Olive water use and yield

– monitoring the relationship

A report for the Rural Industries Research and Development Corporation

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Foreword

While olives have been grown in Australia for over a century, the olive industry has only emerged as a force over the last decade. The scientific investigation of olive culture under the Australian environment has only just begun; so much of the current management of olives still follows traditional European practice. In particular, we need a better understanding of the relationship between the water use of olive trees and their yield in order to develop appropriate irrigation regimes.

This publication presents a project that monitored the water use of trees across four mature groves in South Australia for two growing seasons. The aim of the project was to provide estimates of evapotranspiration during the growing season, characterise the relationship between water use and olive yield, and provide guidelines for efficient management of irrigation water for optimum yields. The report shows how grove management affects water use and that the irrigation regimes of the monitored groves were not optimal for olive yield. It shows the necessity of developing irrigation practices that prevent shortage of water during the middle of growing season in mid-summer, and which partition more of the evapotranspiration through the transpiration pathway to ensure high olive yield and water-use efficiency.

This project was funded from RIRDC Core Funds which are provided by the Federal Government.

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Simon Hearn
Managing Director
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The groves were selected not only on the basis of tree maturity and quality of the sites and their management, but also on the good nature and flexibility of their owners. All growers are respected members of the SA olive industry. We not only thank them for allowing access to their trees, but also freely sharing their knowledge of olive growing.

We also would like to thank Steve Mylius who carried out the field work for this project. Steve was not only the principal liaison with growers, but also responsible for installing and operating the monitoring equipment. There were significant technical problems during this study which Steve met with great patience and fortitude.

Abbreviations

D	vapour pressure deficit
E_o	potential evaporation
E_p	pan evaporation
ET	evapotranspiration
g_s	stomatal conductance
G	soil heat flux
i	sunlight intercepted by canopy
I	irrigation
K_c	crop factor
KL	kilolitre
LAI	leaf area index
ML	megalitre
R	rainfall
R_n	radiation
S	soil water
T	transpiration
T_p	potential transpiration
T_{sap}	transpiration estimated using sap-flow equipment
T_{met}	transpiration estimated using meteorological method
WUE	water use efficiency
WUE_{et}	water use efficiency based on evapotranspiration
WUE_t	water use efficiency based on transpiration

Contents

Executive Summary

Water is the most important environmental parameter determining the future of the olive industry. Although the olive is a hardy crop that yields reasonably well even under water-limited conditions, it is known from overseas work that olive fruit and oil yields respond positively to any additional water up to a limit. While olives have been grown in Australia for over a century there is little known their water relations under Australian conditions. Indeed, much olive irrigation practice follows ad hoc rules-of-thumb in the absence of better information (Burr 1997). It is very likely that olive growers are applying water inefficiently, either too little or too much. The olive industry also has to compete with other established irrigated crop industries such as viticulture for the scarce water resource. Prudent management of water is, therefore, essential for a viable olive industry. An important first step to achieve this is to estimate the water required by olives for evapotranspiration (ET) to achieve profitable production.

Therefore, the aim of this project was to provide estimates of ET during the growing season, characterise the relationship between water-use and olive yield, and provide guidelines for efficient management of irrigation water for optimum yields. These estimates and guidelines would ideally be derived from replicated irrigation trials with mature modern-trained trees on a homogenous site and a suitably flexible irrigation system. Such a trial would not only be very costly, but at the time this project suitable groves were not available. However, scientifically robust estimates can still be achieved through monitoring the relationship between water use and yield across a range of sites.

This project monitored the water use of four South Australian groves over the growing seasons (September to May) of 1999/2000 and 2000/1. The groves were of traditional growers at Waikerie (established in 1988), Two Wells (estab. 1972), Balaklava (estab.1970) and Greenock (estab. 1970). All of these sites had relatively wide inter-row spacing resulting in tree densities (stems/ha) of 156, 204, 190 and 133, respectively. Soil moisture (using a neutron moisture meter), light interception and olive yield was monitored at all sites. The Waikerie site was more intensively monitored using sapflow equipment to estimate transpiration (T).

The management practices followed in the groves (i.e. frequency of irrigation, technology used and row spacing) were reflected in the water used for evapotranspiration (ET) during the growing season. Seasonal ET at Waikerie (average 619 mm) and Two Wells (av. 651 mm) were always within 6% of each other, because of frequent irrigation at both places despite the differences in irrigation technology between the two sites and the presence of a cover-crop at Waikerie. However The ET averaged only 316 mm (3 ML) for the rainfed grove at Greenock.

Irrespective of the irrigation regimes, the groves were under-irrigated in midsummer (December–February period) which caused inadequate supply of soil-water, and this could have penalised the yields. Thus seasonal crop factor (K_c), i.e. the ratio of actual ET to potential ET (ET_o) for these groves averaged between 0.20 and 0.41 during the two seasons. These values were mostly lower than what we estimated if the trees were adequately supplied with water during the mid-summer, and it was apparent that the growers under-irrigated by up to 15%. If the groves were irrigated at levels that met potential water demand by olives, water requirements would be close to 9 ML at Waikerie (where cover crop is maintained throughout the season), 7 ML at drip-irrigated Two Wells, and 3.6 ML at Balaklava. Water requirement for optimum yield at Greenock, if irrigated, would be similar to that at Two Wells, by virtue of the similarity in the interception of sunlight by the olive trees.

We observed a degree of inconsistency in water application practices, reflecting the current lack of definite recommendations on irrigation water management. For example, despite the 2000-01 season being warmer than 1999-00 season, there were no significant increases in the amounts of water applied by the growers in the former season. The proportion of the ET used directly by the olives as transpiration (T) was depended on the amount of sunlight captured by the olive canopies and the amount of soil surface wetted during irrigation. Thus, T accounted for an average of only 63% of ET

at Waikerie because of micro-sprinkler system used compared to 76% at Two Wells where the drip irrigation delivered water close to the trees thereby minimising losses through soil evaporation. The proportion of ET due to T was low at both Greenock and Balaklava, where the groves rely either entirely or significantly on rainfall, because the majority of the soil surface was wet and much water was lost through soil evaporation.

Generally, water uptake by the olives was conservative and seasonal T was stable across the two seasons to reflect water supply and, hence, irrigation practices. Average values of T for the two seasons were 16 kL at Waikerie, 25 kL at Two Wells, 13 kL at Balaklava and 14 kL at Greenock. Peak rates of T were attained in mid-summer when a tree could use up to 120 L per day at Waikerie and 147 L at Two Wells, compared to about 79 L at both Balaklava and Greenock. We found evidence that olives restrained water use from midday onwards by restricting loss of water through the stomata apertures on their leaves during hot and dry days.

Olive trees did not respond to differences in water-use when the seasonal ET was less than 5 ML, but increased dramatically with additional water-supply above this level. It appears that past irrigation practices continued to influence olive yield, and thus, it is important that when new groves are established that appropriate irrigation protocols are implemented right from the onset to avoid persistent periods of limited water supply. This should prime the trees for producing high and consistent yields. It appears that groves that have been under regimes of water-stress may not respond immediately to improved water-supply regimes, and yields may stagnate. This was evident by the variety Kalamata where its efficiency for olive production per unit of transpiration was half under a regime of extended inadequate water-supply compared to the high yield obtained under high rates of water supply.

Averaged across all groves and the two seasons, the olive trees produced about 1380 kg of fresh olive per megalitre of water. Irrigation practices that prevent shortage of water during the middle of growing season in mid-summer, and which partition more of ET through T will ensure high olive yield and water-use efficiency. Transpiration can be maximised by minimising area of the soil surface wetted during irrigation by using technologies that deliver water as close to the olive trees as possible. In medium to heavy textured soils, extending the intervals between applications with increased volume of supply may minimise losses of water through soil surface.

This study has further demonstrated the importance of appropriate water management as an essential component of achieving high and consistent yields from olives. This study was limited in both scope and duration, but it demonstrates the current lack of consistency in irrigation practices amongst even some of the respected and experienced olive growers in South Australia. This is not entirely unexpected since the olive industry is relatively new and is yet to obtain the level of research and extension support available to other perennial horticulture enterprises such as viticulture. The use of K_c provides a means of scheduling irrigation, and the estimates given here can be used to provide first approximations of how much water to apply. It should be noted, however, that K_c is primarily designed to estimate the quantity of water to apply and, not necessarily, when to irrigate which requires some idea about the initial water content and water-holding capacity of the soil.

The scope of this project could not address all the issues of water-use efficiency by olives, and there are still areas for which further studies are required. These include how irrigation management can be employed to lift the productivity of old groves that seem to be primed for low productivity by the long-term low intensity management practices. This should be undertaken in conjunction with acquiring a greater understanding of yield–water-use relationships at the low end of ET range to better manage young groves. Rate of water application should also consider hydraulic conductivity of the soil, so that systems such as drippers can be adjusted to minimise area of soil surface wetted and losses through soil evaporation.

1. Understanding the water use of olives

1.1 Introduction

Olives have been grown in Australia for over a century, yet there is little scientific understanding of how we should irrigate for optimum olive yields. Despite being a parsimonious consumer of soil water, olive trees can increase yield by up to three times more under irrigated regimes. However, over-irrigation can be financially inefficient; predisposes alternate year bearing and infestation with scale insects; and could result in increased percolation and recharge of saline groundwater systems. Unfortunately, there is no consensus on irrigation requirements for olive trees in arid regions and reports of optimum irrigation requirements range from 600 to 1000 mm. These discrepancies probably reflect differences due to management, varieties and environment. It is clear that an understanding of how olives respond to irrigation in our environment is necessary before cost-efficient and environmentally benign irrigation schedules can be developed.

The relationship between applied water and olive yield under Australian conditions could allow informed planning for water resources needed to sustain this emerging industry for the present and for the future. This can only be achieved with properly replicated irrigation trials with mature trees on a homogenous site. Such a trial is not only very costly, but at the time this project suitable groves with mature trees and suitably flexible irrigation systems were not available. Fortunately, a great deal can be understood about olive water-use and olive yield under Australian conditions by monitoring these variables in the selected groves across South Australia. This project has attempted to do this.

This chapter first presents some of the institutional and industrial context of this project, and then a brief review of scientific literature associated with olive water use. The objectives of the project are then listed.

1.2 Background literature

1.2.1 The olive industry

Olive growing in Australia is currently at the stage of attracting great interest and expectations from both small and large investors. Although large areas of mediterranean Australia are ideally suited to the olive tree, early attempts at establishing an industry were unsuccessful. Historically there has been a weak domestic market within Australia because of the tastes of a largely anglo-celtic community. Meanwhile, a significant export market could not be realised because of the large production from Europe with relatively low labour costs.

This has all changed over the last decade. Changes in the domestic market for olive products and the labour markets of traditional olive growing countries have created very favourable conditions for the development of a viable olive industry in Australia. There is currently an estimated 2,500ha of olives across SA, WA, VIC and NSW worth approximately $3 million annually supplying a domestic market. About 80% of this market is of table olives for pickling. However, over the decade from 1983/93 where the import of table olives still rose from 3,400t to 6,700t, while the import of olive oil increased from 5,500t to 17,100t. This 310% increase in total import reflects a very strong and rapid change in consumer awareness of the health benefits of olive oil. The Australian Bureau of Statistics estimates that at the current rate of demand, the import value of olive oil will rise to $200 million by the year 2000 (Booth and Davies, 1995).

The great opportunity for an Australian olive industry lies in not only this increased domestic demand, but also because, with mechanical harvesting, we can now compete with the traditional producers in terms of production costs. A very lucrative export opportunity exists if a sufficiently large and organised industry can be established. RIRDC has already acknowledged this opportunity by sponsoring European study tours (Hobman 1994a) and a preliminary economic study (Hobman 1995), and HRDC has also commissioned a study on olive cultivars (Archer 1996).

In the last few years, we have seen the establishment of an Australian Olive Association in 1994 (http://www.australianolives.com.au) with up to 34 regional grower networks and the launching of a national industry journal (The Olive Press). There is a wide spectrum of investors ranging from individuals managing small hectare cottage-industry concerns to those interested in diversifying their sources of retirement income. Others include both dryland and irrigated farmers in search of diversifying their business, and finally, international agribusiness concerns (Burr, 1997).

The potential for expansion of an olive industry is great. To satisfy the Australian demand for oil and table olives the current 2,500 ha under groves need to expand to 24,400 ha rainfed (500mm); alternatively, 11,300 ha of irrigated groves will be required (Hobman 1994b). Evaluation of the cost efficiency of irrigating olives requires not only knowledge of the relationship between applied water and yield, but also the cost of irrigation water, which in South Australia may range from about \$0.05/KL to \$0.90/KL depending on a grower's access to water.

1.2.2 Scientific understanding of water-use by olives

Water-use by olives has been studied for many years (eg Spiegel, 1955), but the last decade has greatly improved our understanding of the physiological response, including root growth and function, by olives to water stress and to various irrigation techniques. These responses include exchange of water vapour and carbon dioxide through apertures on leaf surfaces, termed stomata, which ultimately determine olive and oil yields. Several attempts have been made to determine appropriate irrigation schedules and also of water application for optimum olive and oil yields. However, there is limited local research in Australia to ascertain the degree of the relationship between water use and yield needed to confidently devise appropriate irrigation schedules for our conditions.

