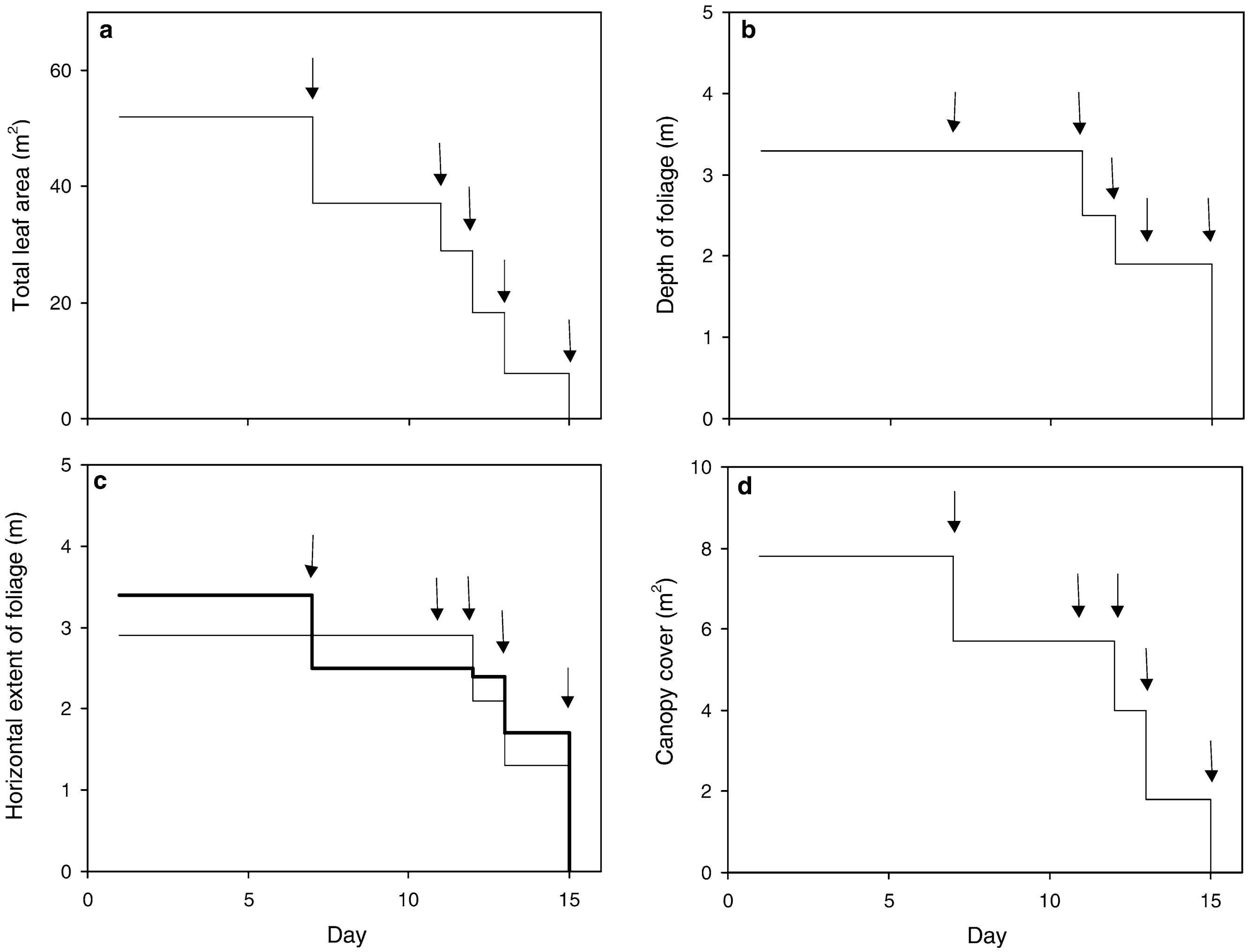

Fig. 7 Changes during the experiment in **a** total leaf area **b** foliage depth **c** foliage extent in east-west (*thin line*) and north-south (*thick line*) aspects and **d** canopy cover. *Arrows* indicate de-branching events

