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REGULAR ARTICLE

The use of sap flow measurements for scheduling irrigation in olive, apple and Asian pear trees and in grapevines

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Abstract We evaluated three approaches for scheduling irrigation in wine grape vineyards and in olive, apple and Asian pear tree orchards, based on sap flow measurements and models of plant transpiration. In the first approach, we analysed how the shape of the sap-flow profile changed in response to root-zone soil water conditions and potential evaporative demand. The second approach was based on a transpiration ratio, as defined from the actual daily water use of a target plant divided by the potential daily water use of similar-sized plants under non-limiting soil water conditions ("well-irrigated" plants). Values of the actual plant water use were always determined from measured sap flow. Two independent methods were assessed for the calculation of potential plant water use; either sap flow was measured in well-irrigated plants or we used a leaf-area based model of plant transpiration. On some occasions water stress was found to modify the shape of the sap velocity profile. However, most of the time the velocity profile was found to be an insensitive indicator for triggering irrigation. The transpiration ratio method, using measured sap flow in well-irrigated plants, was more useful for irrigation scheduling, at least for the two species (i.e. olive and grape) that were investigated here. Nonetheless, realization of such an approach in a commercial orchard may not be practical due to problems associated with irrigation management e.g. excessive vegetative growth may occur on the reference plants over time. Besides, irrigating the orchard to maintain non-limiting soil water conditions is not always the best option for water and nutrient management. The alternative transpiration ratio method based on a leaf-area based model of plant water use, yielded the best results. Modelled transpiration rates always provided reliable information not only for well-irrigated plants, but also for deficit-irrigated plants. This result lends support to the use of the method for irrigation scheduling of vineyard and orchard trees. However, the use of models does require detailed microclimate data as well as a user-friendly technique to quantify plant leaf area. From a practical viewpoint the method should encompass the spatial variability of the soil and plants within the orchard. Accurate quantification of these factors is a cornerstone of precision horticulture and such infor-

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mation would help to minimise risks associated with insufficient as well as excessive irrigation applications.

Keywords Sap flow profiles · Modeling · Irrigation control · Transpiration ratio

Introduction

Improving irrigation management is a crucial part of developing sustainable agricultural practices. There is a growing need to provide a diverse range of agricultural products to feed the increasing world population. Yet consumers are demanding food products that are safe to eat and ones that have been produced in such a way as to minimise the environmental footprint of production. That means using water and agrochemicals wisely. Worldwide there are increasing concerns about the availability and quality of freshwater that must also be shared with other water-user sectors. The problem becomes especially severe in arid and semi-arid areas, where water for irrigation is becoming so scarce. Vineyards and fruit tree orchards are extensively cropped in these areas. Modern farmers are adopting irrigation, not only to ensure profitable yields, but also to protect their commercial enterprises against the risks of drought. Fereres and Evans (2006), among others, have pointed out the need for more accurate scheduling and precise irrigation management of those orchards.

In the last decades, the reaction of the scientific community to this problem has been to invest a substantial amount of research into new irrigation technologies and more efficient scheduling approaches. Plant-based methods are considered to have a greatest potential for irrigation control although, in some cases, there are issues in defining a reference or threshold value (Jones 2004) and other issues including plant variability within the orchard (Naor and Cohen 2003). Improved scientific and practical knowledge on plant responses together with advances in electronic sensors and automated equipment for monitoring and data communication, are helping to overcome some of these limitations (Fereres et al. 2003; Naor et al. 2006). In addition, thermal remote sensing methods can be combined with plant-based methods for precise irrigation of heterogeneous commercial orchards using a manageable number of instrumented plants (Sepulcre-Cantó et al. 2006).

At the research level, sap flow measurements are being widely used for in situ determinations of plant water consumption. Sap flow systems are easily automated, and they have shown to be robust and reliable enough for operation in the field over extended periods of time. Comparisons have been made between sap flow and other water stress indicators used for irrigation scheduling. Examples include apple (Nadezhdina 1999), grapes (Escalona et al. 2002), lemon (Ortuño et al. 2006) and plum (Intrigliolo and Castel 2006), among other species. Besides using sap flow records to study the dynamics of plant transpiration, alternative methods for irrigation scheduling have also been proposed. Nadezhdina and Cermak (1997) used what they called the Sap Flow Index (see Nadezhdina 1999 for details) to control irrigation in fruit tree orchards. A subtle change in the shape of the sap velocity profile, as induced by water stress, has been suggested as a suitable indicator for triggering irrigation. For example, Fernández et al. (2001) and Nadezhdina et al. (2007) both commented on the possibility of using the ratio of sap flow in the inner/outer xylem regions as a trigger for when to irrigate. Another approach to quantify the degree of water stress is to measure sap flow, or some other plant-based water status indicator, in plants that are irrigated to avoid any soil water limitation. Irrigation amounts can then be controlled by comparing those measurements against similar data from representative plants in other parts of the orchard (Goldhamer and Fereres 2001). Alternatively, rather than using well-irrigated plants, a reference rate of plant transpiration based on leaf area and local microclimate can be calculated for the orchard conditions (Green et al. 2006a). User-friendly versions of such models are being developed for controlling irrigation in commercial orchards (Pereira et al. 2006). To our knowledge, a rigorous evaluation of the potential of the above-mentioned approaches for scheduling irrigation in commercial orchards has not been made yet.