The olive tree is adapted to dry conditions and able to produce some olives, albeit of low quality, even under extreme water-limited environments. The small leaves of olives are thick and leathery with waxy cuticular upper surface, while the lower surface is hairy and contain sunken stomata all of which are features evolved to reduce water loss (Beede and Goldhamer 1994). In addition, the water content of olive leaves is very low even under non-stressed conditions compared with other Mediterranean species; e.g 1.56 g of H_2O/ dry matter compared with 5.8 g/g for fig and 5.9 g/g for grape (El-Rahman et al. 1966). Also, the xerophytic nature of olive trees is also associated with its root structure. For instance, the vessel lumina of xylem cells are small (half that of grapes) ensuring low hydraulic conductance (Salleo et al., 1985; Larsen et al. 1989). One consequence of this is that olive trees prevent excessive water loss on days of high water demand by closing their stomata soon after mid-morning (Fernández et al., 1997).

The olive tree is indeed a parsimonious and cautious user of water. This was elegantly illustrated by Moreno et al (1996) in their study of root sap flow of 'Manzanillo' olive trees. A well-watered tree flood irrigated with 730L of water, maintained a daily transpiration rate of 1.65mm^3/mm^2 of leaf area for only 3 days after irrigation when it consumed 110L. After this time, the tree limited rate of transpiration to well below the potential predicted by the Penman-Monteith equation. Meanwhile an unirrigated tree used water at a daily rate of 0.78 mm/mm^2, but which increased 1.12mm/mm^2 following an irrigation of 870L. The later was unable to recover its leaf water potential following wetting due to inability to refill cavitated vessels. These studies suggest that olive tree, once excessively stressed, may fail to fully recover and transpire at their potential rate.

Several schemes have been designed to estimate water requirement by olives. For example, the irrigation requirements of olives are estimated to be about 30% that of prunus and 40% that of citrus species (Bongi and Palliotti 1994). The common method of determining olive water requirements relies on the crop factor K_c (ie ratio of crop water use to potential evaporation) or related methods using pan evaporation (E_p). Doorenbos and Kassam (1986) state that olives are best irrigated using K_c of between 0.4 and 0.6. Several works have attempted to refine this by verifying the water-use of olives to establish K_c for their local conditions, and to characterise relationship between olive yield and irrigation.

Due to large diversity of rainfall, microclimate and soils of olive growing areas, annual water applications could range from 180m^3/ha to 2,600m^3/ha (Gucci and Tattini 1997). In Italy for example, Deidda et al (1990), found the highest yield by 'Manna' table olives when irrigation was determined using a K_c of 0.66. In Greece, however, Michelakis (1990) found no difference in yields of 'Kalamon' and 'Amfissis' table olives irrigated at K_c of between 0.3 and 0.6, equivalent to 260 and 570mm of applied water, respectively. Generally, any water supply through irrigation, above that through rainfall, tends to increase olive yield (Patumi et al., 1999; Serano, 1998). In Israel, Lavee et al. (1990) showed that irrigations of 75, 150 and 200mm in one , two and three irrigations during the season were equally effective in achieving yields by 'Souri' olive trees above rainfed conditions. Most recently, Goldhamer et al (1993, 1994), in California, applied a range of 8 irrigation regimes on 'Manzanillo' olive trees based on K_c of between 0.16 and 0.85 resulting in mean seasonal irrigations of between 232 and 1016mm. They found that there was no significant irrigation-related water stress within the K_c range of 0.65 to 0.85. Although, another study with mature trees irrigated at or below K_c 0.65 found that the trees were still under water stress based on their predawn leaf water potential, ant it was recommended that olives be irrigated based on K_c of 0.75 in California (Beede and Goldhamer 1994).

There is a dearth of scientific information research on water use and irrigation requirements of olives in Australia. Currently, the best a grower can do is use information based on American and European work. However, the values from these regions need verification in Australia to be meaningful for our industry. To do this requires a fully replicated study of water use and olive yield to be meaningful. Unfortunately, such study would require a level of funding that is not readily available. Currently, it would also be very difficult to locate a modern grove with sufficiently mature trees and flexible irrigation system to carry out such an experiment. Fortunately, a survey based on direct monitoring of water balance components of a range of groves will greatly contribute to our understanding of how olive trees use water under Australian conditions. In the current study, water-use and olive yield were determined for selected groves over two seasons. This involved measurements of soil water, olive yield and canopy size, and calculations of transpiration through the olive canopy.

1.3 Objectives of this study

This study was designed to characterise water-use by olives grown on a range of soil types and management practices across the southern district of South Australia. The main aim was to understand the water required for optimum olive production by olives in this region and how the findings can be applied to other olive growing areas of southern Australian. Specific aims were to determine:

1. seasonal water-use or evapotranspiration (ET) and the amount partitioned to transpiration by the trees;

2. the relationship between olive yield and water use efficiency;

3. and how the groves could be more efficiently managed.

2. Monitoring methodology

2.1 Project outline

This project monitored water-use and olive yield in a range of irrigated and rain-fed olive groves between September 1999 and May 2001 in South Australia. Four mature groves on different soil types and management practices were chosen at Waikerie, Two Wells, Balaklava and Greenock for the study. The water-use was estimated from soil water balance for all the groves. This involved monitoring soil water with a neutron-moisture, and water input through rainfall and/or irrigation. Water uptake directly by the trees or transpiration was calculated at all sites. The yield of olives from all the monitored trees was recorded and the broad relationships between water use and yield were described.

2.2 Description of the olive groves monitored

2.2.1 Site selection

The four olive groves described in this section were located after an exhaustive process. Initial contacts with many South Australia olive growers were made through the agency of the industry group Olives SA. While there was no problem finding growers who were kindly disposed to research, it was very difficult to find groves that met the specific requirements of:

- mature (>10 years old), healthy olive-bearing trees
- located on relatively flat ground so that run-off would not confound water balance estimations
- having relatively deep soils with no confounding geological or groundwater features

The four sites covered different evaporation regimes yet within reasonable distance of Roseworthy Campus.

Although there has been an explosion of interest in olive growing in recent years, most growers associated with Olives SA had new, non-bearing groves. Growers having groves with mature bearing trees were of Greek and Italian background and not associated with Olives SA. Contact was made with these growers through word-of-mouth or by just pulling into a driveway next to a suitable looking grove by the roadside. Eventually, agreements were made with six growers from Pt. Germein to Palmer (near Murray Bridge), but only four groves were monitored for the two years because of change in tenure and grove management. Their approximate positions are indicated in Figure 1 and their features are described below.

2.2.2 Site details

Waikerie (34^{o} 9’ S, 140^{o} 0’ E)
This grove was established in 1988 with cultivar Kalamata planted at a spacing of 8 x 5 m. The soil on the site was a calcarosol with a deep sandy A horizon on a gently sloping (about 3%) terrain. The grove was irrigated with micro-sprinklers that supplied approximately 170 litres an hour. The trees were minimally pruned in spring, between September and October, every year. The groundcover consisted of annual ryegrass (*Lolium rigidum*) and some weeds.

Two Wells (34^{o} 34’ S, 138^{o} 30’ E)
The soil here was a sandy loam over clay (calcarosol) and planted in 1977 with olive cv. Verdale was planted in 7 x 7 m grid. The grove was drip-irrigated with each tree supplied with four drippers. Tree pruning was open vase, while the ground area between the tree rows was regularly sprayed with contact herbicide. Thus, the grove was mostly bare of vegetation during most of the growing season.

Figure 1 Location of the four sites

Greenock 1 2

Two Wells 3 4

Balaklava 5 6

Waikerie 7 8

Photos 1 – 8 Site photos

Balaklava (34^o 7' S, 138^o 22' E)
This was located on a Hilltop position with a gently undulating terrain, and was planted with var. Kalamata around 1970 in 5 x 10.5 m rows. The grove was drip-irrigated with each tree supplied with two drippers that supplied water at approximately 10 litre per hour. The soil is a calcic chromosol and has a contrasting textural profile consisting of Clay loam A-horizon over a clayey B-horizon that contains calcium carbonate. The groundcover consisted of unmanaged winter weeds that were green manured in early spring (September) and then later cultivated leaving the ground bare of vegetation.

Greenock (34^o 27' S, 139^o 0'E)
This is a rainfed grove that was established around 1970 when the olive trees of unknown cultivars were planted in 5 x 15 m rows. The soil type had a textural contrasting profile consisting of a clay loam A-horizon over a silty clay B-horizon (red chromosol) on a gently sloping (5%) terrain. The groundcover consisted of unmanaged weeds of native grasses and legume pastures.

Further information on the sites is tabulated in Appendix 1.

2.3 Measurements

2.3.1 Soil water and evapotranspiration

Soil water (*S*) was measured using a neutron moisture probe (Campbell Pacific Nuclear model 503DR) to monitor preinstalled aluminium access to the depths of between 1.8 and 3.0 m depths depending on the site. Three or four tubes were installed around three trees randomly selected at each site in such a way to accommodate tree density and inter-row management for each site. The number and placement of the tubes for each site are presented diagrammatically in Appendix 3. The tubes were monitored at least once a month between early September and end of May. Each tube was read at 0.2 m depth intervals down to 3.0 m depth. Evapotranspiration (ET) or water-use for any time interval (*t1* to *t2*) was calculated as:

$$ET = \left(S_{t1} - S_{t2}\right) + \sum_{t1}^{t2}(R + I) \qquad (1)$$

where *R* and *I* are, respectively, rainfall and irrigation. Rainfall data were obtained from weather stations nearest to each site, while irrigation was estimated with several tipping-bucket gauges fitted with loggers (Wavecom Inc., Adelaide) strategically located across each grove. These devices were used along with the farmers' records, where available, to determine water input by irrigation. In all cases deep-drainage and run-off of water were considered to be negligible on account of the terrain, soil type and water input events. The ET at all sites included water used by the olive tress, cover crops, where present, and water loss through the exposed soil surface.

The ratio of ET to evaporative demand (E_o) or crop factor (K_c) was calculated for each of the measurement periods in both seasons. The E_o was calculated from weather data described below.

2.3.2 Transpiration

Transpiration from the olive canopy (*T*) was calculated as (McNaughton and Jarvis, 1983):

$$T = \frac{(\rho Cp/\gamma)Dg_c}{\lambda} \qquad (2)$$

where ρ is density of air (kg m^{-3}), *Cp* the specific heat of air (1.1 kJ kg- ^{o}C^{-1}), γ psychrometric constant (0.066 kPa ^{o}C^{-1}), *D* is the vapour pressure deficit (kPa), λ is the latent heat of vaporisation (2.4 MJ), and g_c is the canopy resistance. All the variables in eqn 2 were derived from the weather data, except g_c which was obtained as the product of LAI and stomatal conductance (g_s), given that olives are hypostomatous. The g_s was calculated as given by Thorpe *et al.* (1980), but was modified to take account of periods of limited water availability:

$$g_s = g^*\left(\frac{1-\alpha D}{1+\beta / R_p}\right)^* Z \qquad (3)$$

in which g* is the reference conductance for plant well suppled with water (10 mm s^{-1}), α and β are empirical parameters whose values were set, respectively, at 0.2 kPa^{-1} and 75 µmol m^{-2} s^{-1} (Moreno *et al.*, 1996), R_p is photon flux density taken as half of the incident total radiation (R_s) measured at the weather station [R_s (W m^{-2}) ≈ 1.8Q_p]. We scaled the stomatal conductance with *Z*, which is the ratio of water stored in the profile at anytime to the maximum water stored in the same profile observed during the study period. This was introduced to account for reductions in canopy conductance at low levels of soil water availability, and is consistent with the findings by Giorio *et al.* (1999).

Potential transpiration (T_p) was defined as maximum rate of water loss from the canopy in the absence of water-stress, and was taken to be equivalent to the equilibrium evaporation, assuming the process is driven almost entirely by energy supply (McNaughton, 1976):

$$T_p = \frac{s[i(R_n - G)]}{s+\gamma} / \lambda \qquad (4)$$

where *s* is the slope of saturation vapour pressure–temperature curve (kPa $^{o}C^{-1}$), *i* is the fraction of radiation intercepted by the olive canopies, R_n is net radiation (MJ m^{-2}), and *G* is soil heat flux (MJ m^{-2}). Since the canopy was not complete available energy (R_n – G) was scaled with the fraction of sunlight intercepted by the canopy (*i*, described later). Values for G were estimated as given by Meyer et al. (1987):

$$G = 0.377(T_m - T_{av}) \qquad (5)$$

where T_m is mean temperature for the day and T_{av} is the mean temperature for the preceding three days.

2.3.3 Sapflow in olives

Transpiration was also determined by monitoring sapflow with heat-pulse sensors (Greenspan Technology, Warwick, Australia) at Waikerie during the 2000-01 growing season only. Hatton and Vertessey (1990) and Hatton et al. (1990) have presented the principles and assumptions for the application of this technique. The system was installed in September 1999 in the three trees around which soil water was monitored. Each monitoring unit consisted of a pair of probe-sets and a data logger, and powered with a 12-volt lead-acid battery. Each probe-set consisted of a heater located between a pair of temperature sensors. The probe-sets were installed at 15 mm depth into olive trunk with the two sets separated by a distance of at least 0.8 m. The trunk, including probe-sets, was insulated with thick aluminium sheets. Sapflux density was logged hourly, the data were down-loaded weekly and processed with SAPCAL software supplied by the manufacturers. SAPCAL required sapwood diameter, and wood and water fractions of the trunk, all of which were determined as described for grapevines (Yunusa *et al.*, 2000). All other procedures on installation, data logging and analysis were similar to those described for grapevines by Yunusa *et al.* (1997a). Total sapflow were determined on an hourly basis and then scaled to the land area allocated to each tree so that transpiration in depths of water (T) could be determined using the tessellation method (Hatton and Vertessey, 1990).

