Irrig Sci (2012) 30:189–200
DOI 10.1007/s00271-011-0270-8

ORIGINAL PAPER

# Water use by an irrigated almond orchard

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Received: 31 August 2010 / Accepted: 11 February 2011 / Published online: 16 March 2011


**Abstract** The evapotranspiration rate of a high-yielding (4.3 t/ha) almond orchard was measured by the eddy covariance technique. The site was subject to advection (LE/Rn > 1) for one-third of the mid-season. The slope of energy balance equation calculated from half-hourly flux data was 0.87. Flux data were transformed by forcing closure of the energy balance to give a seasonal ET of 1,450 mm (ETo 1,257 mm). This value could be reconciled with ancillary measures of soil salinity and water content, and plant water status. The mid-phase crop coefficient was 1.1 which was 0.1 higher than a recently published value. Use of the transformed value of ET in calculations of field application efficiency and annual drainage gives values of 98% and 24 mm, respectively.

## Introduction

South eastern Australia has recently been experiencing a prolonged drought. Irrigation uses about 70% of diverted and extracted water in Australia (ABS 2004). Drought has quickened the attention that natural resource managers are paying to irrigation efficiency at district and farm level. They derive performance indicators such as field application efficiency and its associated parameter, drainage loss, by constructing soil water balances. There had been some local interest in integrating simplified performance indicators into the irrigation licensing process (RMWCMB 2002). The annual water use by a crop (ET) equates to the sum of irrigation ($I$), rain ($R$) and change in soil moisture ($\Delta S$) minus drainage ($D$):

$$\mathrm{ET} = I + R + \Delta S - D$$

In a semi-arid irrigated region the two major terms of the crop water balance are the (metered) irrigation water delivery and (estimated) crop water use.

Field application efficiency (FAE) equates to

$$\mathrm{FAE} = \frac{\mathrm{ET}}{I + R + \Delta S}$$

and drainage equates to

$$D = I + R + \Delta S - \mathrm{ET}$$

The most common approach to estimating ET has been to express it as a function of the product of a reference crop evapotranspiration (ETo) and a set of crop-specific coefficients (Kc) with adjustments for crop age, cultural practices, and climate (Allen and Pereira 2009; Allen et al. 1998; Doorenbos and Pruitt 1977). Adams et al. (2007) illustrates an approach explored by local resource managers. The crop water use estimate so derived should be "the evapotranspiration from disease-free, well-fertilised crops, grown in large fields under optimum soil water conditions, and achieving full production under given climatic conditions" (Allen et al. 1998). Where these conditions are not achieved, then estimates can be adjusted to account for the degrees of stress.

Communicated by E. Fereres.

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Almonds are the third largest irrigated perennial crop by area grown along the River Murray in South Australia (ABA 2008). Allen and Pereira (2009) provide Kcs for different sizes and ages of almond orchards. Neither they nor the back-mapped citations Snyder et al. (1987) and Doorenbos and Pruitt (1977) provide information on the methods used in their determination, however Sanden (2009) states that almond Kcs were based on soil water balances constructed from sequential measures of soil water content which were made with neutron moisture meters. As such the Kcs would have been an average of observations made within the root zones of individual trees. Studies on a closely related species, peaches, have found that individual tree water use is a function of canopy area and that within a peach orchard tree canopy area can be highly variable (Ayars et al. 2003; O'Connell and Goodwin 2005). It is unclear whether this variation was accounted for when measures on individual trees were transformed into Kcs, which are applied at the level of "large fields" (whole of orchard).

Other sources of Kcs for *Prunus* sp. include a lysimeter based study on peaches (Ayars et al. 2003) and, for younger almonds, a study based on the yield response to treatments which consisted of applying a range of irrigation depths equating to fractions an estimate of crop water use (Hutmacher et al. 1994). In both these approaches, the observations were made on small plots of trees set amongst other plots which were subject to different irrigation regimes. Diaz-Espejo et al. (2005) demonstrated that the water use by well watered sunflower plants was enhanced when it was surrounded by plants experiencing a water deficit and vice versa. They attributed this enhancement to micro-advection. It is likely that micro-advection was present in the aforementioned lysimeter and irrigation treatment studies. Micro-advection would not be present in "large fields" undergoing the same irrigation regime and therefore it is unclear whether the small plot studies are representative of water use at the "large field" level.

In Australia, recent field observations that raising the N, K, and Zn nutritional status to above industry standards of Robinson et al. (1997) increased yields in high-frequency irrigated almond orchard (Ben Brown, Australian Almond Board, personal communication) would support a contention that Kcs based on observations in the late twentieth century were not made on "well-fertilised crops, grown in large fields under optimum soil water conditions".

Ideally Kcs which are to be used to estimate the water use at the whole orchard scale should be derived from measurement made at the same scale on trees where records of soil water and nutrition support a contention that the water use was measured on well-fertilised crops, grown in large fields under optimum soil water conditions.

In this paper, we report on a study where the eddy covariance technique was used to measure the water use of about 4 ha of mature high-yielding almond trees. The study area was surrounded by almonds undergoing a similar irrigation regime. Ancillary measures of orchard canopy size; water, nutrient and salinity status, and climate were also collected. Two of the weaknesses in this approach, uncertainty about the origin of fluxes and lack of energy balance closure, were addressed by calculating monthly flux footprints and deriving ET from fluxes which have been adjusted to close the energy balance.

## Materials and method

### Site description, planting material and culture

The study was conducted in a 481 ha almond orchard located near Loxton in South Australia. The orchard was divided into 10 ha blocks (200 m by 500 m with the long axis aligned north–south) and the flux tower was situated at 34.47035°S and 140.65512°E near the middle of the northern half of a block of trees. The topography of the site was slightly undulating and the area around the tower had a slope of less than 1.5°.

The orchard was planted in 2000 with an inter-row spacing of 7 m and a within row spacing of 5 m. Tree height in August 2008 was 5.5 m. The study block consists of producers, Nonpareil, planted every other row, and pollinators planted as alternating rows of Carmel, Carmel and Peerless, and Carmel and Price. All varieties were planted on Nemaguard rootstock. All but 31 ha of the surrounding orchard was planted between 1999 and 2002.

Nutrients were applied via fertigation. Dosing occurred between September and November and in April with $KNO_3$, Urea, KCl, and $NH_4NO_3$ applied at annual rates of 551, 484, 647, and 113 kg/ha, respectively. The growth of ground cover along the tree line was suppressed with herbicides throughout the year. Growth in the mid-row began in late winter and persisted until herbicide application in late November.