The aim of the present work was to evaluate the potential of sap flow measurements for scheduling high frequency irrigation in vineyards and fruit tree orchards. We investigated whether this control could be achieved either from observations based on changes in the sap velocity profiles or by comparing the ratios of actual plant water use estimated from sap flow to potential water use determined for non-limiting soil water conditions. Potential transpiration rates were determined via two methods: sap flow was measured in well-irrigated plants, or a user-friendly model was calibrated for the orchard conditions. Measurements are reported for olive, apple and Asian pear trees and grapevines from a commercial vineyard.

Materials and methods

Experiments with grapevines

A replicated irrigation trial was established in the spring of 2003 on a commercial vineyard (Nautilus Estate) near Renwick, Marlborough, New Zealand. The vines (*Vitis vinifera* L.) were 10 year old Cabernet Sauvignon planted on a 2.7 by 1.8 m spacing and trellised using a vertical shoot-pruned (VSP) canopy. The Marlborough climate is mild and the vineyard soil comprises a shallow sandy loam (0–30 cm) overlying a stony loamy sand (Ray and Tozer 1990). Control vines (T1) received 100% of the irrigation volume required to meet their crop evapotranspiration demand (ET_c) as determined using the crop coefficient approach (Allen et al. 1998), that also accounted for vine leaf area (determined by the point quadrant method, described in Green et al. 2006b) and effective rainfall. Water-stressed treatments T2, T3 and T4 each received 50, 40 and 30% of ET_c, respectively. Additional details of the experimental site and treatments are described in Green et al. (2006b).

Values of global radiation, air temperature, relative humidity and wind speed measured at the Woodbourne airport (NIWA station number G13585) were used to calculate the grass reference evapotranspiration (E_o, L ground m^{-2} day^{-1}) with the FAO-56 Penman–Monteith equation (Allen et al. 1998), adjusted for our conditions following the approach of Pereira et al. (2006):

$$E_o = \frac{0.408\, s\, R_n + \frac{900 \gamma D_a u_2}{T_a + 273}}{s + \gamma(1 + 0.34 u_2)} \quad (1)$$

where R_n (MJ m^{-2} day^{-1}) is the net radiation, T_a (°C) is the mean air temperature, D_a (kPa) is the mean vapour pressure deficit of the air, u_2 (m s^{-1}) is the mean wind speed, s (Pa °C^{-1}) is the slope of the saturation vapour-pressure versus temperature curve and γ is the psychrometric constant (66.1 kPa). The daily grapevine transpiration for non-limiting soil water conditions (E_{gr}, L plant^{-1} day^{-1}) was estimated from the equation (Pereira et al. 2006):

$$E_{gr} = \frac{E_o A_L}{2.88} \quad (2)$$

where A_L is the plant leaf area (m^2) and 2.88 is the hypothetical grass leaf area index (m^2 m^{-2}). The time course evolution of A_L was determined with the point quadrant method (Smart and Robinson 1991).

During the period January to mid March 2006, sap flow measurements were carried out in the trunks of three vines from each treatment using the Tmax heat-pulse method (Green et al. 2003). One temperature probe (1.2 mm diameter) was placed 12.5 mm downstream from a linear heater, and a second reference probe was placed a further 30 mm downstream. The stem sections near the probes were wrapped in aluminium foil, to minimize the effects of radiant heating on stem temperatures. Heat pulses (100 W over 2 s) were applied automatically, once every 30 min. Raw data were collected by Campbell CR10X data loggers equipped with solar panels (12 V, 5 W) and multiplexers (Campbell AM25T). The procedure used to convert raw heat-pulse data into values of volumetric sap flow is described in Green et al. (2003).

Experiments with olive trees

Two experiments were carried out in a 0.5 ha olive orchard at La Hampa experimental farm, close to Seville, southwest Spain (37°17′N, 6°3′W, 30 m a.s.l.). The orchard was planted in 1969 with *Olea europaea* 'Manzanilla' trees at 7×5 m spacing. The trees have a single trunk with an approximately spherical canopy shape having an average volume of 37 m^3 and an average leaf area density (LAD) of about 1.6 m^2 m^{-3} towards the end of the growing season. For details on the soil and climatic conditions, see Fernández et al. (2006a).