2.3.4 Plant canopy variables

The leaf area index (LAI) for the olives was measured on clear days using plant canopy analyser (LICOR-2000, LI-COR, Lincoln, Neb., USA) in February 2000. Each LAI measurement involved a reading from an open area some distance away from the grove, and from several positions within the grove extending between the selected trees, across the area in between, following the protocol reported by Villalobos *et al.* (1995). At the time of LAI measurements, the fraction of ground cover by olives was estimated from the proportion of sunlight intercepted by the canopy (i) determined with a ceptometer (AccuPAR, Decagon Devices, Pullman USA). Ceptometer readings were taken in the open as a surrogate of above canopy reading (I_o) and at several positions within the grove extending between the selected trees and those adjacent which was averaged to give below canopy reading (I_b). Groundcover or i was obtained as:

$$i = 1 - (I_b/I_o) \qquad (6)$$

2.3.5 Olive yield

Olive yield of the monitored trees was measured by complete hand harvest and weighing of olive on a field balance. Estimates of grove yield were made by harvesting a further 9 to 11 trees in a similar manner.

2.3.6 Weather data

Data for key weather variables of radiation, rainfall, minimum and maximum temperatures, and humidity were obtained from weather stations nearest to the respective sites or from the Patched Point Dataset available at cost from the Bureau of Meteorology (http://www1.ho.bom.gov.au/silo/). The E_o was automatically calculated at the weather stations based on the Priestley-Taylor (1972) approach.

2.4 Data analysis

Data collected from each site were analysed separately. Means and standard errors of means were calculated for each of the two seasons studied.

In-line flow meter (tipping bucket rain gauge with logger)

Neutron moisture probe in position

Sap flow equipment under the sisalation around the tree

Photo 9 Instrumentation at the Waikerie site

3. Results

3.1 Seasons

Although weather data were obtained for all the sites, differences in meteorological variables between the four sites were small. To ensure clarity, therefore, averages were calculated for the variables of interest to obtain the average conditions for the whole district (Fig. 2).

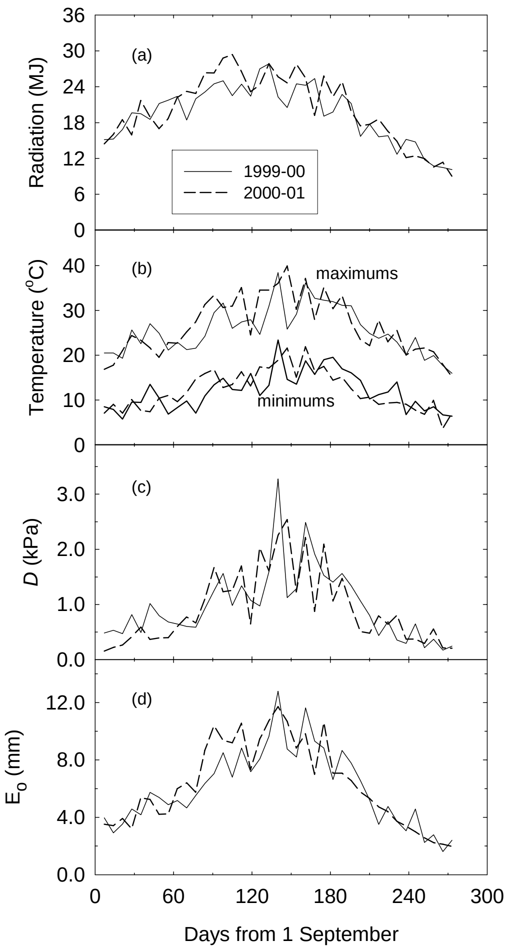

Fig. 2. Weekly averages of daily weather conditions during the growing seasons of 1999–00 and 2000–01 for southern South Australia: (a) solar radiation, (b) minimum and maximum temperatures, (c) vapour pressure deficit (*D*) and (d) potential evaporation (E_o).

All weather variables are consistent with a dry and hot growing season for olives. The seasons experienced mild conditions at the start of the season warming up to daily maximums of around 30°C and very dry when *D* averaged 2.0 kPa and daily average Eo of close to 10 mm. The weather conditions were similar for the two seasons, but the first season of 1999-01 was cooler than the second season of 2000-01. Seasonal averages in 1999-00 were 19.7 MJ for radiation, 18.6 °C for mean temperature, 0.97 kPa for *D* and 5.8 mm for E_o; these values in 2000-01 were 20.2 MJ, 19.2 °C, 1.08 kPa, and 6.3 mm for E_o.

3.2 Plant and water-use variables

There were differences in the water-use between groves consistent with their management and water supply practices. Results from each grove are presented separately below.

3.2.1 Waikerie

Plant canopy and olive yield

The olives at this site produced a LAI of 1.11 and an *i* of 0.52. Thus, almost half of incident solar radiation was transmitted through the tree canopies to the grove floor.

Water input and soil water

In 1999-01 season, there were only 13 weeks that experienced rainfall of at least 10 mm, while irrigation was consistently used in December to supply additional 26 mm (Fig. 3a). Total water-input in this season was 619 mm involving 277 mm of rainfall and 340 mm of irrigation (3.4 ML). There were only four weeks that received rainfall of at least 10 mm in the 2000-01 season (Fig. 3b), but irrigation record was not consistently kept. Rainfall totalled 118 mm, while irrigation totalled 486 mm (3.7 ML). Thus water-input (rainfall and irrigation) in 2000-01 of 555 mm (5.6 MLML) was 11% less than in the first season (Table 1).

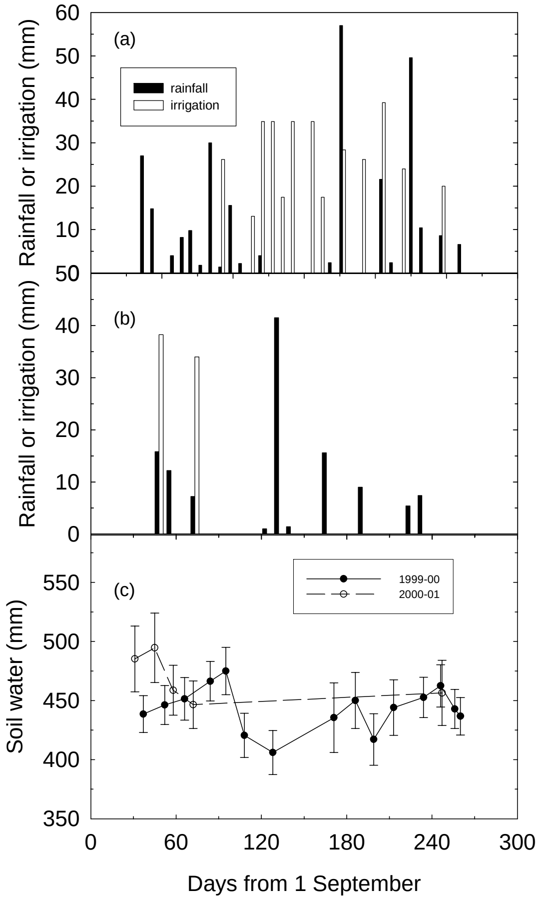

Fig. 3. Water supply and its storage in the soil profile: rainfall and irrigation during (a) 1999-00 and (b) 2000-01 growing season, and (c) water stored in the 3.0 m profile during the two seasons, at Waikerie. Total irrigation between days 70 and 250 in 2000-01 was 414 mm

Water stored in the 3.2 m profile (Fig. 3c) during 1999-01 ranged between a low level of 400 mm, observed in early January 2000, and a high of 480 mm observed earlier in December 1999. Total water stored in the soil was similar for the two seasons except for the profile being wetter at the start of the season in the second season than in the previous season,. The distribution of water in the soil profile when total storage attained highest and lowest values during the study is shown in Figure 4.

This illustrates the pattern of water extraction by the trees. At the highest storage measured soon after irrigation on 5 January (Fig. 4a), there was an exceptionally wet zone in the mid-profile, but soil wetness generally increased with depth. The isolines run largely parallel to each other at all distances from the tree row. In the drier soil profile of 5 January, the various isolines had become deeper at all depths except below 3 m depth, suggesting that maximum depth to which water extraction and possibly root growth occurred did not exceed 3m.

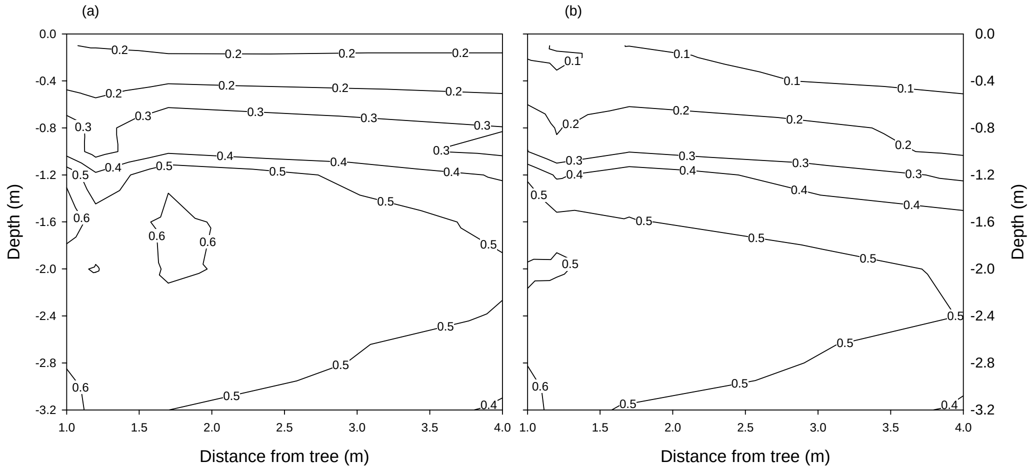

Fig. 4. Distribution of volumetric water content at the (a) wettest profile on 3 December 1999 and (b) driest profile on 5 January 2000 observed at Waikerie.

Crop water-use and crop factor

In 1999-00, ET increased from daily rates of 0.4 mm (16 L per tree) at the start of season in October to 3.9 mm (156 L) in December (Fig. 5a). Rates of ET, however, declined to 2.4 mm during the following 60 days mostly due to reduced irrigation, until after 180 days (February) when the rate increased to approximately 3.1 mm (124 L) for the rest of the season mostly due to rainfall events during this period.

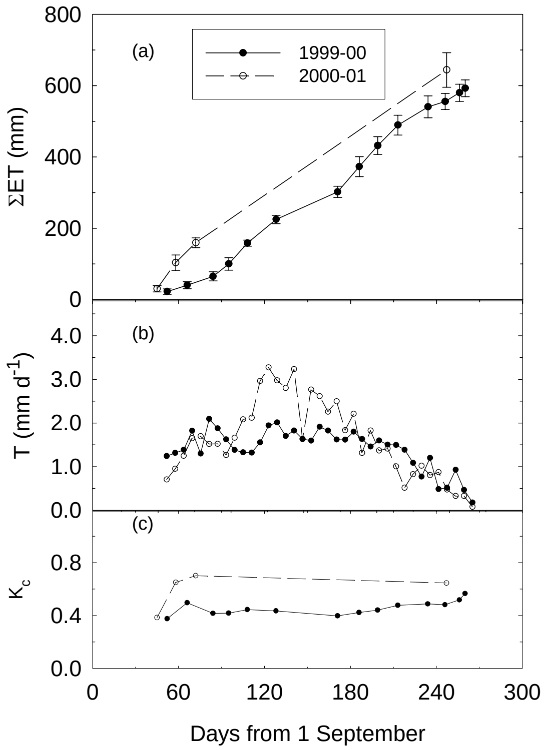

Fig. 5. Water-use from an olive grove during 1999-00 and 2000-01 growing seasons at Waikerie:
(a) cumulative evapotranspiration (ET) and (b) daily rates of transpiration (T), and (c) crop factor. The bars in (a) are standard errors of means.

Trends in rates of ET in the 2000-01 season was similar to that in the first season, but the reduced intensity of measurement in this season did not allow any detailed analysis. Total seasonal ET was 594 mm (5.9 ML) in 1999-00 (Table 1), which was 12% less than the 644 mm (6.4 ML) for the second season. Trends in T or water taken up by the olive trees (Fig. 5b) was similar for much of both seasons except during days 90–180, when daily T in 2000-01 averaged 2.6 mm (104 L per tree) compared to 1.95 mm (78 L) during 1999-00. Total T during the season was 367 mm (15 kL per tree) in 1999-00 and 421 mm (17 kL) in 2000-01. Trends in K_c (Fig. 5c) was largely stable throughout the two growing seasons and produced with average values of 0.37 in 1999-00 and 0.39 in 2000-01 (Table 1).

Table 1. Summary of water-use during the growing season (September–May) for four groves in South Australia: water-input, evapotranspiration (ET), transpiration (T) ratio of T/ET, and the crop factors

Variables[1]		**Waikerie**	**Two Wells**	**Balaklava**	**Greenock**
		1999-00 season			
Water-input (mm)	Rainfall	277	89	375	365
	Irrigation	340	409	159	-
	Total	617	498	534	365
Water-use (mm)	ET (± SEM)	594 ± 26.4	634 ± 21.7	555 ± 16.1	366 ± 12.7
	T	367	484	246	184
	T/ET	0.62	0.76	0.44	0.50
Crop factors	K_c	0.38	0.41	0.33	0.23
	K_t	0.21	0.34	0.15	0.12
		2000-01 season			
Water-input (mm)	Rain	118	153	171	206
	Irrigation	486	371	318	-
	Total	604	524	489	206
Water-use (mm)	ET (± SEM)	644 ± 37.1	669 ± 28.8	491 ± 17.2	267 ± 15.0
	T	421	505	220	177
	T/ET	0.65	0.75	0.45	0.66
Crop factors	K_c	0.39	0.39	0.29	0.23
	K_t	0.25	0.30	0.13	0.11

[1] Growing season taken from September–May, but ET calculation started late in September in some cases.