### Weather, irrigation and soil measurements

Data for the calculation of reference crop evapotranspiration (ETo), assessment of climate and measurements of class A pan evaporation with a bird guard (Epan) were sourced from an Australian Government Bureau of Meteorology (BoM) station, which was located about 5 km north-west of the study block at Loxton (station number 024024). This site was surrounded by irrigated crops. ETo for two different reference crops, grass and alfalfa, were calculated following the procedures of Allen et al. (1998) and Walter et al. (2000).

Irrigation was scheduled to maintain the estimated soil water deficit at less than 40 mm (excepting in the period just prior to harvest). A 40 mm irrigation was applied whenever the cumulative estimate of crop water use reached 40 mm. The daily crop water use was estimated as the product of the appropriate monthly crop factor and depth of evaporation from a Class A evaporation pan. For the months of August through to April the monthly crop factors were, 0.3, 0.6, 0.9, 1.0, 1.0, 1.0, 0.8, 0.6, 0.5, respectively.

Irrigation was applied through below-canopy, full cover sprinklers (R10, Nelson, Walla Walla, WA) operating at 0.25 MPa and delivering about 5 mm/h. Sprinklers were located in the tree line and spaced at 5 m. The volume of irrigation was measured by impeller meters (model WT Mk II, Arad, Dalia, Israel).

Water table depth was monitored using a test-well with a casing depth of 4.1 m which was located near the flux tower. It was read at least once a month between July 2008 and June 2009. The test-well was dry at all readings.

Irrigation water was drawn from the River Murray at the Loxton Irrigation Pump station and daily records of water salinity at this site were downloaded from http://e-nrims.dwlbc.sa.gov.au/swa/. The EC of water received by the trees was expressed as a volume-weighted average and for this purpose it was assumed that rainfall had an EC of 0.04 dS/m (Blackburn and McLeod 1983).

Soil salinity was measured on soil samples taken at two sites within the northern half of the block to a depth of 1.2 m at 1.75 m out into the row in August 2008 and April 2009. The soil salinity (ECe) was quantified as the electrical conductivity in dS/m at 25°C of the saturated soil paste extract.

The soil water content (SWC) was monitored with time domain reflectometry (TDR100 with probes CS610, Campbell Scientific Inc, UT, USA) probes located at depths of 5, 15, 45, 70, and 100 cm depths and a neutron moisture meter (NMM) (CPN International, CA, USA) with access tube depths of 1.2 m. Monitoring sites were located at 0.7, 2 and 3.5 m into the row.

TDR probes were calibrated in re-packed soil cores. The NMM probe was calibrated in situ and in order to extend the range of the calibration this data was supplemented with data collected in previous seasons at wetter sites on the same soil series, Mallee highland soils.

Comparison between SWC recorded with TDR and NMM showed that the measures did not align. TDR measures were drier than NMM measures. This was attributed to poor correspondence between laboratory-based calibration and that applicable to soils in situ. The SWC % (w/v) equated to that measured with NMM and was estimated from TDR measures using the following relationship

$$\mathrm{NMM}_{0-100} = 0.99 \times \mathrm{TDR}_{0-100} + 5.82 \quad \text{with} \quad R^2 = 0.71 \quad \text{and} \quad P < 0.001$$

The calculation of the soil water stress coefficient which was used in simulating crop ET required information on the water retention curves of soils at the site and the soil water content at field capacity (or the upper drained limit). This was drawn from Meissner (2004) who fitted the parameters of the Van Genuchten (1980) model of the relationship between volumetric water content and matric potential to a large data set generated from local soils following the procedure described in Cock (1984). Meissner (2004) characterised the parameters in terms of soil properties: particle size analysis, field texture, bulk density, reaction to 1 N HCl and carbonate type. Soils at the site were matched to those in this data set based on undertaking measurements of bulk density and particle size (Indorante et al. 1990) and combining these data with information on field texture, reaction to 1 N HCl and carbonate type which was contained in an unpublished report of an extensive pre-plant soil survey of the orchard based on a 75 × 75 m grid. The water content at field capacity was set at that retained at a matric suction of 8 kPa.

The soil texture and reaction to acid varied with depth. Between 0 and 30 cm the soil was a loamy sand with nil reaction to acid, from 30 to 50 cm it was a loamy sand with medium reaction to acid, from 50 to 85 cm it was a sandy loam and from 85 to 170 cm a sandy clay loam; below 50 cm depth soils had a very strong reaction to acid, which indicates high calcium carbonate content. For these 4 layers the values of total available water (TAW) were 107, 80, 139 and 169 mm/m and the value of volumetric water content at field capacity (upper drained limit) were 19.0, 17.0, 24.7, and 30.7% (w/v), respectively. In the 120 cm deep root zone the TAW was 156 mm. The TAW was calculated following Allen et al. (1998) with TAW equated to the difference between the soil water content at field capacity and at permanent wilting point.

### Plant measurements: phenology, canopy cover, cover crop; water, nutrient and salt status; and yield

Buds burst on 1 August 2008; flowering ended on 31 August 2008; pit hardening occurred 13 October 2008, hulls split on 25th January 2009, and the crop was harvested on 7 March 2009.

Leaf area index was measured with LAI-2000 plant canopy analyser (LI-COR, NE, USA). We followed the manufacturer's protocol for the measurement of light transmission in non-homogenous canopies. Measurements were made in 4 rows either side of the flux tower site, a 45°

viewing ring was used and the tower provided a platform for above canopy measurements. The density and percentage area of orchard floor occupied by cover crop and percentage area shaded by the tree canopy at around noon were estimated from down-row photographs.

The pre-dawn leaf water potentials were measured on trees, which were located alongside the flux tower, with a Scholander pressure bomb. Leaves were enclosed in an aluminised plastic bag, excised and sealed within the chamber which was pressurised at a rate of 0.01 MPa/s.

The nutrient status of Nonpareil trees was assessed in blocks adjacent to the experimental block. The variety mix, age and culture of these trees were the same as those in the study block. Fully expanded leaves on non-fruiting spurs were sampled in January 2009. The leaves were acid washed, dried at 70°C, and ground to pass a 1 mm mesh. Nitrogen was measured by automated dry combustion (LECO corp., St Joseph, MI). Phosphorus and metals were determined by ICP-AES (Thermo Scientific, England) on samples digested with nitric acid and hydrogen peroxide.

Tree salinity was measured on the leaf samples used for assessing nutrient status. Chloride content of a cold water extract was determined colorimetrically with a flow injection analyser (Lachat, Loveland, CO, USA). Sodium was determined on digested samples by ICP-AES (Thermo Scientific, England).