Experiment 1 Between 8 May 2006, day-of-year (DOY) 128, to 18 July (DOY 199), a plot of 32 trees was irrigated daily using a deficit irrigation amount equal to 20% of ET_c. Hereafter we denote these trees as the deficit irrigated (DI) treatment. Over the course of the experiment we observed a marked decrease both in the plant water status and soil water content (see below). The trees were subsequently given a recovery irrigation (130% ET_c) between DOY 199 to DOY 208. This irrigation was sufficient to rewet the soil close to field capacity. Here ET_c was calculated using the crop coefficient recommended by Fernández et al. (2006a) for our orchard conditions. At the same time, three trees within the plot were chosen as the reference, and they were irrigated during the entire experimental period (OI trees) using daily irrigation amounts of 130% ET_c. Sap flow was recorded in the trunk of three DI trees and three OI trees, for every day of the experimental period. Measurements were made using the Tz heat-pulse method (Green et al. 2003) that has previously been validated for olive by Fernández et al. (2006b). Three sets of probes were installed into each trunk. Each probe set had two temperature probes, and they were located at a distance of x_u=5 mm upstream and x_d=10 mm downstream of the linear heater probe. Each temperature probe consisted of four thermocouples, at depths of 5, 12, 22, and 35 mm below the cambium. Heat pulses (60 W over 1 s) were applied once every 30 min. A datalogger (model CR10X, Campbell Sci, Logan, UT) was used to control the heaters and record the raw heat-pulse data.

Midday stem water potential (Ψ_{stem}, MPa) was recorded at 5–7 d intervals in both the OI and the DI trees. A pressure chamber (Soilmoisture Equipment, Santa Barbara, California, USA) was used to monitor the xylem water potential at the petiole of leaves wrapped in aluminium foil some 2 h before midday. Two leaves per tree were sampled from the base of shoots in the trunk or main branches of three OI and three DI trees (n=6).

Soil water contents (θ, m^3 m^{-3}) over the root-zone depth 0.2–2.0 m were monitored using a neutron probe (Troxler 3300, Research Triangle Park, NC, USA). Corresponding values of θ in the top 0.0–0.2 m were determined gravimetrically. Profiles of soil water content were measured once every 10–20 days throughout the experimental period. Neutron access tubes were installed along the tree row, at distances of 0.5, 1.5, and 2.5 m from the trunk of one DI tree, and at distances of 1.5 and 2.5 m from the trunk of the other DI trees. In the case of the OI trees, a single access tube was installed at a distance of 1.5 m from the tree trunk because it was anticipated there would be less spatial variation in θ around the OI trees cf. the DI trees. Recorded values of θ were used to calculate a depth equivalent of water. The soil moisture results were then expressed in terms of the relative extractable water (REW) as defined by Granier (1987).

Experiment 2 Sap flow measurements were made in the trunk of a single tree under a partial root-drying (PRD) treatment (see Fernández et al. 2006a, for details). The irrigation season of the experimental year, 2004, went from May 25 to September 12. All measurements reported here were taken towards the end of the irrigation season, when the tree leaf area was 67.5 m^2 and the average REW was 0.51. Details on these measurements are given in Fernández et al. (2006a). This data is used to compare measured sap flow (E_p, L tree^{-1} d^{-1}) against tree water use calculated using the Penman–Monteith equation. Following Moreno et al. (1996) tree water use is calculated as:

$$\lambda E_{ol} = f_l \frac{sR_{n,l}}{s+\gamma\left(2+g_{b,l}/g_{c,l}\right)} + f_l \frac{\rho c_p D_a g_{b,l}}{s+\gamma\left(2+g_{b,l}/g_{c,l}\right)} + f_s \frac{\rho c_p D_a g_{b,s}}{s+\gamma\left(2+g_{b,s}/g_{c,s}\right)} \quad (3)$$

where E_{ol} has units of g s^{-1} m^{-2} leaf plan area; f_l=A_l/A and f_s=A_s/A, being A (m^2) the total (one-sided) leaf area that comprises an area of sunlit leaves (A_l) and shaded leaves (A_s); $R_{n,l}$ (W m^{-2} of leaf plan area) is the net, all-wave radiation of the lit leaves (assumed to be zero for the shaded leaves); D_a is in Pa, g_c is the leaf stomatal conductance (m s^{-1}) and g_b is the leaf-canopy boundary-layer conductance (m s^{-1}); λ is the latent heat of vapourisation (2.454 J kg^{-1}). The leaf stomatal conductance was calculated as:

$$g_c = g_m f(\mathrm{PPF}) f(T_l) f(D_a) f(\theta) \quad (4)$$

where PPF is the incident photosynthetically active photon flux, T_l is the leaf temperature and g_m is the reference stomatal conductance measured under standard conditions (PPF=1,600 µmol m^{-2} s^{-1}, T_l=25°C, D_a=1 kPa, θ at field capacity=0.21 m^3 m^{-3}). The f functions are described in Diaz-Espejo et al. (2006). For the purpose of calculation, the fractions of sunlit and shade leaves, i.e. f_l and f_s respectively, were estimated using the RATP model of Sinoquet et al. (2001). This model calculates radiation transfer through the canopy, and aspects of that model are described by Diaz-Espejo et al. (2002).