Day 12

$$A_{SH} = 0.14(\pm 0.01)t^2 + 0.10(\pm 0.03)t + 2.47(\pm 0.13);$$
$$R^2 = 0.94, n = 11 \qquad (7c)$$

Day 13

$$A_{SH} = 0.17(\pm 0.01)t^2 + 0.05(\pm 0.03)t + 0.82(\pm 0.14);$$
$$R^2 = 0.96, n = 11 \qquad (7d)$$

where t was solar time (h) relative to solar noon.

Effects of de-branching on A_{SE}, f, ECC and EAS

Measurements of A_{SE} near solar noon decreased from 6.8 m^2 in the period before de-branching to 1.2 m^2 on day 13. In contrast, corresponding measures of f at solar noon remained constant at 0.85 for most of the experiment. f decreased to 0.76 and 0.67 on day 12 and 13 (Fig. 8a, b). ECC derived from Eq. 7 (t = 0) decreased from a maximum of 5.7 m^2 on day 5 to 0.8 m^2 on day 13 (Fig. 8c). Excepting day 11, Fig. 8d shows that de-branching events caused major reductions in EAS. The decrease in leaf area effected by de-branching on day 11 had no significant effect on CC, ECC and EAS.

Relationship of TWU to ET$_o$

Daily sums of TWU were compared with daily sums of ET$_o$ weighted for CC, ECC and EAS on the assumption that leaf area remained constant between de-branching events (Fig. 9a–c). Changes in TWU (l/day) were linearly related to CC-weighted ET$_o$ (CC.ET$_o$; l/day), ECC-weighted ET$_o$, and EAS-weighted ET$_o$:

$$\mathrm{TWU} = 1.10(\pm 0.026)\mathrm{CC.ET_o}; R^2 = 0.94, n = 13 \qquad (8a)$$
$$\mathrm{TWU} = 1.52(\pm 0.049)\mathrm{ECC.ET_o}; R^2 = 0.89, n = 13 \qquad (8b)$$
$$\mathrm{TWU} = 1.05(\pm 0.033)\mathrm{EAS.ET_o}; R^2 = 0.90, n = 13 \qquad (8c)$$