Orchard managers separately measured field weights (hull, shell and kernel) for Nonpareil, Peerless and Carmel harvested in the study block (weights from Price were not separately recorded for this block). The field weights, weight of kernel and marketable kernel were measured for the entire orchard and the ratios derived from these measures were used to calculate marketable kernel weight from field weights measured in the study block.

## Eddy covariance flux measurements: equipment and data processing

The eddy covariance method directly estimates the fluxes of sensible and latent heat. The latent heat flux from a crop equates to the crop evapotranspiration. The fluxes were derived from measurements of 3-D wind speed and direction, and sonic temperature made with a sonic anemometer (CSAT3, Campbell Scientific Inc., UT, USA) and of water vapour and carbon di-oxide concentrations and atmospheric pressure made with an open path infra-red gas analyser (model LI7500, Li-Cor Inc., NE, USA). These instruments were mounted on a fixed tower at a height of 10 m. Ancillary recordings also made at this height included: wind speed and direction measured with a cup anemometer and a wind vane (model 034B windset, Met One Instruments, OR, USA); air temperature and humidity quantified with an aspirated and shielded temperature and humidity probe (model HMP45a, Vaisala, Finland); the net radiation calculated from measurements of the four components of the radiation balance (short down and up-welling and long down and up-welling radiation) recorded with a radiometer (model CNR1, Kipp and Zonen, Netherlands); sunshine hours and diffuse radiation quantified with a radiometer (model BF3, Delta-T Devices, Cambridge, UK); and photosynthetically active radiation (PAR) measured with a radiometer (model LI190SB, Li-cor Inc., NE, USA). Rainfall was gauged with an automated rain gauge (model TE525MM, Texas Electronics, TX, USA) mounted at 5.7 m, just above the canopy on a pump-up tower.

Soil heat flux was evaluated with 6 heat flux plates (model CN3, Middleton Solar, Australia) located across the inter-row at 10 cm depth and one self-calibrating heat flux plate (model HFP01SC, Hukseflux Thermal Sensors, Netherlands). The latter was collocated with one of the six non-calibrating types (CN3), and after filtering for spikes the ratio of these two plates was used as a correction factor to adjust the spatial average of the six plates.

Soil heat storage was calculated from TDR measures of soil water content and soil temperature recorded with 8 thermocouples (model 105T, copper-constantan, Campbell Scientific Inc., UT, USA) located across the inter-row, four each at 2 cm and 6 cm depth, half way between the heat flux plates. Calculations followed the method of Hanks and Ashcroft (1980) and Klute (1986).

Data were collected from the 20th of August 2008 to the 9th of June 2009. High-resolution flux data were recorded at a 10 Hz interval, while ancillary data were gathered at intervals of 5–15 min; all data was averaged to a 30-min interval.

Post acquisition, the eddy covariance (EC) data were processed according to standard procedures developed within the EC flux measurement community (Lee et al. 2004). A planar fit coordinate rotation was applied to the flux data at monthly intervals, Wilczak et al. (2001). The procedure consists of a linear multiple regression followed by two rotations of the fluxes into the mean wind field. The density terms for the open path infra-red gas analyser were accounted for applying the Webb et al. (1980) correction to the half-hourly data. Gap-filling and $u^*$-filtering was performed using the online scheme developed by Reichstein et al. (2005) [http://gaia.agraria.unitus.it/database/eddyproc/].

The degree of energy balance closure is an objective measure for evaluating the quality of eddy covariance (EC) flux measurements. The surface energy balance can be stated thus: the net radiation equals the sum of sensible ($H$) and latent (LE) heat fluxes, plus the soil heat flux ($G$) and energy requirements of photosynthesis ($P$) that is $Rn - Q = H + \mathrm{LE}$, where $Q$ is the sum of $G$ and $P$. The energy consumption by photosynthesis was estimated according to Blanken et al. (1997). The energy balance was calculated from half-hourly data.

In the field, the energy balance is rarely closed (Foken et al. 2009). The variation in energy balance was investigated following the approach of Barr et al. (2006) with the use of the closure fraction (CF). The CF equates to the quotient of ($H$ + LE) and ($Rn - Q$).

Failure to account for some of the sensible and latent heat fluxes can cause the CF to fall below unity (Wilson et al. 2002). If the EC measures do not account for all LE, then they will underestimate crop evapotranspiration. This possibility was addressed using the approach of Blanken et al. (1998), Barr et al. (2000), and Twine et al. (2000), wherein the energy balance for half-hourly data is closed by multiplying LE and H by the inverse of the closure fraction. We refer to the rate of evapotranspiration derived from this transformation as $ET_{EBFC}$.

The flux footprint describes the source area of the fluxes measured at the eddy covariance station. Footprints were calculated for half-hourly data using the ART-Footprint tool (Spirig and Neftel 2007; Neftel et al. 2008) which implements the Kormann–Meixner method (2001). A monthly ET-weighted average footprint was compiled by weighting the half-hourly footprint with the half-hourly ET values from the flux station.

Along the River Murray in South Australia, irrigation has developed in a strip of land hugging both sides of the river. The climate is semi-arid and well-irrigated surfaces represent an oasis in this environment. Regional and local advection of energy can be an important component in the energy balance. Advection can enhance evapotranspiration. We assessed the presence of advection by applying the criteria of De Bruin et al. (2005), that is, that advection is indicated when the ratio of daily latent heat flux to daily net radiation is greater than unity.

### Simulating ET crop

The crop ET was simulated using the single crop coefficient approach

$$ET_{crop} = ET_o \times K_c \times K_s$$

(with $K_c$ and $K_s$ representing the crop coefficient and water stress coefficient).

The set of $K_c$ used in the simulations were those which were appropriate for the values of LAI, projected canopy cover and cover crop presence at the site (Allen and Pereira 2009). The values for the mid and end phase were adjusted for drier than average climate (Allen et al. 1998). The duration of each phase and the intervening phases was set as per Allen et al. (1998) for a "low latitude deciduous orchard" that was: initial phase 20 days, development 70 days, mid phase 120 days and late phase 60 days.

The calculation of $K_s$ followed procedure described in Allen et al. (1998). The value of the water stress coefficient ($K_s$) was estimated as a function of: rootzone depth, readily and total available water (RAW, TAW), the depletion factor ($p$), and the daily ET, irrigation and rain. The daily rootzone depletion ($Dr_n$) was calculated as

$$Dr_n = Dr_{n-1} + I_n + R_n - ET_n$$

with $K_s$ calculated using a value of $Dr_{n-1}$ ($I$, $R$—irrigation and rain).