Experiments with apple trees

Experiments with apple (*Malus domestica* Borkh.) trees were made in the summer of 1998/1999 in a commercial orchard of ‘Fuji’/MM106 spaced at 2.5× 5 m and trained to a central leader system. The orchard was near Blenheim, Marlborough, NZ and the soil was a Wairau series deep silt loam overlying a loamy and sandy C horizon (Ray and Tozer 1990). Trees were irrigated via micro-sprinklers, and the control trees were given adequate water to replace 100% of ET_c as determined from a crop-factor calculation (Allen et al. 1998). Meanwhile, deficit-irrigated trees were supplied with just 50% of ET_c. Sap flow measurements were made in the trunk of one control and one deficit-irrigated tree. The measurement period was about 160 days, from late November 1998 to early May 1999. We used the Tz method of Green et al. (2003) with two sets of heat-pulse probes per tree. The probes were installed at a height of about 0.2 m and just above the graft union. Temperature probes were placed 10 mm downstream and 5 mm upstream a 1.8 mm diameter stainless-steel heater. Each probe had thermo-couples at depths of 5, 10, 15, and 20 mm depths below the cambium. Trunk diameters were about 135 mm. Heat pulses (60 W over 1 s) were activated once every 30 min and signals and processing were done using a Campbell CR10X datalogger.

Soil water content was measured once a week using a hand-held Time Domain Reflectometry (TDR) system. Stainless steel rods of length 0.32, 0.62, and 1.02 m were installed along the tree row about 0.5 m on either side of the tree trunk.

The trees were summer pruned on 4 February 1999. The leaf area of pruned leaves was determined by passing a sub-sample (10% by weight) through a LICOR 3100 leaf area meter (LI-COR, Lincoln, NE, USA). The number of leaves remaining on the tree was then counted and the total leaf area determined by multiplying leaf number times average leaf area (determined from the sub-sample). Thereafter, by the end of April 1999 and just prior to natural leaf fall, every 20th leaf was harvested from the tree. The corresponding leaf area of this 5% sub-sample was determined as described above. The average leaf area per tree was found to be 41 and 25 m^2 prior to and after summer pruning, respectively.

Supporting meteorological data were obtained from a weather station located at the Marlborough Research Center, approximately 8 km from the orchard.

Experiments with Asian pear trees

Experiments were carried out at the lysimeter facility of Massey University, Palmerston North, NZ. The lysimeter facility is located within a 1.1 ha block of Asian pears. Details of the facility have been reported previously (Chalmers et al. 1992). Briefly, the facility consists of 12 drainage lysimeters, each constructed from a steel cylinder 1.2 m deep with a 1 m diameter. Each cylinder is surrounded by a concrete sleeve giving a 1.2 m tree spacing within the row. Row spacing is 5 m. The tops of the inner cylinders are about 0.1 m above ground level. The bottom 0.15 m of each steel container is filled with sand, while the bottom 0.05 m of each steel cylinder is conical in shape to provide drainage to a central discharge point.

Lysimeters were carefully packed in 0.1-m layers with Manawatu fine sandy loam (sandy, mixed, mesic-Dystric Fluventic Eutrochrept), the same soil as in the surrounding orchard. Total soil depth was 1.0 m. One tree of the Asian pear (*Pyrus serotina*) cultivar ‘Hosui’, grafted onto seedling rootstock, was planted in each lysimeter in Sep. 1987 and trained onto a Tatura trellis. Irrigation and fertilizer was applied to each tree via a closed nutrient-irrigation system fed from two 9,100-l tanks. Irrigation was applied to the surface of each lysimeter via eight pressure-compensated drip emitters rated at 2 L h^{-1} (Netafim, Israel). Emitters were located in a circle some 0.3 m from the tree trunk to provide uniform water distribution. Lysimeters were covered with reflective, opaque plastic covers to minimize rainfall entry and reduce soil evaporation.

A single access tube for a neutron moisture meter was placed 0.2 m from each tree trunk. Soil water contents were measured using a neutron hydroprobe (Model 503DR, CPN, Martinez, CA, USA). The measurements were made twice-weekly at 0.2-m depth intervals, from 0.2 to 1.0 m beneath the soil surface.