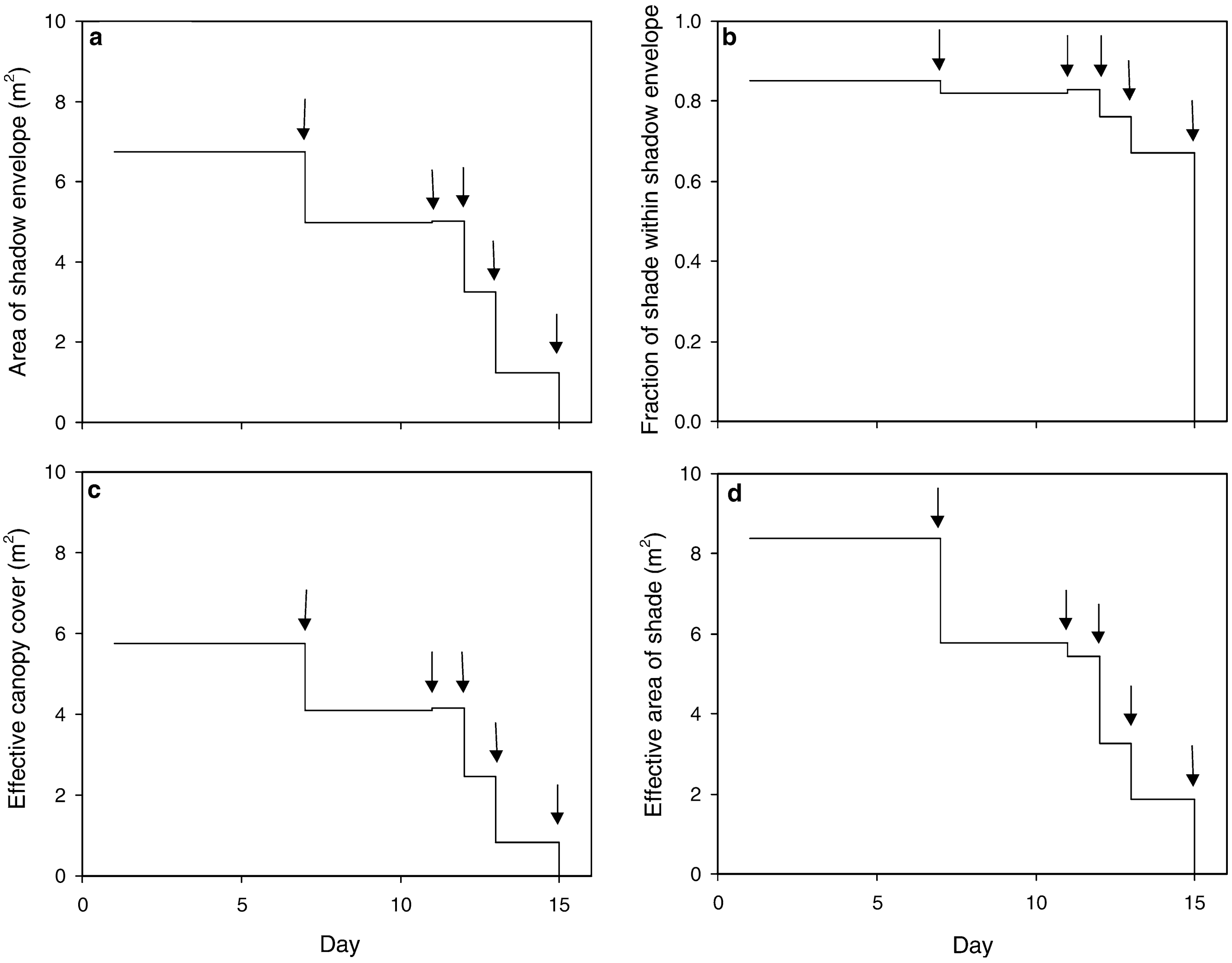

Fig. 8 Changes during the experiment in **a** area of shadow envelope cast by the tree on the soil surface at solar noon **b** fraction of shade within the shadow envelope at solar noon **c** effective canopy cover and **d** effective area of shade. *Arrows* indicate de-branching events

Similarly, daily TWU was related to the daytime sum of the product of instantaneous $\mathrm{ET_o}$ and A_{SH} (A_{SH}-weighted $\mathrm{ET_o}$) (Fig. 9d):

$$\mathrm{TWU} = 1.04(\pm 0.038)\sum[\mathrm{A_{SH}ET_o}]; R^2 = 0.87, n = 13 \tag{9}$$

Estimates of K_{cb} corresponding to Eqs. 4a, 4b and 4c were therefore 1.10 (± 0.026) CC, 1.52 (± 0.049) ECC and 1.05 (± 0.033) EAS, respectively.

Discussion

K_{cb}-adjusted $\mathrm{ET_o}$ provides a potentially simple practical method to estimate peach TWU. In this study, $\mathrm{ET_o}$ was weighted by CC, ECC and EAS to account for the reduction in TWU effected by de-branching. The weighting for CC was approximately 40% greater than that for ECC (Eqs. 8a and 8b), primarily because CC was not adjusted for effects of sunfleck (*f*) in calculations of the area of vertically projected foliage. Estimates of CC were also subject to the assumption of a circular projection of foliage on the soil surface. CC additionally takes no account of the solar zenith angle, which varies in the approximate range, 13–50° in Northern Victoria during the growing season. The use of CC-weighted $\mathrm{ET_o}$ is hence subjected to practical variations in *f*, foliage extent and solar zenith angle.