## Results

### Weather, soils, irrigation, nutrients, salinity, plant water status, canopy development and yield

Between 21 August 2008 and 31 May 2009, the value of ETo was 1,365 mm. Table 1 shows the monthly values of ETo. During the mid-season (between October and February) the ratio of ETo tall to ETo short was 1.33. The standard Kc's listed in FAO 56 (Allen et al. 1998) apply to a temperate climate with average wind speed and minimum relative humidity of 2 m/s and 45%, respectively. The Loxton BoM station nearby the site displayed drier conditions with a minimum monthly relative humidity less than 30% (Table 1).

The prevailing wind direction at the site was SSW (Fig. 1) and in this direction the downwind distance between the tower site and the edge of the irrigated almond orchard was 0.7 km.

Figure 2a shows the seasonal course of the daily values of soil water content in the top 1 m of the soil. During the season, irrigation regularly returned the soil water content to above 20% until February. Following withholding of irrigation in March the values fell to below 15%.

Records of NMM (data not presented) showed that water was being extracted to 1.2 m. During the season the values of soil water content recorded by NMM at depths of less than and equal to 80 cm ranged above upper drained

**Table 1** The monthly averages from August 2008 to May 2009 of the daily values of ETo (mm/day), class A pan evaporation (mm/day), wind speed (U, m/s) and minimum relative humidity (%) for the Australian Government Bureau of Meteorology station at Loxton (Ref. No. 024024) which was about 5 km from the flux tower site

| | Aug | Sept | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May |
|---|---|---|---|---|---|---|---|---|---|---|
| ETo (short) | 2.0 | 3.8 | 5.2 | 5.5 | 5.8 | 7.5 | 7.0 | 4.6 | 3.0 | 1.9 |
| ETo (tall) | 2.8 | 5.3 | 7.0 | 7.4 | 7.6 | 10.1 | 9.6 | 6.3 | 4.2 | 2.6 |
| A pan | 2.3 | 5.2 | 7.0 | 7.8 | 8.4 | 11.0 | 10.2 | 6.3 | 4.3 | 2.4 |
| U | 2.0 | 1.9 | 2.0 | 2.2 | 2.3 | 2.0 | 2.4 | 1.9 | 1.6 | 1.1 |
| RH min | 44 | 27 | 21 | 25 | 28 | 13 | 19 | 25 | 33 | 46 |

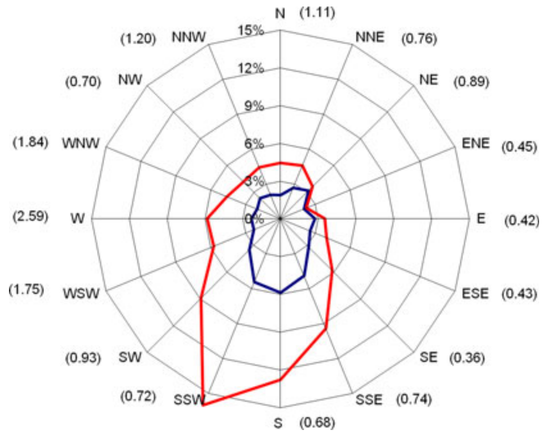


**Fig. 1** Frequency of wind direction for all wind speeds (*outer solid line*) and direction and frequency of winds with a speed below 2 m/s (*inner solid line*). The percentages show values in a 22.5 degree resolution centred on N (north) to NNW (north–north–west). *Values in brackets* refer to the distance in km between tower and edge of the irrigated almond orchard

limits of the soils, whereas at depths of 100 and 120 cm the high ends of the ranges, 27 and 24% (w/v), respectively, were well below the upper drained limit of 31% (data not shown).

The average soil salinities in August 2008 and April 2009 were 1.7 and 1.6 dS/m. These values were higher than the average of 1.1 dS/m recorded from 3 soil pits in the experimental block during pre-plant soil survey in 1998 (J. Garvie, Century Orchards, pers. comm.). They are also just above 1.5 dS/m, the value that Ayers and Westcot (1985) list as the threshold for soil salinity affecting almond growth.

Over the season, 1,304 mm of irrigation was applied and 105 mm of rain fell at the tower site. The volume-weighted salinity of water received by the trees was 0.35 dS/m. This value is at the lower end of the medium salinity range of 0.3–0.8 dS/m (Hart 1974) and well below the threshold for salinity effects on almond growth of 1.0 dS/m (Ayers and Westcot 1985).

The concentration of elements in leaves indicated that their nutritional status was adequate (Robinson et al. 1997). The respective concentrations of N, P, K, Ca, and Mg were 2.7, 0.12, 2.3, 3.9, and 0.77% (w/w), and of Zn and Mn 105 and 145 ppm.

Tree salinity was measured on the leaf samples used for assessing nutrient status. The concentrations of Na and Cl were 0.04 and 0.61%. The value for Na was in the adequate range, but that for Cl was well above the lower bound, 0.3%, of the range indicative of excessive/toxic concentrations of Cl (Robinson et al. 1997).

Except for the period during which irrigation was withheld prior to harvest in March and April, the values of pre-dawn leaf water potential remained above −0.4 MPa (Fig. 2b), a level which is indicative of an absence of stress in *Prunus* crops (Remorino and Massai 2003).

Between November and February, the LAI was 2.9 ± 0.1 (mean ± SE) (Fig. 2c). Around noon between December and February, the tree canopies shaded 65 ± 4% of the orchard floor. Self sown cover crop occupied 50 ± 4% of the orchard floor centred on the mid-row between August and November. Cover in this area was continuous from September onward.

The yield of marketable kernels from Nonpareil trees was 4.3 t/ha and those from Carmel and Peerless were 4.6 and 3.1 t/ha.