3.2.2 Two Wells

Plant canopy
The LAI and *i* at this site were 0.99 and 0.40, respectively, and so 60% of sunlight was transmitted below the tree canopies to the floor of the grove.

Water input and soil water
There were several weeks that received small amounts of rain in 1999-00, but only four weeks had a total rainfall of at least 10 mm (Fig. 6a); total rainfall for the season was just 89 mm. Irrigation during the first season was regular at an average weekly rate of 15 mm (0.15 ML) producing a seasonal total of 409 mm or 4 ML (Table 1). The 2000-01 season had a wet start with more than 40 mm rain in the first two weeks (Fig. 6b), but only seven of the remaining 35 experienced rainfall of at least 10 mm. Total rainfall during this season was 153 mm, while irrigation totalled 371 mm or 3.7 ML. Water supply during the two seasons was 498 mm (5 ML) in 1999-01 and 524 mm (5.2 ML) in 2000-01.

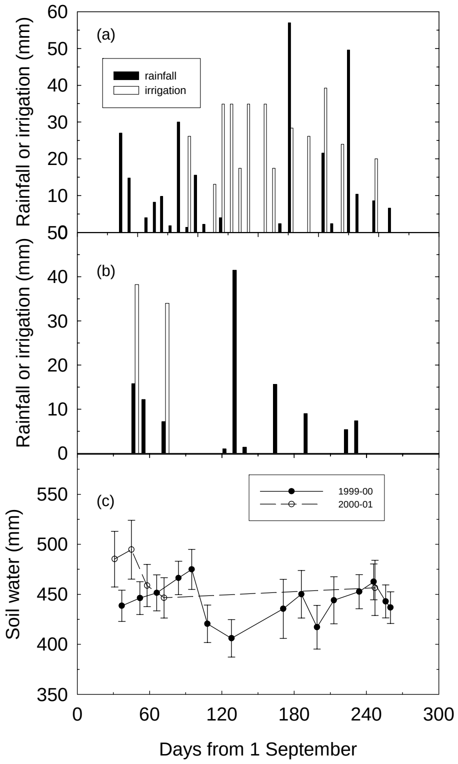

Fig. 6. Water supply and its storage in the soil profile: rainfall and irrigation during (a) 1999-00 and (b) 2000-01 growing season, and (c) water stored in the 3.0 m profile during the two seasons at Two Wells.

Water stored in the 3.0 m profile in 1999-00 declined gradually from the initial value of 300 mm to 240 mm before recovering to a peak of 350 mm following a rainfall event and frequent irrigation (Fig. 6c). Stored water at the start of the season in 2000-01 was similar to that in the previous season, but the 40 mm rainfall within a one-week period after day 45 kept the soil moist, unlike in the previous season.

Maximum storage of soil water during the study was observed following an irrigation around day 155 in 1999-00 and distribution of water in the soil profile was uniform across the grove with isolines running mostly parallel to each other at all distances from the tree (Fig. 7a). Extraction of soil water by the olives was most apparent in the top 1.2 m of the soil profile up to distances of 2.5 m from the tree (Fig. 7b). It appears thus that there was an absence of roots below 2m depth given that the similarity in isoline, remained largely unchanged between the two periods.

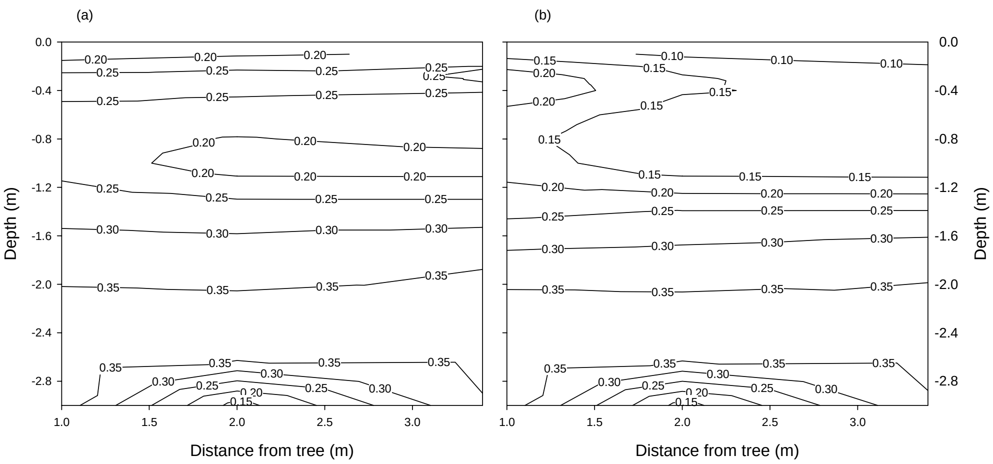

Fig. 7. Distribution of volumetric water content at the (a) wettest profile on 29 September 2000 and (b) driest profile on 4 January 2000 observed at Two Wells.

Crop water-use and crop factor

Soil water was used at a relatively constant rate at this site with ET (Fig. 8a) rate of 2.8 mm per day in the first seven months, but declined to 0.77 mm in the last two months of the season.

ET in the 2000-01 season was similar, almost identical, to the first season, except for the late start in measurement during the former. Total ET (Table 1) for the two seasons were 634 mm (6.3 ML) in 1999-00 and 669 mm (6.7 ML) in 2000-01.

Transpiration (Fig. 8b) during the two seasons was similar, except for higher rates in summer of 2000-01 than of 1999-00; daily averages, respectively, were 2.54 mm (124 L per tree) and 2.02 mm (99 l). Totals for T during the two seasons were 484 mm (20 kl per tree) in 1999-01 and 505 mm (23 kl) in 2000-01 (Table 1).

The K_c (Fig. 8c) oscillated between 0.35 and 0.5, but mostly just below 0.4 in both seasons. Average values for the season were 0.41 in 1999-00 and 0.39 in 2000-01 (Table 1).

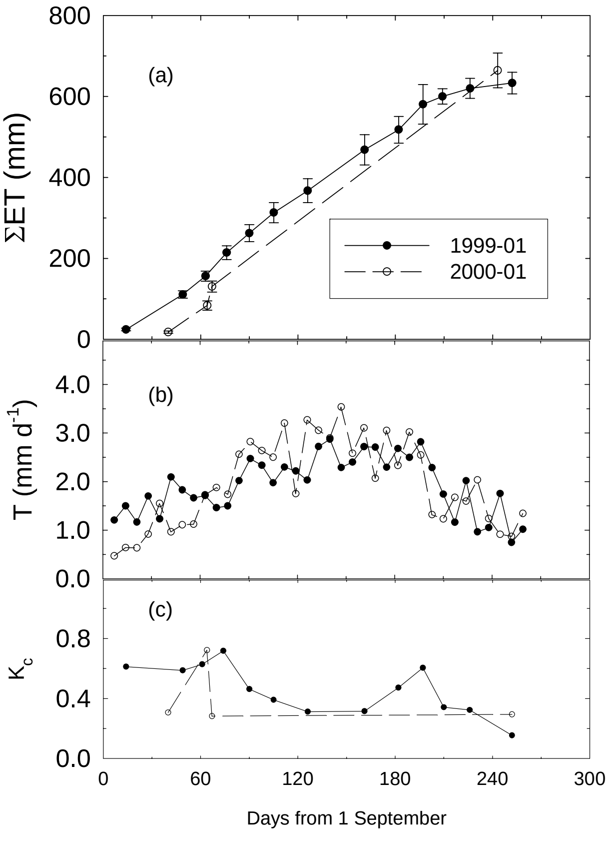

Fig. 8. Water-use from an olive grove during 1999-00 and 2000-01 growing seasons at Two Wells:

(a) cumulative evapotranspiration (ET) and

(b) (b) daily rates of transpiration (T), and

(c) (c) crop factor.

The bars in (a) are standard errors of means.

3.2.3 Balaklava

Plant canopy
Wide spacing at this site meant that both LAI and *i* were low having values of 0.58 and 0.17, respectively. Olive canopies, therefore, did not shade large portions of the grove floor.

Water input and soil water
Rainfall during 1999-00 totalled 378 mm most of which fell in over 13 weeks each of which received at least 15 mm (Fig. 9a). Irrigation during this season was light with water application not exceeding 15 mm in any given week to produce a seasonal total of 159 mm (1.6 ML). There was 85 mm of rainfall in the first 60 days of the 2000-01 season (Fig. 9b) and the total for the season was 171 mm. The frequency of irrigation at the start of this season was lower in the first 120 days, but the amounts applied were larger, than in the previous season. Total irrigation during the second season was 318 mm (3.2 ML). Total water input was 537 mm (approx 5.4 ML) in 1999-00 and 489 mm (4.9 ML) in 2000-01 (Table 1).

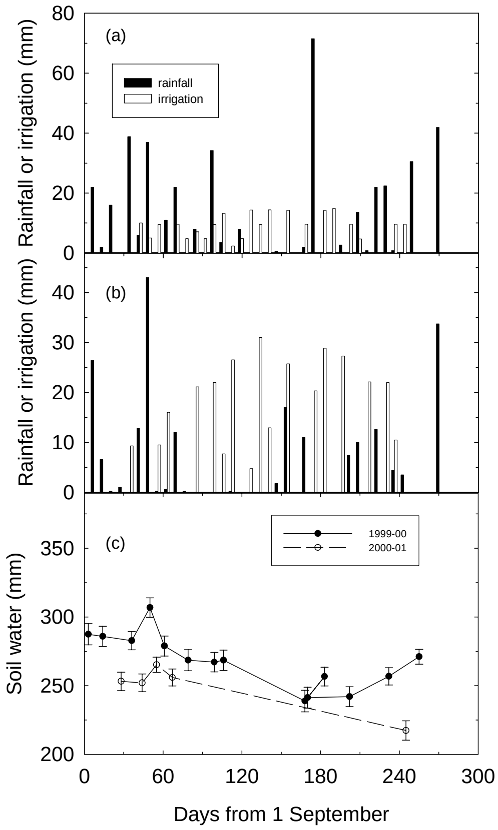

Fig. 9. Water supply and its storage in the soil profile: rainfall and irrigation during (a) 1999-00 and (b) 2000-01 growing season, and (c) water stored in the 3.0 m profile during the two seasons at Balaklava.

In 1999-00, water stored in the 1.8 m profile (Fig. 9c) declined from the high levels observed at start of the season of 280 mm to 230 mm by day 265. In 2000-01, water stored in the soil declined from 250 mm at the start of season to a minimum of 215 mm at the end of the season.

Distribution of soil water (Fig. 10) was consistent with the drip irrigation used in the grove such that at high water content, the profile became drier with distance from the tree (Fig. 10a). The trend in water distribution was reversed for a dry soil (Fig. 10b) indicating a greater extraction of water near the tree. It also appears that water extraction by the olive in this grove might have extended beyond 1.8 m considering the disappearance of 0.40 isoline seen in October (Fig. 10a), but which had disappeared in the dry profile in May (Fig. 10b).

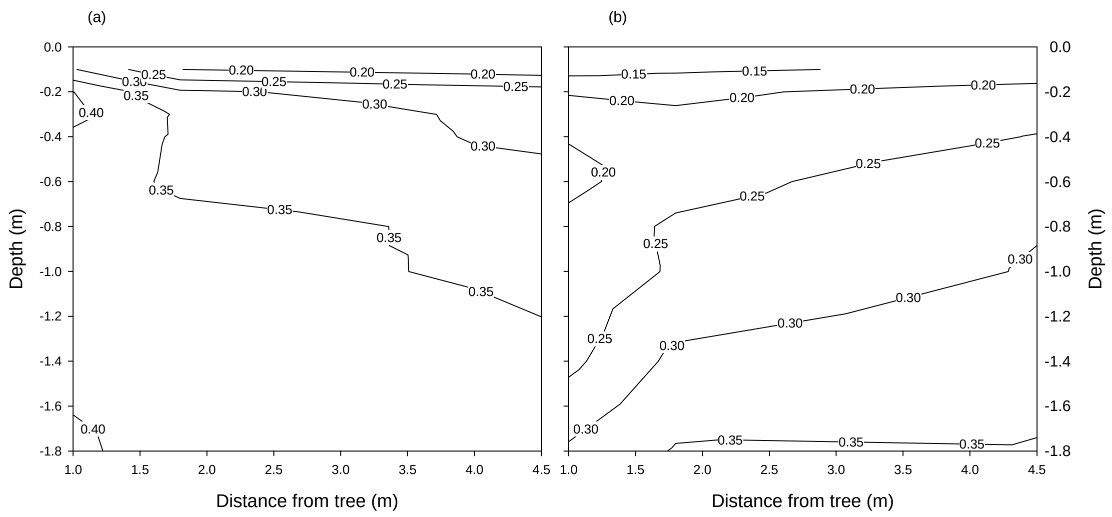

Fig. 10 Distribution of volumetric water content at the (a) wettest profile on 20 October 2000 and (b) driest profile on 2 May 2002 observed at Balaklava.