Allen et al. (1998) recognised the limitations of CC and suggested a range of procedures to estimate ECC from CC and measurements of plant height and width when viewed from the east or west. ECC, unlike CC, can also be measured by simple direct methods based on the area of shade on the soil surface at solar noon. In this experiment, ECC was derived from measurements of A_{SE} and *f*. De-branching significantly reduced A_{SE} with

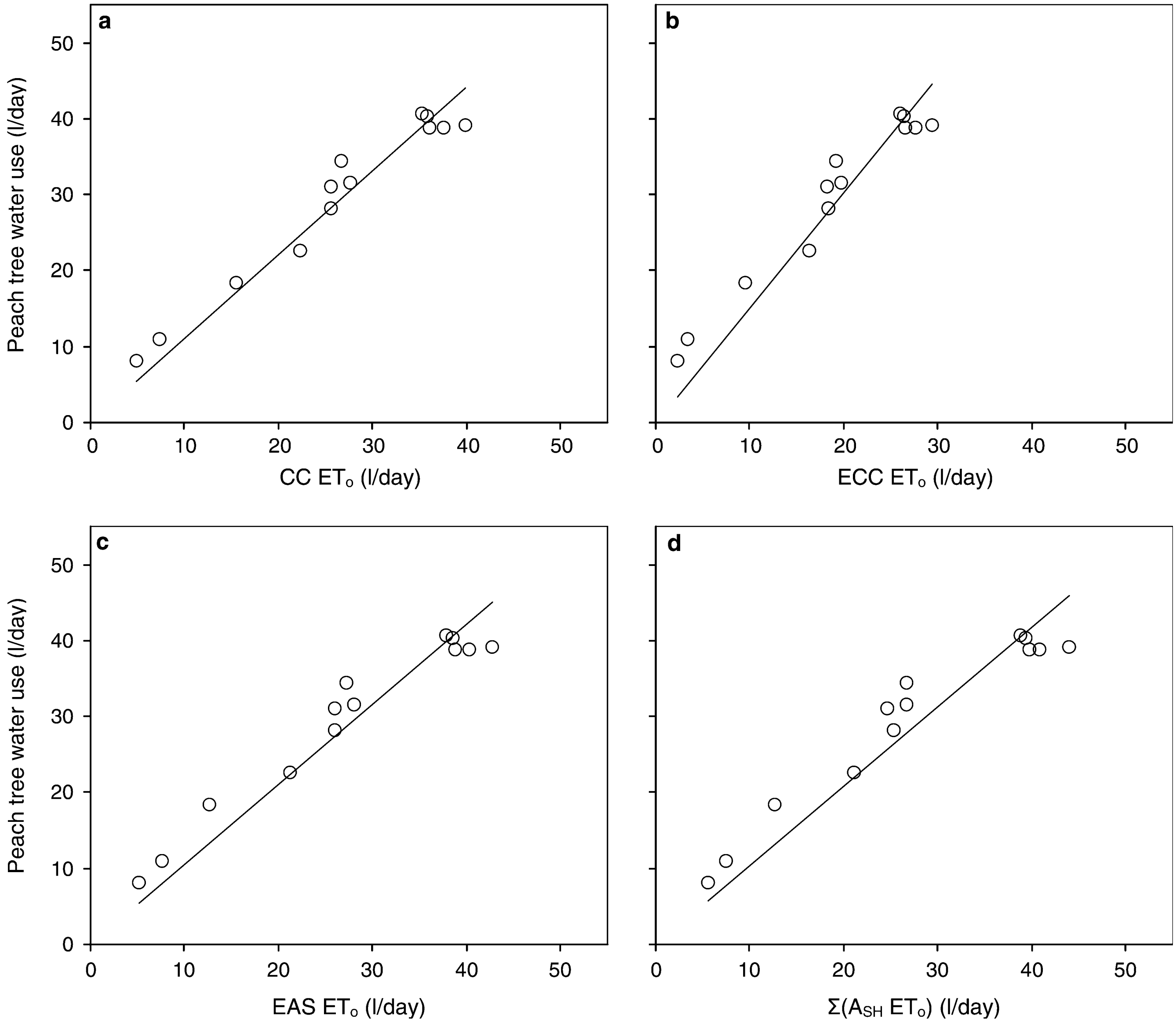

Fig. 9 Daily peach tree water use in relation to **a** canopy cover (*CC*)-weighted daily reference crop evapotranspiration (ET$_o$), **b** effective canopy cover (*ECC*) weighted daily ET$_o$, **c** effective area of shade (*EAS*) weighted daily ET$_o$, and **d** daily-integrated product of instantaneous reference crop evapotranspiration (ET$_o$) and instantaneous area of shade cast by the tree on the soil surface (A_{SH}). Linear regression lines were fitted with intercept = 0 (see text for coefficients and standard errors)

minor effects on f. The ECC based estimate of K_{cb} for the isolated tree in this experiment was similar to the ECC based estimate of K_{cb} reported by Ayars et al. (2003). Ayars et al. (2003) estimate K_{cb} of a peach orchard as 1.5 ECC over the range of ECC, 0.15–0.7. In that case, ECC was measured as the proportion of PAR intercepted over the planting square at midday. Similarly, Valancogne et al. (2000) estimated K_{cb} as 1.6 ECC in peach based on a single estimate, ECC = 0.25.

While ECC potentially accounts for effects of f, A_{SE} and θ, ECC fails to account for the daytime variation in the area of shade cast by trees, dependent on foliage display and tree size. 'Effective' canopy cover may be misrepresented by a single measure of A_{SH} made at solar noon. A_{SH} of the isolated tree varied systematically during the day in this experiment and showed a pronounced minimum at noon (Fig. 4, Eqs. 7a, 7b, 7c, 7d). A full description of the diurnal changes in A_{SH} copes with differences in TWU associated with complex tree geometries (Eq. 9).