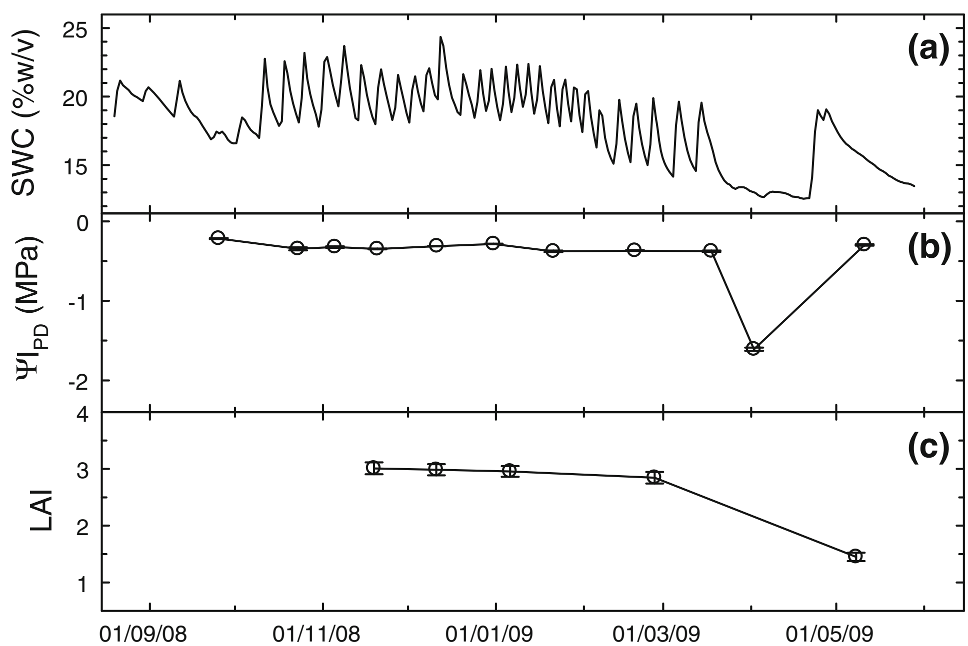


**Fig. 2** The seasonal variation in soil water content in 0–100 cm (*a*), pre-dawn leaf water potential (*b*), and LAI (*c*). *Bars* in *b* and *c* represent 1 × SE (standard error)

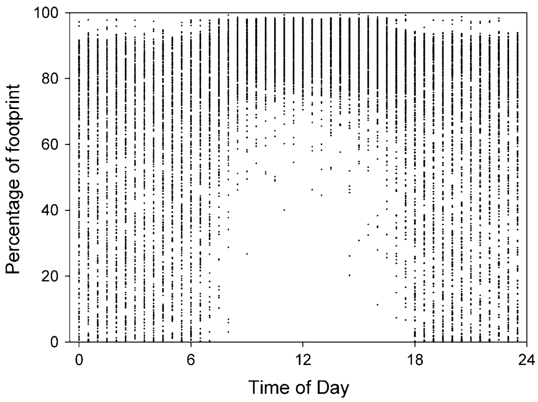


**Fig. 3** The effect of time of day on the percentage of the footprint lying within the northern section of the experimental block (late August 08 to early June 09). Based on half-hourly data

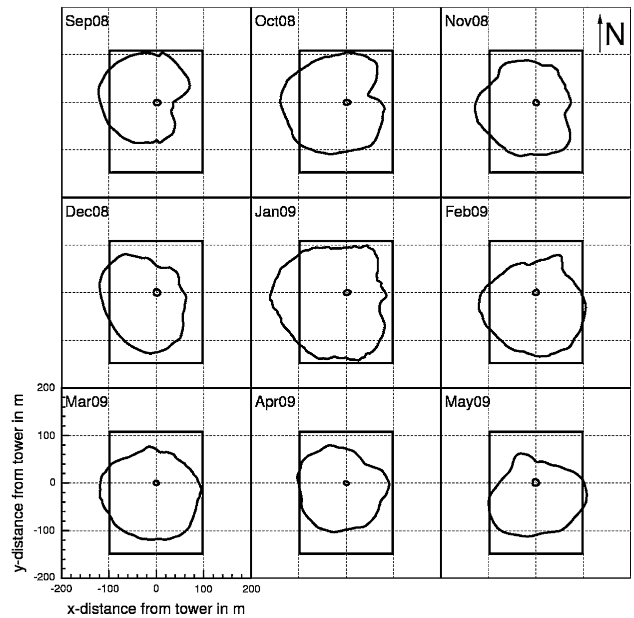


**Fig. 4** Monthly ET-weighted averaged footprint for the source area for 90% of the flux. *Rectangle* describes the boundaries of the northern section of the study block

## Flux source

The flux footprint describes the source area for atmospheric eddies measured at a flux tower site and depends on the wind direction and micro-meteorological conditions. The size of the footprint reduces as the mechanical (wind speed) and convective (buoyancy) turbulences increase. Figure 3 shows the diurnal variation in the percentage of the footprint area lying within the northern half of the study block. During nighttime, when convective turbulence was low, the footprint area was large and less of it was within the study block. During daytime, when convective turbulence was high, on average over 90% of the foot print area was within the study block. These half-hourly values were weighted with half-hourly values of ET in order to produce a monthly ET-weighted footprint. Figure 4 shows the ET-weighted footprint for each month. In all months, except January, the footprint was nearly entirely contained within the study block. In all months it fell well within the area of land occupied by the irrigated almond orchard.

## Diurnal variation in energy components, advection and energy balance

Figure 5 shows the diurnal variation in half-hourly rates of net radiation, fluxes of sensible and latent heat (crop evapotranspiration) and ground heat flux. On a day where overall conditions were not advective (Fig. 5b) all energy components were positive during the day. Net radiation was distributed amongst positive latent and sensible heat fluxes and positive heat flux into the soil. Under mild advective conditions (Fig. 5a), the sensible heat flux was negative during the day. This indicated that sensible heat was an additional source of energy. The input of sensible heat flux increased the values of outgoing latent heat flux to above those of net radiation. Under extreme advective conditions (Fig. 5c) the strong advective input of sensible heat flux pushed values of outgoing latent heat flux to well above those of the net incoming radiation. The weather on this day was associated with the most lethal bushfires in recent Australian history. The class A pan evaporation was 18.9 mm.

Advective conditions were present 25% of the days between September 2008 and May 2009; that is the daily values of latent heat flux to net incoming radiation (LE/Rn) were greater than unity (Fig. 6). These conditions were present on about 10 days per month between September and March and on 1 day a month in April and May.

Figure 7 displays the two sides of the energy balance equation, sensible and latent heat flux versus net radiation minus the sum of the soil heat flux (*G*) and energy requirements of photosynthesis (*P*) for each half-hourly measurement between late August 2008 and early June 2009. Forcing the regression through zero gives a slope of 0.87. The depression of the slope below unity indicates that eddy covariance measures may not account for all sensible and latent heat fluxes. Limiting the data to the period September to mid March, where soil water content remained above 14% (w/v), gives a slope of 0.91. The rise in the slope indicates that the data accounted for more of the latent and sensible heat fluxes.