Evapotranspiration and crop factor

The ET for both seasons was similar, and except for the late start to monitoring in 2000-01, the rate of crop water use would be almost identical (Fig. 11). Daily rates for ET averaged 2.7 mm in the first 120 days, followed by mid-season (days 120–180) depression to 2.4 mm, and then finally to 2.0 mm towards the end of the season.

ET for the growing season was 555 mm (5.6 ML) in 1999-01 and 491 mm (5.0 ML) for 2000-01 (Table 1). Except for some brief differences during the first 60 days when the daily rate was 0.91 mm (48 L per tree) in 1999-01 compared to 0.74 mm in 2000-01, T (Fig. 11) was generally similar between 1999-00 and 2000-01. Rate of T attained peak values of about 1.25 mm (66 L per tree) per day between days 120 and 180, before declining to just 0.61 mm (32 l) towards the end of the season. Total T during the two seasons was 246 mm (13 kl per tree) in 1999-01 and 220 mm (12.6 kl) in 2000-01 (Table 1). K_c was mostly around 0.2 except during rainy periods such as at the start of the seasons when it could be as high as 0.6 (Fig. 11c). Seasonal Kc was 0.34 in 1999-00 and 0.29 in 2000-01, while that based on T averaged 0.14 for both seasons (Table 1).

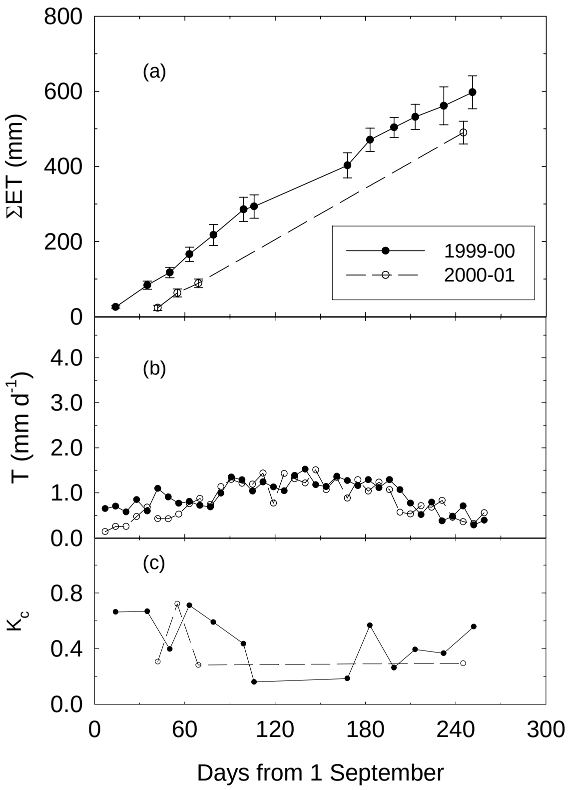

Fig. 11 Water-use from an olive grove during 1999-00 and 2000-01 growing seasons at Balaklava:
(a) cumulative evapotranspiration (ET)
(b) daily rates of transpiration (T),
(c) crop factor. The bars in (a) are standard errors of means

3.2.4 Greenock

Plant canopy

The olives in this grove produced a LAI of 0.60 and an *i* of 0.41, reflecting the wide rows used at this site.

Water input and soil water

This site was rainfed and rainfall was frequent in the first three months of the 1999-00 season, including the five of the 10 weeks that received total rainfall of more than 20 mm each in both seasons (Fig. 12a). The mid-summer period (days 120– 180) was particularly dry, but the end of the season was relatively wet. The season was drier in 2000-01 (Fig. 12b), especially in mid-summer was longer, extending from day 70 to day 160, than in the first season. Total rainfall was 365 mm in 1999-00 and 206 mm in 2000-01.

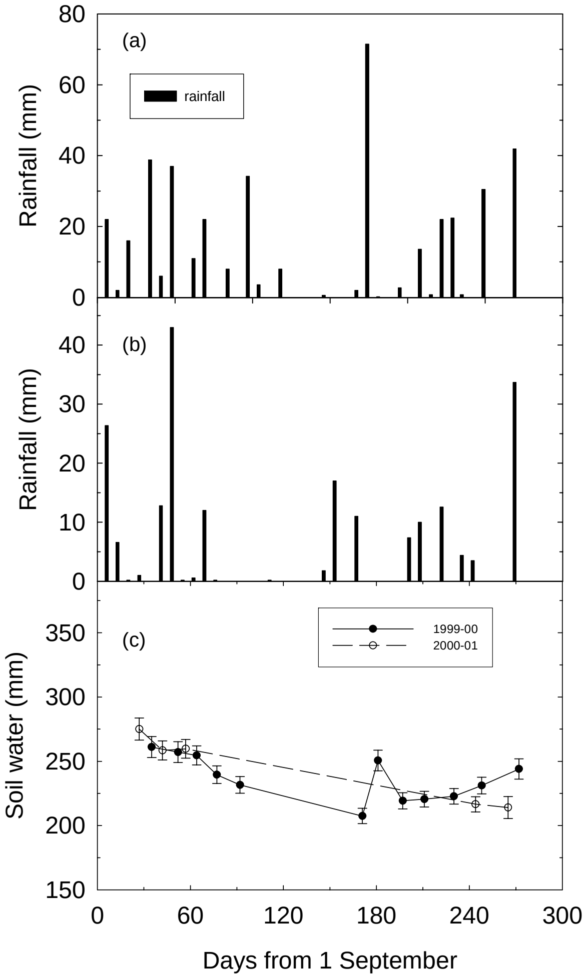

Fig. 12. Water supply and its storage in the soil profile: rainfall during (a) 1999-00 and (b) 2000-01 growing season, and (c) water stored in the 3.0 m profile during the two seasons at Grenock.

Water stored in the soil over 3.2 m depth in the season (Fig. 12c), declined from a mean of 270 mm to about 230 mm at the end of the season. The increase in storage at day 175 in 1999-00 was a response to the rainfall of 70 mm at this time. The soil profile was much drier at a distance of 1 m from the tree, where there were distinct depression in isolines between 1 and 2 m depths (Fig. 13a). Distribution of water in the dry soil (Fig. 13b) indicated that the trees extracted water up to a depth of 2.5 m, but at distances beyond 2.5 m much of the extraction was largely limited to the top 1 m layers of the soil.

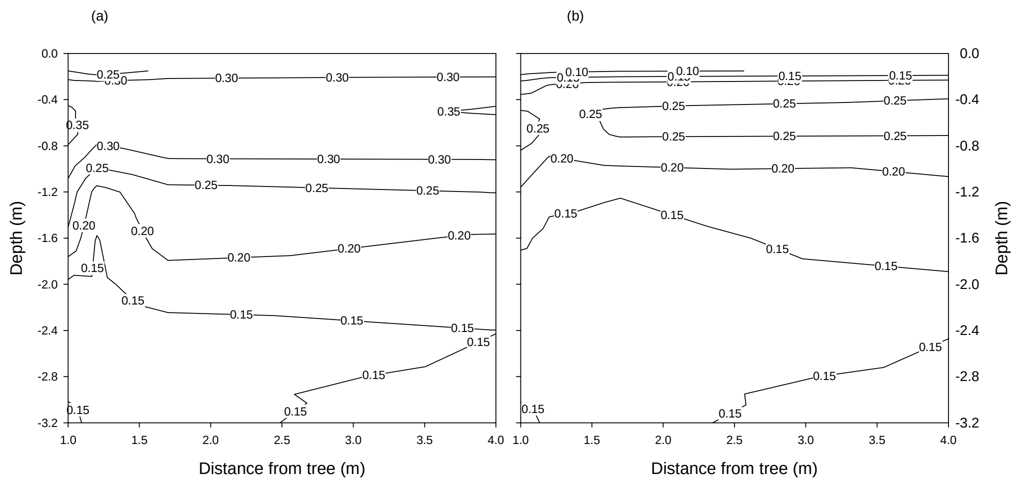

Fig. 13. Distribution of volumetric water content at the (a) wettest profile on 27 September 2000 and (b) driest profile on 18 February 2000 observed at Greenock

Evapotranspiration and crop factor

Water-use in both seasons was virtually the same up to day 180, when daily ET was 1.33 mm (Fig. 14a). Consistent with more rainfall during the terminal period in 1999-00 (after day 180), however, daily rate of ET was 1.30 mm, which was 83 % higher than 0.71 mm for the same period in 2000-01. Total ET for the two seasons was 366 mm (3.7 ML) in 1999-00 and 267 mm (2.7 ML) in and 2000-01 (Table 1). Water used directly as T by the olives (Fig. 13b) was similar in both seasons, although T was 0.72 mm per day during the first 60 days in 1999-00, which was twice the rate for the same period in 2000-01. Totals for T during the two seasons were 184 mm (13.7 kL per tree) in 1999-01 and 177 mm (13.2 kL) in 2000-01 (Table 1).

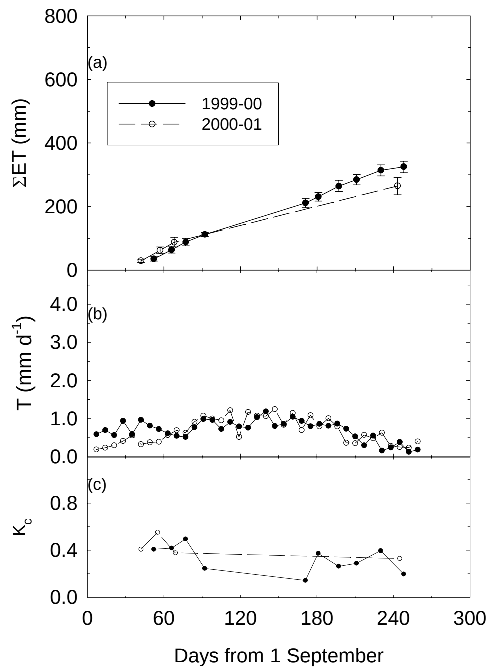

Fig. 14. Water-use from an olive grove during 1999-00 and 2000-01 growing seasons at Greenock:

(a) cumulative evapotranspiration (ET) and
(b) (daily rates of transpiration (T), and
(c) crop factor.

The bars in (a) are standard errors of means

3.3 Summary of water-use for all sites

Input of water in both years was highest at the sprinkler-irrigated grove at Two Wells, where both ET and Kc were highest, while the two variables were lowest in the rainfed grove at Greenock (Table 1). The grove at Two Wells also used more water in T than any of the other groves in both years (Table 1). Direct uptake of water by the olives at Two Wells was always at least 20 % higher than at Waikerie, even though both groves produced similar magnitude of plant canopy that was almost twice that of the rainfed grove at Greenock.

Water required during the growing season by a typical grove in the southern districts of South Australian was estimated based on maximum T expected from a canopy of a given size using eqn. 1, and assuming that ET/T observed at Waikerie roughly applied across the region. Estimates for monthly water requirement between November and January range between 30 and 173 mm, ie up to 1.7 ML per month depending on the size of the trees (Table 2). Accordingly, K_c ranged between approximately 0.10 and 0.70. The amount of water required for the whole season was approximately between 182 mm (1.8 ML) for groves with small trees and 1084 mm (about 10.1 ML) for groves with large trees. The LAI for the various light interception levels presented in Table 2 were estimated from a regression of LAI on *i* measured at the four groves to provide another measure of tree size.

3.4 Diurnal trends in transpiration using sapflow at Waikerie

It is good practice to test the validity of transpiration obtained with sapflow measurements, rather than rely entirely on experiences elsewhere (e.g. Moreno *et al.*, 1996). This is because of possible influences of physiological and anatomical differences between varieties in the current studies and those used in the previous studies elsewhere. In the current study, the validity of sapflow data was confirmed by comparing daily T values obtained through this method with those determined by micrometeorology (eqn. 2) for the 1999-00 season:

$$T_{sap} = 0.33 * T_{met} + 38.5 \qquad n = 190 \qquad r^2 = 0.54 \qquad (7)$$

Diurnal trends in T (Fig. 15) showed that the olive trees transpired rapidly soon after sunrise reaching peak values just before noon, after which the rate remained largely stable until around 1500 hrs before declining rapidly to base levels just after sunset. Although the trends in T for the two periods featured were similar, peak values were larger and attained earlier during days 148–151 than in the earlier period of days 110–113. Peak rates of T of about 6 L during the second period were up to 55% larger than for the first period.

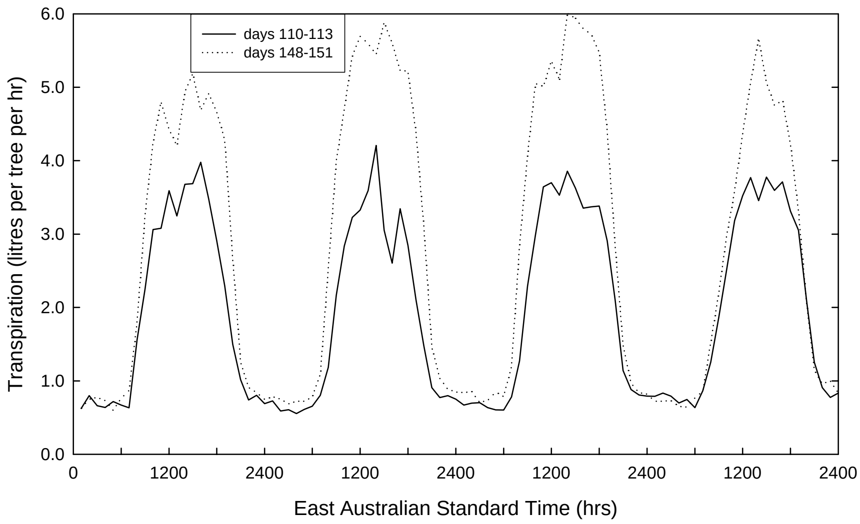

Fig. 15. Diurnal trends in transpiration by olives monitored with heat-pulse sapflow systems during days 110–113 (20–23 December 1999) and days 148 –151 (28–31 January 2000) at Waikerie during 1999-00 growing season.