Trees were irrigated to pot capacity and all fruit were removed during the first three years after planting to maximise tree growth and improve tree establishment. Irrigation experiments began during the 1990/1991 season. Irrigation water was withheld from four trees, at three different growth stages for up to 14 days at a time, in order to induce short-term water stress (Caspari et al. 1993a). Long-term (up to 73 days) deficit irrigation was also applied, either early or late in the 1991/1992 season, on four trees each, while the remaining four trees received full irrigation (Caspari et al. 1994).

Sap flow during several periods in the 1990/1991 and 1991/1992 growing season was measured using the Tz method (Green et al. 2003). Two to four sets of heat-pulse probes were installed into the tree trunk at heights of between 0.2 and 0.4 m above the ground. The temperature probes were placed 10 mm downstream and 5 mm upstream a 1.8 mm diameter stainless-steel heater. Each probe had temperature sensors at depths of 5 and 10 mm (Jan. 1991), 5, 10, 15, and 20 mm (Oct. 1991), and 4, 8, 12, and 24 mm (Jan. 1992) depths below the cambium. Different probe sizes were used to accommodate the growth of these trees, with trunk diameters increasing from about 60 mm (Jan. 1991) to 80 mm (Jan. 1992) during the course of the experiment.

Leaf water potential (ψ_{leaf}) was measured using a Scholander pressure chamber (Soilmoisture Equipment, Santa Barbara, CA, USA). Leaf stomatal conductance (g_s) was measured on fully expanded, sunlit leaves with either a transit-time porometer (Delta-T Devices, Model Mk3, Cambridge, UK) or a LI-COR 1600 steady-state porometer (LI-COR, Lincoln, NE, USA).

Tree transpiration was calculated using a modified Penman–Monteith model as described in Caspari et al. (1993b). Meteorological data were obtained from a weather station located approximately 1 km from the lysimeter facility.

Results

Analysis of sap velocity profiles for each species, recorded under a range of soil moisture conditions and atmospheric demands, are presented in Figs. 1, 2, 3 and 4. Firstly we present data for grapevines between the hours of 1200 and 1630 each day. The trunk diameter of these vines was 30–35 mm and so the sap velocity was recorded at just two depths, namely 5 mm and 12 mm below the cambium. Figure 1 shows the time course for the ratio between the sap velocity recorded by the outer and inner temperature sensor. Typically, this velocity ratio was about 7:1 indicating substantially more flow usually occurred in the outer xylem vessels of grape. This ratio remained quite conservative (0.12±0.02) across many consecutive days. However, during a couple of days, there were a few ‘spikes’ in the velocity ratio and these were observed immediately following large inputs of water via irrigation or rainfall. This result indicates that a greater fraction of the sapwood cross-section was conducting water immediately following a re-wetting event. However, for this vine of the T2 treatment, the usual weekly irrigation that replaced 50% of the weekly amount of water used by the vine, often had little, if any, impact on this ratio.

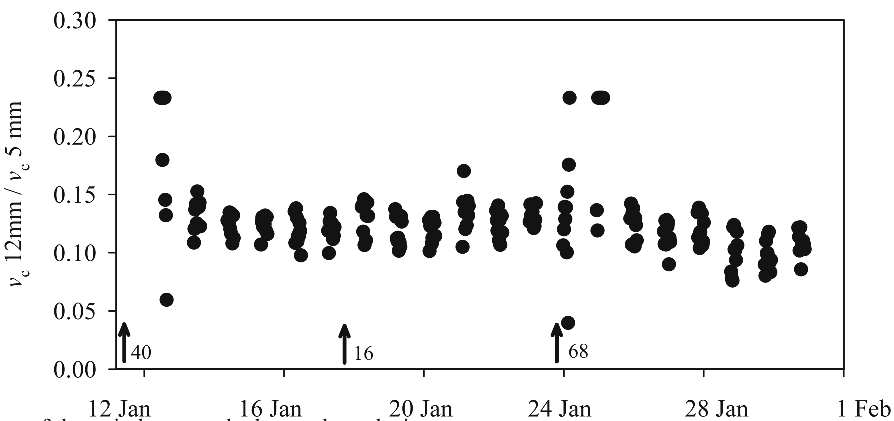

Fig. 1 Time course of the ratio between the heat pulse velocity corrected for wound effects (v_c) at 12 mm below the cambium and that recorded at 5 mm below the cambium. Data correspond to sap flow measurements made every half hour in a vine of the T2 treatment (50% ET_c). For each experimental day, we have represented data recorded from 12.00 to 16.30 New Zealand standard time (NZST), only. The days in which water was supplied, either by irrigation or rainfall, are marked with arrows; the number close to each arrow is the number of litres supplied per plant