## Seasonal course of daily crop water use

The seasonal course of the daily measures of ET together with the seasonal course of a running 3-day average of ETo along with value for Ks, the water stress coefficient, are

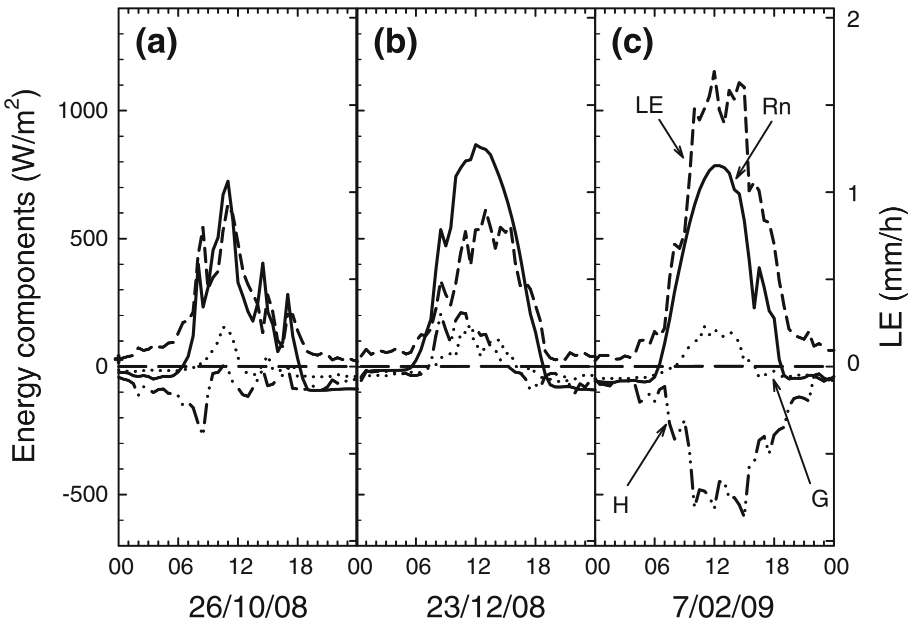


**Fig. 5** Diurnal variation in the components of the energy balance: *LE* latent heat flux, (*dashed lines*), *Rn* net radiation (*solid lines*), *G* soil heat flux (*dotted lines*), *H* sensible heat flux (*dashed dotted lines*) for days where advective transfer of energy was weak (**a**), near absent (**b**) or strong (**c**). LE in mm/h was estimated assuming $T = 20°C$

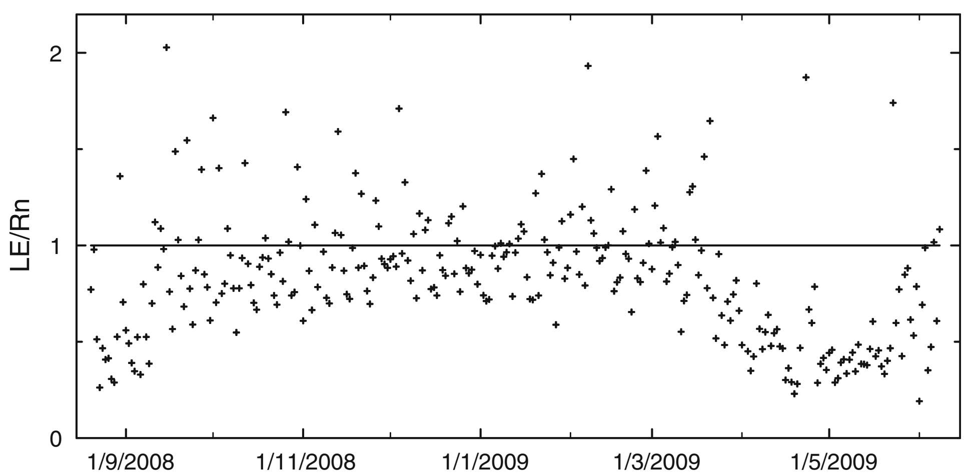


**Fig. 6** The seasonal variation in the ratio of the daily values of the latent heat flux (evapotranspiration) to net radiation. *Solid line* delineates non-advective (*below the line*) from advective (*above*) conditions

shown in Fig. 8a. The total ET for the period 21 August 2008 to 31 May 2009 was 1,257 mm. Over the same period, the sums of irrigation and rain were 1,304 and 105 mm, respectively and the drawdown on soil water store was 65 mm. Using these inputs to construct a seasonal water balance ($D=I+R+\Delta S-\text{ET}$) gives an estimated depth of water draining below the rootzone of 217 mm. At this level of ET, the frequency and depth of irrigation and rain was sufficient to prevent the value of Ks from falling below unity, indicating that ET was not limited by availability of soil water.

As previously noted in discussion of energy closure, the values of ET measured by the EC technique may not account for all latent and sensible heat fluxes. If so, then ET will be underestimated. This possibility was accounted for by forcing closure of the energy balance (EBFC). Figure 8b shows the values of ET after forcing energy closure. With EBFC the cumulative sum of ET in the period 21 August 2008 to 31 May 2009 was 1,450 mm. Substituting the summed ET value into the seasonal water balance, with aforementioned values for *I*, *R* and $\Delta S$, gives an estimated depth of seasonal drainage of 24 mm. In contrast with the untransformed data, the associated values of Ks do not remain at unity across the entire season. The depression of Ks to well below unity after mid March indicates that ET was limited by availability of soil water.

## Simulation of almond evapotranspiration

The daily ET was simulated using the single crop coefficient approach (Fig. 8c). Between 21 August 2008 and 31 May 2009 the cumulative sum of ET was 1,383 mm. As with the transformation of measured ET ($\text{ET}_{\text{EBFC}}$), the Ks values associated with this simulation indicate that ET was limited by the availability of soil water after mid March. If ET had not been limited by the availability of soil water

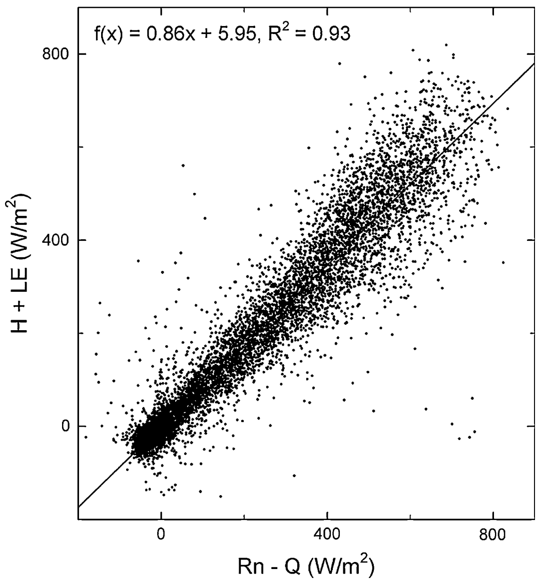


**Fig. 7** Regression of half-hourly values of surface energy balance components, sensible plus latent heat flux (H + LE) and net radiation minus soil heat flux and energy requirements of photosynthesis ($R_n - Q$)

(i.e. Ks set to 1), then the cumulative sum of simulated ET would have been 1,415 mm.