Table 2. Estimates of upper limits for monthly water-requirements estimated for a drip-irrigated grove with trees that shade the soil surface to different degrees in southern South Australia [1]

Ground cover (%)	Approx olive LAI	Water-use Variable	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Seasonal total or average
10	0.38	ET (mm)	14.2	18.4	24.5	29.3	28.6	24.8	21.8	13.0	7.5	181.9
		K_c	0.12	0.12	0.12	0.11	0.10	0.10	0.12	0.12	0.11	0.11
20	0.55	ET (mm)	28.3	35.2	46.9	58.5	57.2	49.6	41.9	27.0	15.0	359.6
		K_c	0.24	0.23	0.23	0.22	0.20	0.20	0.23	0.25	0.22	0.22
40	0.88	ET (mm)	56.6	70.4	93.8	114.4	114.4	99.2	83.7	52.9	30.6	716.1
		K_c	0.48	0.46	0.46	0.43	0.40	0.40	0.46	0.49	0.45	0.45
60	1.55	ET (mm)	85.0	107.1	142.8	172.9	171.6	151.3	127.4	79.9	45.6	1083.5
		K_c	0.72	0.70	0.70	0.65	0.60	0.61	0.70	0.74	0.67	0.67

[1]Estimates based on assumptions for drip-irrigated groves with no groundcover; for full cover-irrigated groves the requirement could be up to 50% higher than those in the table depending on whether there is groundcover.
At low end of the scale (5% cover), it is assumed that majority of water will be used by the trees; values are not expected to be substantially higher for covers exceeding 60%.

The mean weather conditions for the two periods were largely similar in terms of temperature (17.9 °C for days 110–113 vs 21 °C for days 148–151) and E_o (8.7 mm vs 8.9 mm), but differed in radiation (21 MJ vs 27 MJ) and D (0.9 kPa vs 1.2 kPa). The second period was, therefore, warmer and less humid than the first. Also, stomatal conductance (g_s) measured at the same site on day 151 declined from morning high of close to 3 mm sec^{-1} to less than 1.5 mm sec^{-1} by 1500 hrs (Fig. 16). Whereas D, increased gradually from the low values of about 1.5 kPa in the morning to peak values of 2.8 kPa around 1500 hrs before it began to decline to 2.0 kPa by 1800 hrs (Fig. 16).

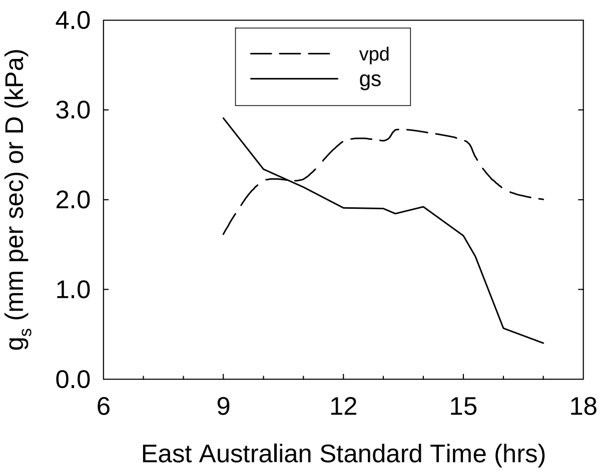

Fig. 16 Diurnal trends in stomatal conductance (g_s) measured with a porometer, and vapour pressure deficit (D) on day 151 (10 May 2000).

3.5 Olive yields and water-use efficiency

Olive yield in 1999-00 was highest at Two Wells, where the amount of olive produced was at least seven times greater than at any of the other sites (Table 3). The yield was particularly low at Waikerie in this year, partly because of the local strong winds that led to loss of significant amounts of olives before they were picked, but the season might have been a low-yielding or "off" year for this grove.

In 2000-01 Waikerie produced the highest yield that was more than twice that achieved at Two Wells and at least 12 times the yields at either Baklava or Greenock. In both years, olive yields at Balaklava and Greenock were within 10% of each other. At all sites, the yields were lower in 2000-01 than in 1999-00, except at Waikerie where olives were lost in the first season.

The amount of olives produced per unit of water used as ET (WUE_{et}) in 1999-00 was lowest at Waikerie (Table 3), where 2.2 kg of olives was produced per mm of ET per hectare. This value was just 7% of that found at Two Wells. In the following year the WUE ranged between 3.2 kg ha^{-1} mm^{-1} at Balaklava and 32.1 kg ha^{-1} mm^{-1} at Waikerie. Data in Table 3 shows that for Waikerie in 2000-01 and Two Wells in 1999-00, the olives produced an average of 3177 kg per megalitre (or 100 mm) of water used as ET, compared to an average of just 500 kg obtained for either Balaklava or Greenock.

The efficiency of water-use for olive production based on T (WUE_t) was lowest at Balaklava in both seasons, but similar at Waikerie and Two Wells in 2000-01; the loss of olives at

Waikerie in 1999-00 also resulted in low WUE_t (Table 3). When these WUE_t values were averaged for the two seasons, they showed that for every litre of water used in ET, the olive tree produced between 0.4 and 2.1 g of olives (Table 4). Corresponding values for WUE_t ranged between 0.9 and 2.8 g (Table 4).

Table 3. Olive yield and water-use efficiency (± standard error of means, SEM) for fresh olive production based either on evapotranspiration (WUE_{et}) or on transpiration by olives (WUE_t).

Grove	**1999-00**	**2000-01**
	Olive yield (kg ha^{-1})	
Waikerie	1302 ± 593	20694 ± 730
Two Wells	19921 ± 2747	7752 ± 861
Balaklava	2750 ± 589	1580 ± 377
Greenock	2554 ± 669	1626 ± 630
	WUE_{et} (kg ha^{-1} mm^{-1})	
Waikerie	2.2 ± 0.25	32.1 ± 3.23
Two Wells	31.4 ± 3.81	11.6 ± 4.54
Balaklava	4.7 ± 0.59	3.2 ± 1.46
Greenock	7.0 ± 0.77	6.1 ± 2.38
	WUE_t (kg ha^{-1} mm^{-1})	
Waikerie	3.6	49.2
Two Wells	41.8	15.4
Balaklava	11.1	7.2
Greenock	13.9	9.2

[1] Substantial amounts of olives lost due to local strong winds

Table 4. Efficiency of olive production by individual tree based on water used (litres) as either evapotranspiration (WUE_{et}) or transpiration (WUE_t) averaged over the two seasons

Grove	**WUE_{et} (g l^{-1})**	**WUE_t (g l^{-1})**
Waikerie	1.8	2.8
Two Wells	2.1	2.8
Balaklava	0.4	0.9
Greenock	0.7	1.2

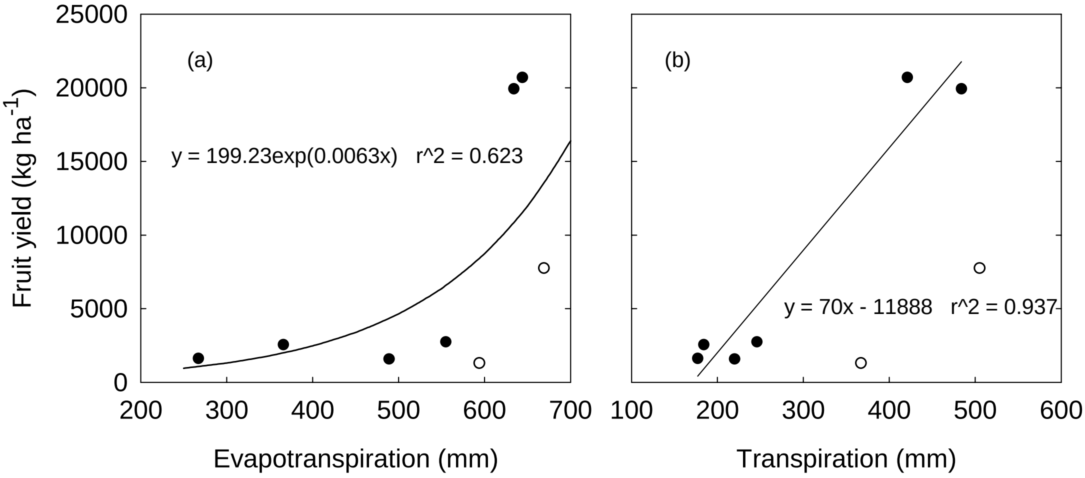

Fig. 17. Relationship between fresh olive yield and either (a) evapotranspiration (ET) or transpiration (T) for a range of groves in south Australia in 1999-00 and 2000-01 growing seasons. The open symbols are outliers excluded from the regressions.

To determine the relationship between yield and water-use for the region, the data from the four groves were pooled in regression analyses, but excluding data for 1999-00 at Waikerie and for 2000-01 at Two Wells as outliers. Exclusion of the low yields at the two groves was justifiable on account of the observation by Serrano (1998) that olives are not particularly responsive to water supply in "off" years. Figure 17a shows an exponential increase in yield with seasonal ET values above 600 mm, below this threshold there was no significant response in olive yield to ET. The relationship between yield and T, showed a linear increase in olive yield with T (Fig. 17b).

4. Discussion

4.1 Olive yield and water-use efficiency

4.1.1 Yield fluctuations

Olive yield fluctuated between the two years of study (Table 3), especially at Waikerie and Two Wells. Reasons for these fluctuations in yields of up to 250% at Two Wells and 16 times at Waikerie were not clear. Except at Waikerie, where there was olive loss in 1999-00 due to local storms as explained earlier, the general decline in olive yield in 2000-01 could be associated with seasonal effects. Differences in the olive yield between seasons bore no association with water-supply to the groves, which remained largely similar between the two seasons except for an average increase of 7% in 2000-01 at Waikerie and Two Wells (Table 1).

Olives have been reported to alternate seasons of high yields ("on" years) with those of low yields ("off" years), and the yield during the "off" years can be reduced by as much as 90% relative to those of the "on" years (Serrano, 1998). Sibbett (2002) discussed a range of possible factors that cause this phenomenon, which include irrigation and time of harvest. This alternating low and high yielding response may be a feature of many olive crops, since a similar seasonal response in olive yields has been observed in grapevines (McCarthy, 1995, Yunusa *et al.*, 1997b). Declines in yield at both Balaklava and Greenock in "off" year did not exceed 55%, probably because the low input management practices over several decades at these groves had conditioned the trees to producing low, but stable yields. Serrano (1998) argued that once olives are adapted to a certain water-supply regime, it takes quite sometime before the trees become responsive to new water-supply regimes.

4.1.2 Response to ET and T

Olive yields were responsive to the amounts of water used as either ET or T above threshold value (Fig. 17). The magnitudes of both ET and T were consistent with the amounts of water supplied to the groves through rainfall and irrigation. Olive yields were responsive to ET only when the seasonal total ET exceeded 500 mm (Fig. 17a) when every additional millimetre of water used in ET produced an exponential increase in olive yield. The poor response of olive yield to water-use at low water supply was not clear, but was largely due to the data for the older groves at Balaklava and Greenock as explained above. However, where irrigation accounted for the bulk of the water supply at Waikerie and Two Wells, olive yields increased with water-use.

A similar pattern was observed in the response of yield to T, by which there were no differences in yield when seasonal T was less than 250 mm, despite the difference in total T of up to 50 mm (Fig. 17b). A proper evaluation of water-use efficiency was that based on individual trees, which provided a measure of the physiological efficiency with which the olive use water to fix carbon. The olives used in this study could be grouped into two belonging to either 'high' or 'low' levels of water input. Trees in the 'high' group at Waikerie and at Two Wells produced 2.8 g of fresh olive per litre of water (Table 4) compared to the average of 1.1 g by the 'low' group at the other two sites. This was astonishing since the 'high' group consisted of two different varieties, while the 'low' included variety Kalamata, which was also used at Waikerie. It seems therefore that long-term management, especially of irrigation, may condition the inherent yield capacity of olives to producing large or small amounts of olives, consistent with the hypothesis of Serrano (1998) that olives adapt and yield according to their water supply regimes.

4.1.3 Water-use efficiency

It is not certain whether other factors such as nutrient availability either through fertilisation or inherent in the soil had some influence in this dichotomy of the groves. This was a possibility given that the groves were on deep sand at Waikerie and on sandy-loam at Two Wells, in which a wide exploration by roots for water and nutrient could have been enhanced compared to the fine textured soils at the other two sites (see Appendix 2). Taking the average water-use efficiency based on ET for the two seasons produced a district mean for water-use efficiency of 1379 kg of fresh olives for every megalitre of water used as ET, but this value increased by almost 62% to 2234 kg when the water-use was through transpiration.

There is a dearth of information on the water-use efficiency of olives in literature for Australian environments, but the amount of olive produced per unit of water used (Table 3) was within the range of between 8 and 17 kg ha^{-1} mm^{-1} found in the northern hemisphere (Michelakis, 1990). Data on water supply and use were not detailed enough in 2000-01, but the yield of almost eight tons at Two Wells show that reductions in yield in 'off' seasons can be minimised with consistent irrigation regimes (Table 3). When compared to other crops, the values found in the current study are low even at Waikerie and Two Wells, considering that grapevines produced 6000–9000 kg per megalitre with drip irrigation (Yunusa *et al.*, 1997a) or 1300–4000 with furrow irrigation (Yunusa *et al.*, 1997b). The low values for the olive here was probably the result of higher oil content of about ~ 20% for olives (Patumi *et al.*, 2002) compared to grapes.