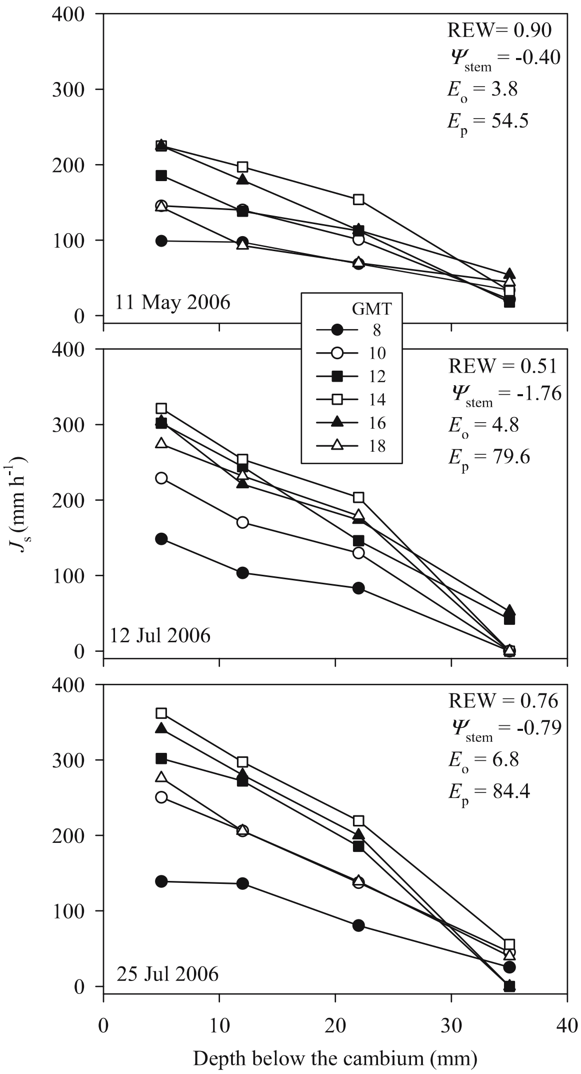

Fig. 2 Sap flow density (J_s) profiles measured in an olive tree on days with different soil and atmosphere water stress conditions. *REW* Relative extractable water; Ψ_{stem} stem water potential (MPa); E_o FAO56 Penman–Monteith grass reference evapotranspiration (mm day^{-1}), E_p tree water use (L day^{-1}) estimated from sap flow measurements, *GMT* Greenwich mean time. See text for details on the measurements

In the case of both apple and olive, the shape of the sap velocity profiles was some times modified by water-stress events, in the sense that lower sap flows were observed close to the cambium cf. deeper into the xylem (data not shown). However, such phenomenon happened only on a few occasions. More often, we observed very little variation in the shapes of the sap velocity profiles. As a consequence, the ratios (i.e. outer flow to inner flow) did not change significantly either in olive (Fig. 2) or apple (Fig. 3), despite a large range in both the soil water availability (0.50< REW<0.90) and the atmospheric demand (3.8<E_o< 9.6). In the case of olive, midday values of stem water potential, Ψ_{stem}, dropped as low as −1.76 MPa which indicates a moderate water stress (Fernández et al. 1997; Fig. 2). In the case of the Asian pear trees (Fig. 4), greater sap velocities were actually recorded deeper into the xylem and this behaviour is opposite to that of the other tree species reported here. Once again, however, the shape of the sap velocity profiles did not appear to be modified, in most cases, by changes in the root-zone soil water conditions.