## Discussion

### Crop water use

Measurements of evapotranspiration were performed in a high-yielding orchard which had good nutritional status, an adequate supply of water up until harvest, but which may have experienced a slight salinity stress. The block, from where data on crop yield and canopy, crop water status, soil water content and salinity were obtained, accounted for approximately 90% of the total flux footprint. The remaining 10% was largely sourced from irrigated almonds of similar age and undergoing similar culture.

For the period prior to harvest the measured latent and sensible heat fluxes accounted for 91% of the available energy (Rn—*G*—*P*). This is at the higher end of the range Wilson et al. (2002) found for a number of Fluxnet sites, which had on average a 20% imbalance.

If water use by the study block equated to the untransformed estimate of crop ET, 1,257 mm, then substitution of this value into the annual soil water balance gives an annual drainage rate of 217 mm. Further, using the untransformed estimate of daily ET to model the soil water stress coefficient (Ks) gives Ks values of unity which indicates an absence of water stress (Fig. 8).

If seasonal drainage equated to 217 mm, then we would expect low values of soil and plant salinity and periodic high values of soil water content at the root zone base.

The value of soil salinity which we could expect once the system reaches steady state can be estimated as a function of the EC of water received, the leaching fraction ($LF = D \times [I + R]^{-1}$) and the crop water extraction pattern (Hoffman and van Genuchten 1983). The EC of water received, after accounting for salts added as fertigation and partially removed in harvest material, was 0.42 dS/m. If drainage was 217 mm, then the LF was 0.15 and assuming 40–30–20–10 vertical soil water extraction pattern gives a steady-state ECe of 0.6 dS/m. The soil salinity recorded in

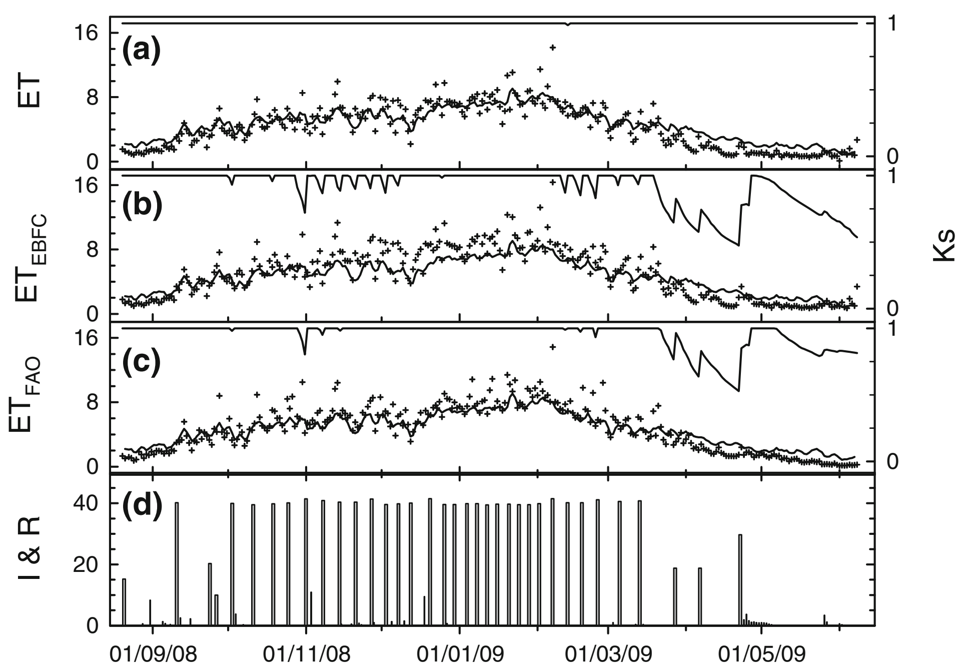


**Fig. 8** Daily rates of crop water use, irrigation and rain (mm/day). **a** ET measured without energy balance closure forcing, **b** ET with forced closure of the energy balance and **c** ET estimated using the single crop coefficient approach of FAO. In figures **a**–**c** the *thick solid line* in *lower segment* represents the 3-day running average of ETo and the *thin solid lines* in *upper segment* represents the value of the crop water stress coefficient (Ks). **d** Irrigation and rain, *grey* and *black bars* respectively

pre-plant survey, 1.1 dS/m, represented the steady-state soil salinity under dryland conditions. Given the soil is progressing toward a new steady state under irrigated conditions, then with drainage of about 217 mm we would expect the current salinity to lie somewhere between 0.6 and 1.1 dS/m. As the upper end of this range is well below the threshold for salinity damage of 1.5 dS/m (Ayers and Westcot 1985), then we would not expect tree leaf concentrations of Cl to exceed 0.3%, the upper end of the adequate level (Robinson et al. 1997). Both the measured soil and plant salinity values, 1.6 dS/m and 0.6% (Cl) were well above the values expected if the annual drainage had equated to 217 mm. Further, both NMM measures of soil water content at 100 and 120 cm depth and TDR measures at 100 cm showed that the soil water content remained at least 2.5% (w/v) below the values at field capacity. These data indicate that the drainage volume was likely to be very much less than that calculated from the soil water balance assuming a seasonal ET of 1,257 mm.

If the values of Ks remained at unity throughout the season, then we would not expect the trees to have experienced water stress. During harvest the observed depression of pre-dawn leaf water potential to −1.5 MPa (Fig. 2) indicates that the trees were experiencing severe water stress. This observation cannot be reconciled with the value of Ks modelled using daily untransformed measures of ET.

The use of the untransformed measure of ET to calculate the expected soil salinity and infer the plant water status does not align with measured values. The slope of the energy balance equation constructed using measured fluxes was less than unity. This supports a proposition that the eddy covariance measures of ET did not account for all latent heat fluxes. This short-coming can be addressed by transforming sensible and latent (ET) flux measures to close the energy balance.

Transforming the measures of sensible and latent heat flux increased the estimate of crop ET from 1,257 to 1,450 mm. Repeating the above considerations with this value of ET produced an annual drainage rate of 24 mm which gives a leaching fraction of 0.02 and an expected steady-state soil salinity of 2.0 dS/m. The current value of soil salinity, 1.6 dS/m, lies between the value prior to development and that expected should current conditions prevail until steady state is reached. Further, this small volume of drainage aligns with the absence of an elevation of the soil water content at the root zone base to above field capacity.

During harvest the value of Ks modelled using daily transformed measures of ET was 0.68 (Fig. 8) indicating the presence of well developed soil water stress which aligns with the observed depression of pre-dawn leaf water potential during this period (Fig. 2).

The use of the transformed measure of ET to calculate expected soil salinity and the soil water availability (Ks) aligns with observed values.