4.2 Use of soil water and crop factor

4.2.1 Water supply

A common feature of water-use at all sites was the decline in the rate of ET during the mid-season (days 120 to 180), especially at Greenock. This response was apparent in 1999-01, but was not picked up in 2000-01, because measurements were too few. 1n 1999-01, for instance, daily E_o in mid-summer averaged 9.5 mm (Fig. 2), in excess of daily water input (rainfall + irrigation) of between 2.7 mm at Greenock (Fig. 12) and 5.2 mm at Two Wells (Fig. 6), and maximum daily ET of 5.1 mm found at Two Wells (Fig. 8a). The resulting K_c of only 0.40 at Waikerie (Fig. 5c) 0.37 at Two Wells (Fig. 8c), were marginally lower than the expected for these groves in which the olive canopies had a minimum groundcover of 40% (Table 2). Similarly the K_c at Balaklava (Fig. 11c) was below the expected 0.21 in mid-season. Thus application of water at the irrigated sites did not keep pace with water required for transpiration by the olive trees.

The mid-season depression in ET was not apparent at Two Wells (Fig. 8a), which produced the highest yield in 1999-00, probably because irrigation was maintained at relatively constant rate (Fig. 6a, b). Giorio *et al.* (1999) demonstrated how a decline in the relative water content from 0.84 to 0.74 reduced leaf water potential by 126%, stomatal conductance by 78%, and conductance of CO_2 to just 9% of its original rate. Chartzoulakis *et al.* (1999) reported that water stress induced changes in leaf anatomy allowing olive varieties to maintain photosynthesis, albeit at low rates, even when stomatal conductance is substantially reduced. These anatomical changes in leaves involved increases in the thickness of the mesophyll, which lengthens the path CO_2 has to travel from the stomatal cavity to sites of fixation within the chloroplast. Reductions in these physiological processes during periods of low availability in mid-season, could have occurred in the current study to further explain the low yields, especially at Balaklava and Greenock.

Patterns of distribution of soil water at the dry end relative to that at high water storage provided indication of extraction pattern and, possibly, rooting pattern by olives especially at

Two Wells and Balaklava where there were no cover-crops during most of the growing season. Since olive trees are the dominant water users (see T/ET values, Table 1), it could be assumed that distribution of soil-water was associated with the pattern of water extraction, and rooting, by the trees. It appeared that rooting depth of olive did not extend below 2.0 m even at the rainfed Greenock. Deeper water extraction would have been expected from the rainfed grove at Greenock (Fig. 13). However, root growth could have been restricted to less than 1.6 m depth by the underlying dense clayey subsoils (see Appendix 2) as was also the case at Two Wells (Fig. 7) and Balaklava (Fig. 10). These data also suggest that lateral water extraction by the olives did not extend substantially beyond a distance of 2.0 m in almost all cases

4.2.2 Sensitivity to soil water supply

Although olive may be hardy in terms of its adaptation to water-stress conditions, data presented here show that this crop is sensitive to soil-water supply and so K_c needs to be precise for effective water management. The values for seasonal K_c found here (Table 1) were generally low, but consistent with the small fractions of incident energy intercepted by the olives and lapses in irrigation practices. For instance, the seasonal K_c of 0.40 for Waikerie was lower than 0.62 found for a drip irrigated grove in Spain, in which the trees covered 40% of the ground surface and produced LAI of about 1.3 (Villalobos *et al.,* 2000), similar to those at Waikerie.

Low K_c in the current study could be associated with low rates of T, because limited soil-water availability in these groves that must have restrained g_s. Peak g_s at Waikerie (Fig. 15c) was 4.5 mm s^{-1} or just over half the 8.5 mm s^{-1} found by Villalobos *et al.* (2000) because stored soil-water had declined to 80% in midsummer at all sites (Figs. 3c, 6c, 9c, 12c). This meant that the trees experienced some degree of water stress at the time when large amounts of water was needed to support the peak rates of T prevalent at this time (Figs. 5c, 8c, 11c, 14c). This was demonstrated by the reductions in T from individual trees at Waikerie, which was 47 litres during days 110–113, when soil water storage was low (Fig. 3c), compared to 67 litres during days 148–151 (Fig. 15). This happened despite the earlier period being comparatively cooler and more humid than days 148–151. Peak rates of T from individual trees were almost 30% larger than 4 litres per day for variety Manzanillo, found by Moreno *et al.* (1996) in Spain, despite similarity in canopy dimension between the two studies. This suggested some strong varietal differences in rates of transpiration, since the trees in that previous study were adequately supplied with water.

On the whole, transpiration accounted for about 70% of ET at Waikerie and Two Wells compared to 40% at Balaklava and Greenock (Table 1), consistent with differences in light interception by the trees. The stability in the value of *i* also ensured stability in the basic crop factor (K_t) for individual groves remained largely constant during the two years of this study.

4.2.3 Water management

Water application regimes at the three irrigated groves were highly variable between seasons, which suggested a lack of consistency in irrigation schedules and in the amounts of water applied. This was expected since up to the current time there had been a dearth of definite recommendations for irrigation practices for olive producers. For instance, higher irrigation would have been expected in 2000-01 at all sites when the season was warmer and drier (average E_o = 1695mm, average rainfall = 162mm) than 1999-01 (E_o = 1577mm, rainfall = 277mm) (Table 1). Data on irrigation show that irrigation at the three irrigated groves in 2000-01 increased by only 29% compared to a 33% shortfall in rainfall, relative to the previous season. Thus, K_c averaged 0.38 for the three irrigated groves in 1999-00, almost 6% lower than in the following season. If irrigation had been higher in 2000-01 to maintain K_c at the same levels as in the previous season, perhaps the reductions in olive yields in the second season would not have been as large as observed (Table 3). Except at Greenock in 1999-00, ET was greater than water input during the season (Table 1) indicating that the trees also used antecedent soil moisture possibly from pre-season rainfall.

Total water-input tended to be higher than total ET at both Waikerie and Two Wells in 1999-00 and at Two Wells in 2000-01 (Table 1), due to late rainfalls (Fig. 3a, Fig. 7a, b) that were not used up by the crop before the end of the season. Water requirements and associated K_c estimated for groves containing a range of tree size (Table 2), is meant to provide initial guidelines for irrigators. It is instructive that the upper values of 0.70 for K_c are consistent with the work of Goldhammer *et al.* (1998) in which no increases in either yield or gross margin was obtained with irrigation application higher than K_c of 0.75. In this environment, that translates to a maximum water requirement of 890 mm or almost 9 ML.

4.3 Conclusion

This study has further demonstrated the importance of appropriate water management as an essential component of achieving high and consistent yields from olive trees. Although this study was limited in both scope and duration, it demonstrated the current lack of consistency in irrigation practices amongst some of the respected and experienced olive growers in South Australia. This is not entirely unexpected since olive is a relatively new industry that is yet to obtain the level of research and extension support available to other perennial horticulture enterprises such as viticulture.

The first objective in this study of determining seasonal water-use was achieved, and it ranged from an average 340 mm (3.4 megalitres) for the rainfed grove at Greenock to 740 mm (almost 7.5 megalitres) for the drip-irrigated grove at Two Wells, which respectively, corresponded to K_c of between about 0.20 and 0.41. The low end of the ET range was less than 360 mm needed to prevent water-stress in groves where the olive trees covered 20% of the ground-surface area. Conditions of inadequate water-supply occurred mainly in midsummer (December–February period), when water supply was far less than water requirement, and could be a major cause of the low yields.

The use of K_c provides a means of scheduling irrigation, and the estimates given in Table 2 are to be used to provide first approximations of how much water to apply. It should be noted, however, that K_c is primarily designed to estimate the quantity of water to apply and, not necessarily, when to irrigate which requires some idea about the initial water content and water-holding capacity of the soil. The majority (average ~70%) of ET was used for transpiration at the high yielding groves at Two Wells and Waikerie, but only an average of 50% of ET was so partitioned at the low yielding groves at Balaklava and Greenock.

There was a positive relationship between amount of olives produced and the amount of water used either as ET or T. It appears that past irrigation practices continued to influence olive yield, and thus, it is important that when new groves are established that appropriate irrigation protocols are implemented right from the onset to avoid persistent periods of limited water supply. This should prime the trees for producing high and consistent yields. Groves that had been under regimes of water-stress may not respond immediately to improved water-supply regimes, and yields may stagnate. This was evident in this study by the variety Kalamata that had its efficiency for olive production per unit of transpiration halved under extended inadequate water-supply regimes compared to high yield obtained under high rates of water supply.

Averaged across all groves and the two seasons, the olives produced about 1380 kg of fresh olive per megalitre of water. Minimising soil surface area wetted during water application by using drippers increased the proportion of soil water used by the olives for transpiration. Irrigation practices that prevent shortage of water during the middle of growing season in mid-summer, and which partiton more of ET through T will ensure high olive yield and water-use efficiency. Transpiration can be maximised by minimising area of the soil surface wetted during irrigation by using technologies that deliver water as close to the olive trees as possible. In medium to heavy textured soils, extending the intervals between applications with increased volume of supply may minimise losses of water through soil surface.

Future studies should investigate how irrigation management can be employed to lift the productivity of old groves that are managed at low level of intensity Greenock. This should be undertaken in conjunction with acquiring a greater understanding of yield–water-use relationships at the low end of ET range to better manage young groves.

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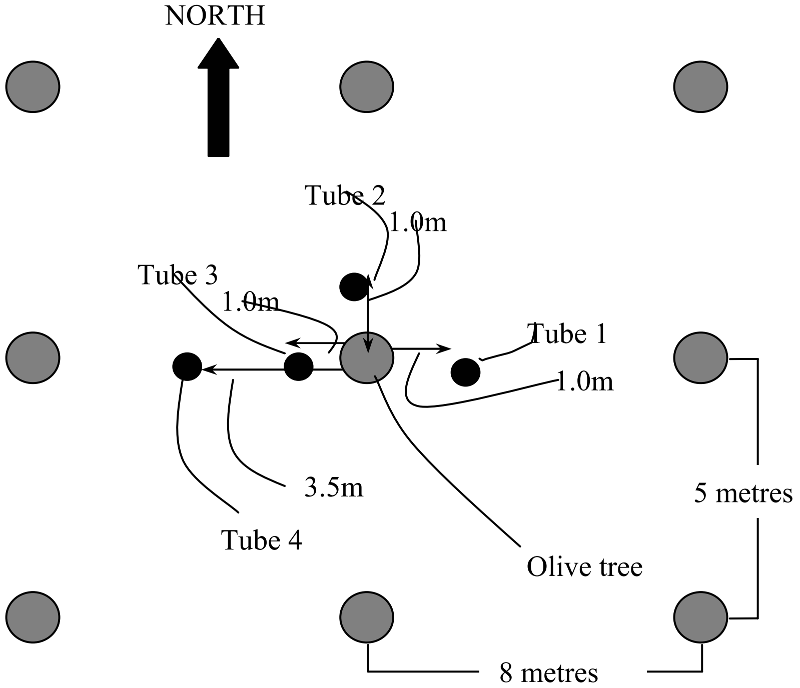
Appendix 1 Details of sites and management characteristics used in the study

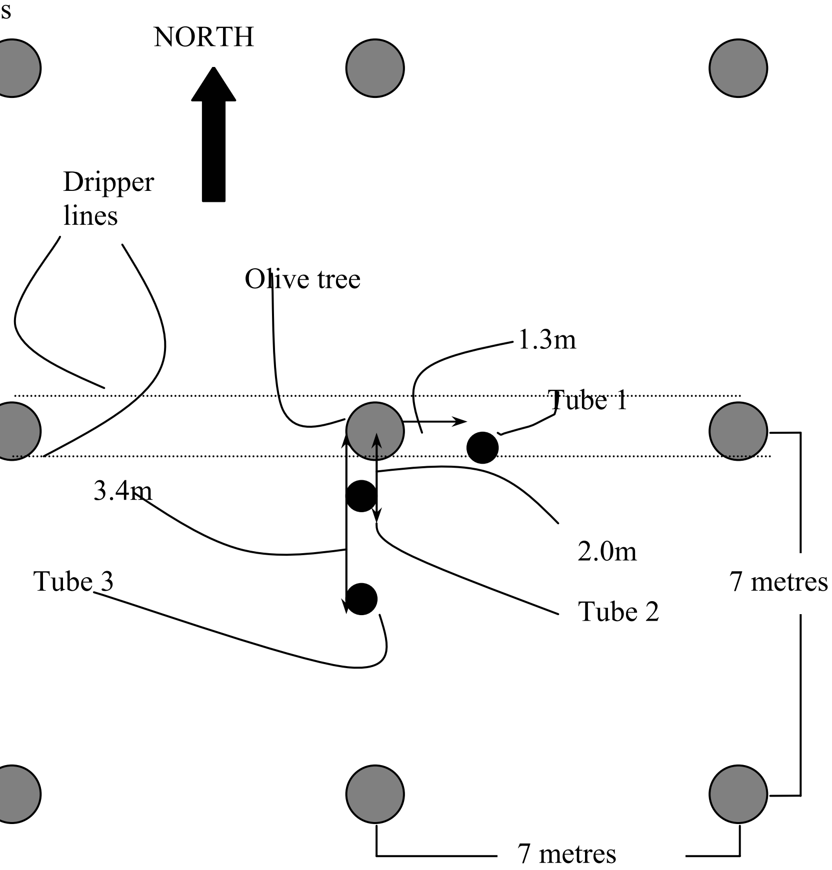
Characteristics	Waikerie	Two Wells	Balaklava	Greenock
Geographic coordinates	34^o 9' S, 140^o 0' E	34^o 34' S, 138^o 30' E	34^o 7' S, 138^o 22' E	34^o 27' S 139^o 0'E
Elevation				
Annual average rainfall (mm)	310	375	400	500
Annual average evaporation (mm)	1850	1770	1850	1710
Olive variety	Kalamata	Verdale	Kalamata	Unknown
Approximate age	1988	1972	Approx 1970	Unknown, approx. 1970
Spacing between row X between trees	8 m x 5 m	7 m x 7 m	10.5 m x 5.0 m	15 m x 5 m
Pruning regime	Minimal pruned modified central leader system	Open vase	Open vase	Vase shape but unpruned in recent years
Row orientation	North–South	East–West	North–South	North –South
Irrigation water supply	Murray River	Bore	Mains water	Rainfed
Irrigation system	Under tree, full cover micro-sprinklers @ approx 170 litres/hour	Four drippers/ tree located providing a total of approx. 32 litres/hour	Two drippers/ tree placed 1.5m either side of the tree trunk supplying of 10 litres/hour	Not aaplicable
Topography	North east facing slope of approx. 3%	Flat	Hilltop position gently undulating	East facing slope of approx. 5%
Soil type	Deep sand	Sandy loam over clay	Clay loam over calcium carbonate and clay	clay loam over silty clay
Ground cover management	mowed sward of perennial grasses and annual weeds	Tree rows sprayed with knockdown herbicide	Unmanaged winter crops that were green manured early in spring, then left as bare fallow	Unmanaged annual weeds