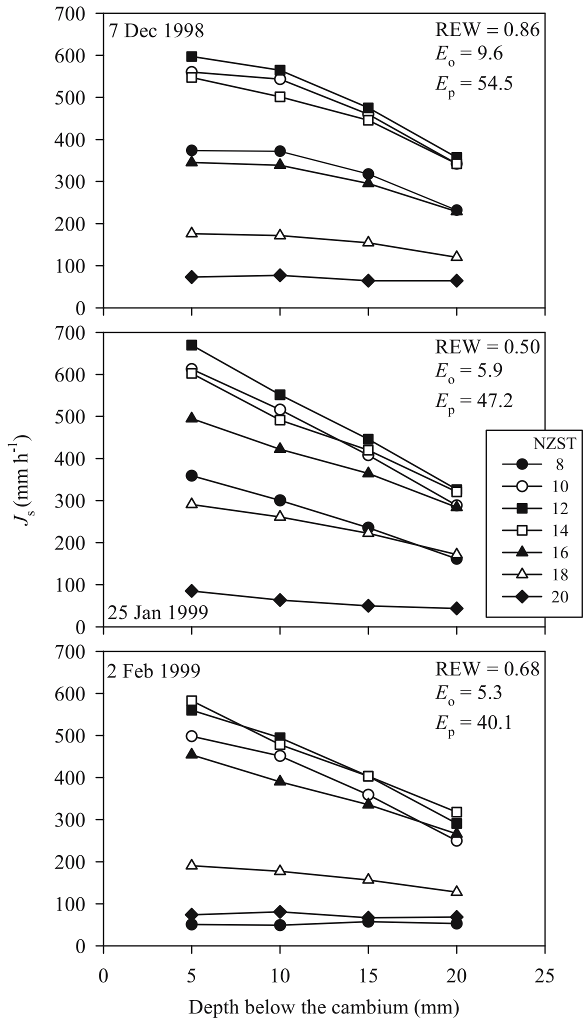

Fig. 3 Sap flow density (J_s) profiles measured in an apple tree on days with different soil and atmosphere water stress conditions. *REW* Relative extractable water, E_o FAO56 Penman–Monteith grass reference evapotranspiration (mm day^{-1}), E_p tree water use (L day^{-1}) estimated from sap flow measurements, *NZST* New Zealand standard time. See text for details on the measurements

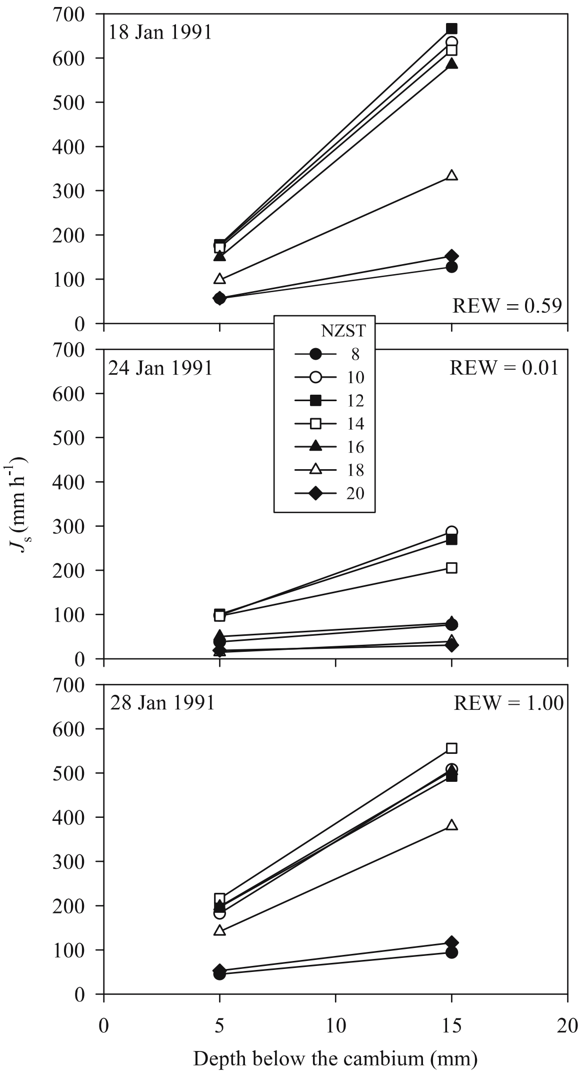

Fig. 4 Sap flow density (J_s) profiles measured in an Asian pear tree on days with different soil water stress conditions. *REW* Relative extractable water, *NZST* New Zealand standard time. See text for details on the measurements

Figures 5 and 6 show the time courses of the transpiration ratio (TR) for grapevines and olive trees, respectively. In this case, TR is calculated by dividing the daily water use of deficit-irrigated plants by the corresponding transpiration rate of plants growing under non-limiting soil water conditions. Figure 5 shows the TR results for grapevines under three levels of irrigation treatment. Generally the deficit-irrigated vines had much lower transpiration rates and so TR< 1. Vines having the largest deficit i.e. T4 treatment that received 30% of ET_c, had TR<0.5 between 17th and 22nd January. Thereafter, a combination of irrigation and a large rainfall event (55 mm) reduced the water stress and lead to a concomitant increase in TR. In the T2 and T3 treatments, irrigation events around 15th January also provided a short-term respite for the mild water stress. Because the results have not been scaled for the leaf area of each vine, TR>1 following the late rainfall event.

The time course for TR values of olive was also highly influenced by plant water stress (Fig. 6). Large drops (~20%) in TR were observed around DOY 170 and 190, which coincided with the deficit irrigation period of the DI trees. The pattern of TR was in broad agreement with the pattern of the stem water potential. Thereafter, and following a recovery irrigation, we observed increasing values of TR and an increase in soil water content. During the interval DOY 210–220, maximum TR values were lower than those recorded around DOY 150–160. This mismatch in TR is most likely explained by different soil and plant water status, as shown by REW and ψ_{stem}, respectively. The largest day-to-day changes in TR occurred during periods of variable atmospheric demand, e.g. ET_o varied from 5.5 to 7.2 mm day^{-1} between DOY 210 and 224. This result suggests that evaporative demand alters the plant's expression of the degree of water stress. On the other hand, the behaviour of the control trees at this time of the experiment could have been affected by the long period with a possible excess of water in the soil.