Table 2 shows the Kcs that Allen and Pereira (2009) specified for almond crops on a monthly basis assuming that the initial phase commenced at bud burst on 1 August 2008. The Kc sets were adjusted for non-standard climate and the presence of a cover crop. The values in May reflect linear progression between the end phase value of Kc (end of April) and the value of Kc after leaf fall at the start of June. The abrupt change to mid-phase values reflected the suppression of the cover crop at the end of November.

The mid-phase Kc covers the period November until February. Up until the end of November the measured ratio of the transformed ET:ETo represents that with the presence of trees shading 65% of the orchard floor and a cover crop occupying 50% of the orchard floor. After this date, the ratio of ET:ETo represents that expected with the presence of trees shading 65% of the orchard floor. The value for November is 1.24 and that for December through to February is 1.22. Adjusting these values to equate to those expected under a standard climate gives respective values of 1.10 for the period when 50% cover crop was present and 1.12 for the period after it was suppressed. The

**Table 2** For the period September 2008 to May 2009, the monthly values of Kc from Allen and Pereira (2009), the monthly averages of the daily values of ETo, ET crop, ET crop with forced closure of the energy balance, water stress coefficient associated with water use at $ET_{EBFC}$ rates, and the crop coefficient for $ET_{EBFC}$ at monthly average values of Ks > 0.97

| | Sep | Oct | Nov | Dec | Jan | Feb | Mar | Apr | May |
|---|---|---|---|---|---|---|---|---|---|
| Kc[a] A&P | 0.84 | 1.08 | 1.17 | 1.12 | 1.12 | 1.12 | 1.02 | 0.86 | 0.46 |
| ETo | 3.83 | 5.15 | 5.53 | 5.81 | 7.51 | 7.03 | 4.58 | 3.03 | 1.86 |
| ET | 2.97 | 4.81 | 5.92 | 6.59 | 7.53 | 7.04 | 4.00 | 1.47 | 0.83 |
| $ET_{EBFC}$ | 3.40 | 5.53 | 6.79 | 7.60 | 8.64 | 8.10 | 4.62 | 1.82 | 1.00 |
| Ks($ET_{EBFC}$) | 1.00 | 0.97 | 0.97 | 0.99 | 1.00 | 0.97 | 0.91 | 0.67 | 0.82 |
| $Kc_{EBFC}$ | 0.93 | 1.11 | 1.24 | 1.30 | 1.16 | 1.21 | >1.03[b] | >0.61[b] | >0.55[b] |

[a] Values for high-density almond orchard adjusted for local climate and the presence early in the season of a cover crop over part of the orchard floor

[b] These values are an underestimate of Kc because Ks ($ET_{EBFC}$) <0.97

respective values for a standard climate in Allen and Pereira (2009) are 1.02 and 1.00. During the mid phase the Kc that we observed was 0.1 higher than tabulated values. Under local conditions, a 0.1 increase in the value of Kc during the mid phase equates to an increase of 78 mm (6%) in the estimate of crop evapotranspiration.

### Advection and almond Kc

The study orchard experienced advective conditions. The effect of advection was investigated over the interval corresponding to the mid-phase period of crop coefficient sets. We avoided the period at the start of this phase when the cover crop was present and used data collected between the start of December and the mid March. During this period the crop LAI was about 3 and daily Ks values were mostly above 0.95, that is the ratio of ET:ETo was equivalent to Kc. Days where the ratio of LE:Rn was greater than unity were classified as advective. On advective days, the average values of ETo, 7.3 mm, trended higher ($P = 0.06$) than the values of 6.5 mm on non-advective days. The average values of ET:ETo on advective and non-advective days were equivalent at 1.24 and 1.20, respectively. The climate on both sets of days was non-standard; on both days the average values of minimum relative humidity were 20%, but the average wind speed on advective days, 2.6 m/s, was higher than that of 2.0 m/s on non-advective days. Adjusting the calculated Kc's for non-advective and advective days to standard climatic conditions (minimum relative humidity 45% and wind speed 2 m/s) gives a value of 1.08 and 1.10, respectively.

Over the last decade, satellite-based energy models have been used to estimate crop Kcs, for example the application of METRIC (Tasumi et al. 2005) to almonds (O'Connell et al. 2010). These estimations are based on using ETo for alfalfa which is also known as ETr. The average values of ET:ETr on advective and non-advective days were equivalent at 0.93 and 0.90, respectively. Adjusting these values back to standard climatic conditions gives values for non-advective and advective days of 0.81 and 0.76, respectively.

### Field application efficiency

The Adams et al. (2007) approach to estimating the rate of water use by almond orchards along the lower River Murray used a set of Kcs similar to those provided by Allen et al. (1998). For almonds with no ground cover, from August through to May the values were 0.4, 0.6, 0.8, 0.9, 0.9, 0.9, 0.9, 0.8, 0.7, 0.3. Simulating crop ET with these values of Kc gave a cumulative sum of ET for the period 21 August 2008 to 31 May 2009 of 1,215 mm. Substitution of this figure into the orchard water balance (assuming all other inputs remain constant) gives an estimated seasonal drainage of 259 mm, which equates to a leaching fraction of 0.18, and a field application efficiency of 82%. Substitution of the transformed measured value of ET ($ET_{EBFC}$) into the water balance gives a drainage of 24 mm and a field application efficiency of 98%. For the study site, the use of the ET for almonds derived from estimates based on Kcs of Allen et al. (1998) in the calculations of irrigation efficiency and drainage losses leads to their under and over estimations, respectively.

## Conclusions

Almond evapotranspiration was measured by eddy covariance technique and after correction by forcing closure of the energy balance the resultant mid-phase Kc for standard climatic conditions was 1.1. This value is 10% higher than that recently listed in Allen and Pereira (2009). The site was subject to advection for one-third of the mid-season. The same Kc was found to apply during advective and non-advective conditions. Use of corrected measured rates of ET in the calculations of field application efficiency and drainage gave higher and lower values, respectively, than those calculated using an approach that has been explored by resource managers (Adams et al. 2007).

**Acknowledgments** The authors wish to thanks the staff at Century Orchard Pty Ltd, particularly Geoff Ablett and Jason Garvie, for access to the orchard and assistance with field work; Tony Adams and Jahangir Alam of the Irrigated Crop Management Service, PIRSA, for helpful discussion and provision of weather data: Julie Styles for setting up the programs used to process flux measures; and our partners at CSIRO Marine & Atmospheric Research, Dr Helen Cleugh and colleagues, for support during project inception and establishment; Dr Gerrit Schrale for project management. The research was supported with funds from the National Action Plan for Salinity via the Centre for Natural Resource Management, and the River Murray Levy. A summer scholarship from the National Program for Sustainable Irrigation supported Samantha Connor's participation in the project.

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