Appendix 2 Field layout indicating location of tubes relative to the trees

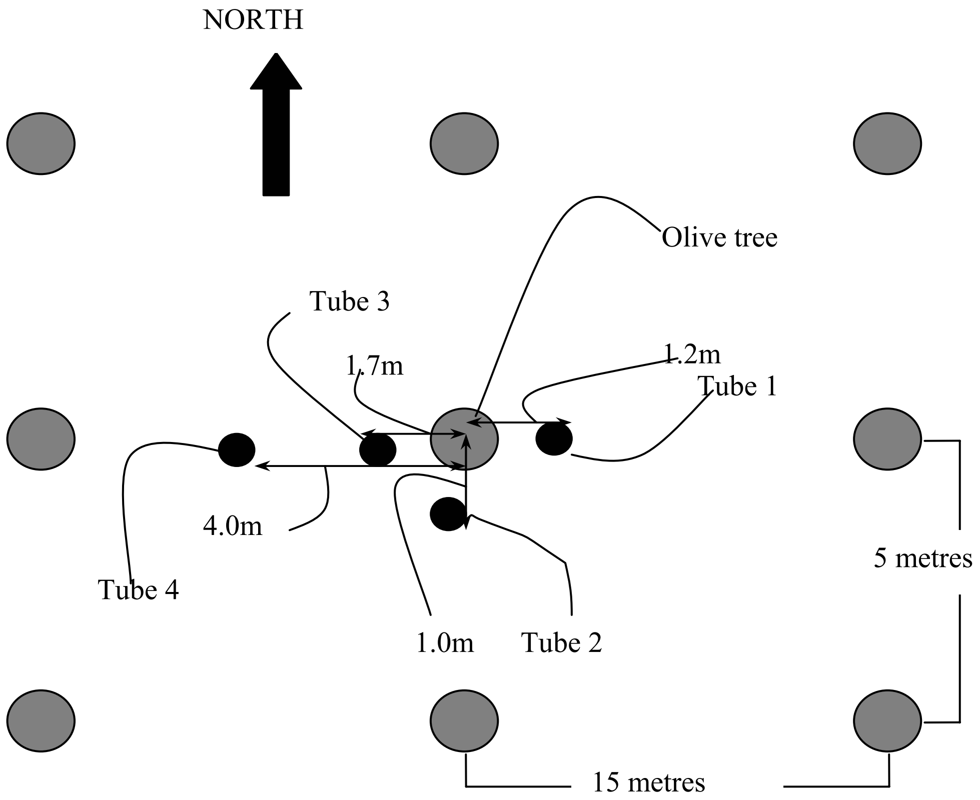
Waikerie



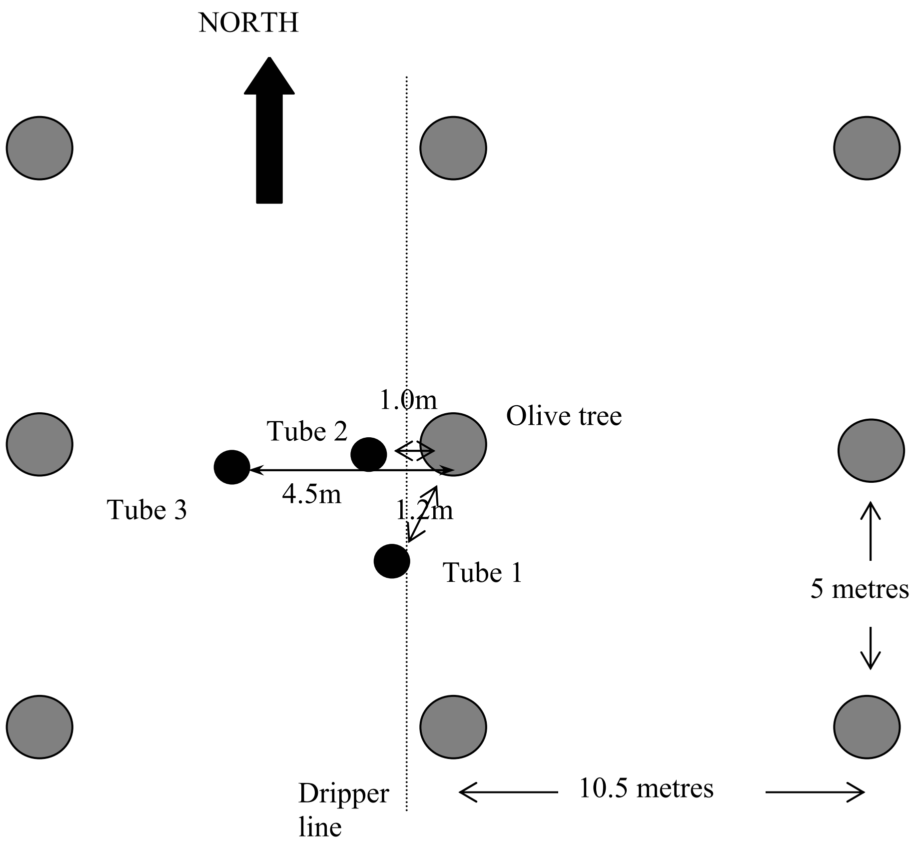
Two Wells



Greenock


NORTH
Olive tree
Tube 3
1.7m
1.2m
Tube 1
4.0m
Tube 4
1.0m
Tube 2
5 metres
15 metres

Balaklava


NORTH
1.0m
Olive tree
Tube 2
Tube 3
4.5m
1.2m
Tube 1
5 metres
Dripper
line
10.5 metres

Appendix 3 Estimation of daily ET

In estimating monthly water requirements, it was necessary to split periodic ET determined with eqn 1 to obtain daily values based on the E_o. This was assumed that ET for any given day depended on the potential rate for that day. Thus, it was possible to estimate ET for any day *n* (ET_n) from its evaporative demand ($E_{o,n}$) and the sum of E_o for the period ($\Sigma E_{o,p}$) concerned as follows:

$$ET_n = ET\left[\frac{E_{o,n}}{\sum E_{o,p}}\right]$$

This approach assumes that soil water was more/less equally available between measurements of soil water. This may not necessarily the case, but was considered not to be a major issue in this analysis. The application of this scheme is presented in Appendix 4.

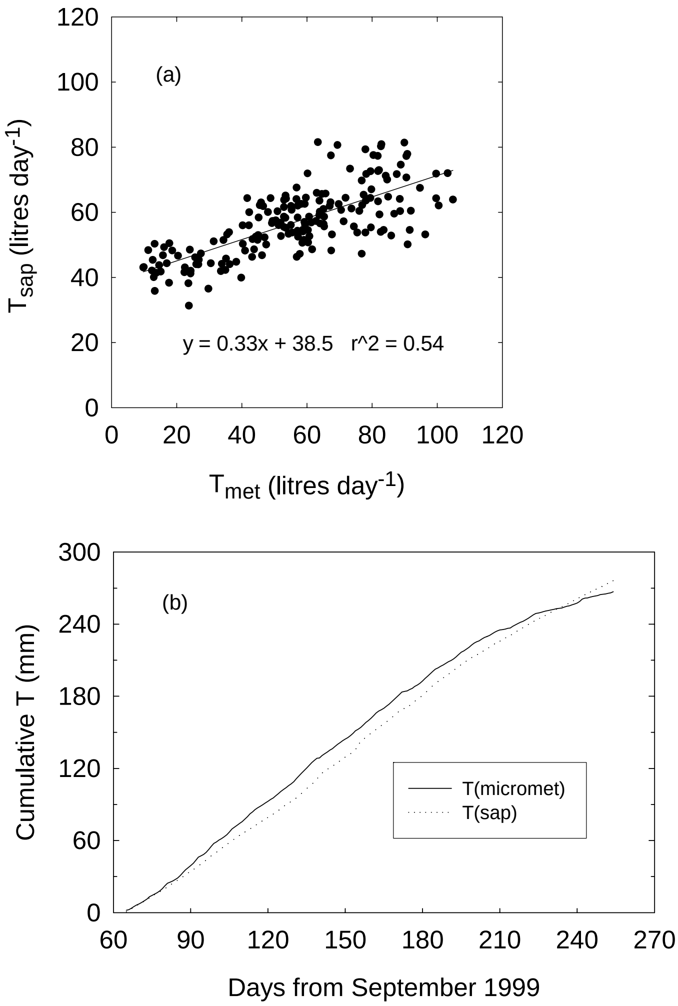
Appendix 4 Weather

Averages for monthly evapotranspiration (ET), crop factor (K_c), transpiration by olives (T) and base crop factor during the two growing seasons in southern South Australia

Variable	Grove	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total or Average[1]
E_o (mm)	District	118	153	204	266	286	248	182	108	68	1633
Rain (mm)	District	42	43	32	21	11	31	25	31	37	272
ET (mm)	Waikerie	65	42	87	139	124	110	118	63	66	635
	Two Wells	80	97	110	105	100	89	71	41	42	652
	Balaklava	71	80	83	72	75	83	63	45	43	615
	Greenock	49	59	48	33	40	38	37	25	38	367
K_c	Waikerie	0.55	0.27	0.43	0.52	0.43	0.44	0.65	0.58	0.97	0.39
	Two Wells	0.68	0.63	0.54	0.39	0.35	0.36	0.39	0.38	0.62	0.40
	Balaklava	0.60	0.52	0.41	0.27	0.26	0.33	0.35	0.42	0.63	0.38
	Greenock	0.41	0.39	0.24	0.12	0.14	0.15	0.20	0.23	0.56	0.27
T (mm)	Waikerie	20	52	73	74	73	56	47	34	19	448
	Two Wells	29	43	56	66	76	65	55	38	22	450
	Balaklava	14	22	28	36	39	34	30	18	15	236
	Greenock	15	19	23	27	31	27	21	12	12	187
K_b	Waikerie	0.17	0.34	0.36	0.28	0.26	0.23	0.26	0.32	0.28	0.28
	Two Wells	0.25	0.28	0.28	0.25	0.27	0.26	0.30	0.35	0.32	0.28
	Balaklava	0.12	0.14	0.14	0.14	0.14	0.14	0.16	0.17	0.22	0.15
	Greenock	0.13	0.12	0.11	0.10	0.11	0.11	0.12	0.11	0.18	0.12

[1] ET and T are the sums for the season, K_c and K_b are seasonal averages

Appendix 5 Comparison of sapflow *vs* micrometeorological estimation of transpiration



Comparison of transpiration determined with sapflow heat-pulse sensors and with micrometeorology approach during 1999-01 season: (a) daily rates of volume of water uptake by the olives, and (b) cumulative depths of water uptake by the olives.

Appendix 6 Olive yields

Details of fresh olive yield for olives grown in four groves harvested in 1999 and 2000 in South Australia

Groves	2000	2001
Waikerie		
Average site yield kg/ha	**1302**	**20694**
Standard deviation	1780	2191
Sample size	12	4
Average tree yield kg/tree	5	83
Max tree yield kg/tree	26	93
Min tree yield kg/tree	0	71
Two Wells		
Average site yield kg/ha	**19921**	**7548**
Standard deviation	8242	3171
Sample size	10	9
Average tree yield kg/tree	98	37
Max tree yield kg/tree	180	58
Min tree yield kg/tree	65	22
Balaklava		
Average site yield kg/ha	**2750**	**1580**
Standard deviation	1768	1131
Sample size	9	9
Average tree yield kg/tree	14	8
Max tree yield kg/tree	29	18
Min tree yield kg/tree	4	1
Greenock		
Average site yield kg/ha	**2554**	**2348**
Standard deviation	2007	1856
Sample size	13	9
Average tree yield kg/tree	19	18
Max tree yield kg/tree	54	38
Min tree yield kg/tree	0	0