We accounted for daytime changes in A_{SH} by taking the mean of measures at solar noon and 3 h each side of solar noon (effective area of shade, EAS). This approach is simple and practical and may potentially be used as the basis for direct weighting of ET$_o$ for trees of different size and foliage display. Our data suggest the relationship, K_{cb} = 1.05 (± 0.033) EAS (Eq. 8c), which implies TWU of a well-watered tree approximates the unit rate of water use described by ET_o (Allen et al. 1998) over the area of shade cast by the tree on the soil surface. Extrapolation of our results obtained with an isolated tree which was pruned periodically should be done with caution, as pruning changed drastically the root-leaf area ratio and such changes could affect the water use patterns of the remainder of the tree canopy.

In an orchard, the concept of EAS-weighted ET_o may be used to estimate TWU for irrigation requirements. EAS is expressed in terms of the fraction of shade cast by the trees on the soil surface, in which case TWU is simply expressed in terms of "mm". The approach provides for values of K_{cb} that vary to a maximum 1.0 under conditions where an orchard is under full shade for the greater part of the day.

Conclusions

We found that K_{cb} of an isolated tree was directly related to EAS, the area of shade on the soil surface during the major part of the day. The primary requirement of micro-irrigation is to satisfy TWU and this can be achieved by weighting ET_o for EAS. However, at the orchard scale, undisturbed tree canopies may behave differently than our isolated tree and additional irrigation amounts will be needed for understorey water use associated with soil evaporation and cover crop evapotranspiration from the irrigation wetting pattern. Further work is needed to replicate the results observed here and to extend the procedure to trees in an orchard and determine the radiation partitioning between the tree and the understorey wetted area.

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