Calculations with the alternative transpiration ratio method based on a leaf-area based model of plant

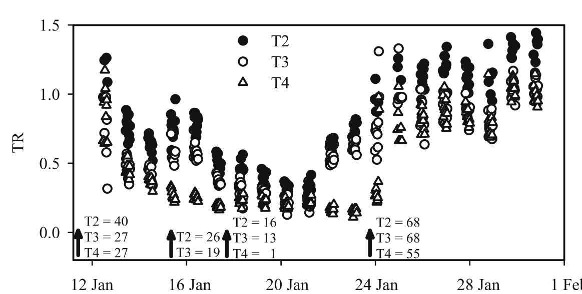

Fig. 5 Time course of the transpiration ratio (TR=E_p deficit treatment/E_p fully irrigated treatment, being E_p the plant water use estimated from sap flow measurements) estimated from sap flow measurements made every half hour in vines of the T2 (50% ET_c), T3 (40% ET_c) and T4 (30% ET_c) treatments. For each experimental day, we have represented data recorded from 12.00 to 16.30 New Zealand standard time (NZST), only. The days in which water was supplied, either by irrigation or rainfall, are marked with arrows; the number close to each arrow is the number of litres supplied per plant and treatment

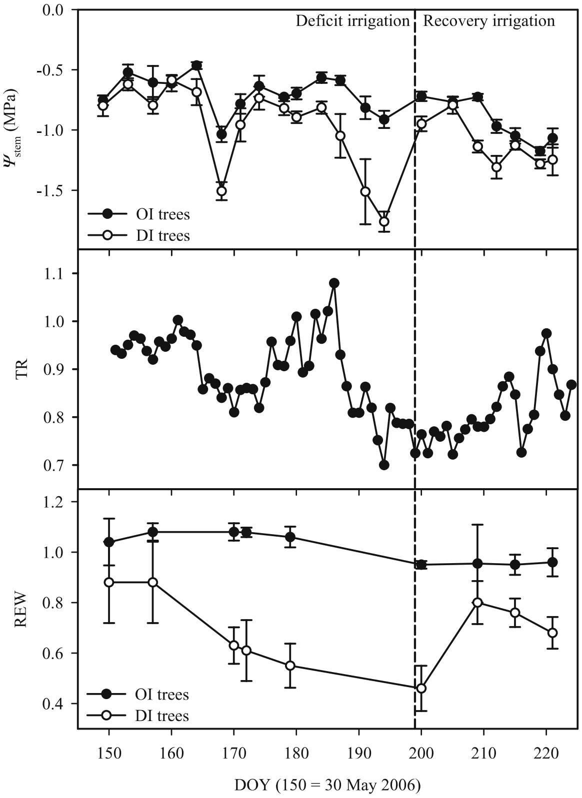

Fig. 6 Time course of the transpiration ratio (TR=E_p deficit irrigated trees/E_p overirrigated trees, being E_p the daily plant water use estimated from sap flow measurements) calculated from measurements in the olive trees of Experiment 1 (see text for details). Also shown are the stem water potential (Ψ_{stem}) of the instrumented trees, and the relative extractable water values (REW) for each treatment. *DI* Deficit irrigated, *OI* over-irrigated. The *dash line* represents the change in the irrigation regime of the DI trees (see text for details). Data points are the average of three values; *vertical bars* represent±the standard error

water are shown in Figs. 7, 8, 9 and 10. Figure 7 shows the time course of the daily grapevine transpiration estimated from sap flow measurements in T4 vines (irrigated at 30% of ET_c) vs. the simulated E_{gr} value for non-limiting soil water conditions. Beyond February 20, actual values of vine transpiration were clearly lower than potential values, triggering irrigation events on March 1, 8 and 15. As shown in the figure, those irrigation events were enough to avoid a further decline between the actual and the potential E_p values. Yet, even with irrigation, the vines did not recover their potential transpiration rate and they remained under a mild water stress.

A similar modelling exercise for the PRD olive trees (irrigated at 50% of ET_c) showed a couple of key features that need to be considered when using models for irrigation scheduling. Figure 8 shows some calculations of tree water use for 2 days of contrasting weather. Values of E_p under non-limiting soil water conditions ("Modeled 1" in the figure) were different on both days mainly due to the prevailing weather conditions since the REW values were 0.51 in August 24 and 0.57 in September 2. When the model accounted for actual values of soil water content then the resulting hourly values of E_p ("Modeled 2" in the figure) were reduced and they became quite similar to the measured sap flow. This good agreement confirms that the $f(\theta)$ developed by Diaz-Espejo et al. (2006) produces a reliable estimate of the impacts of water stress on tree water use.

In the case of apple trees with non-limiting soil water conditions, there was very good agreement between the modeled E_p and the measured sap flow (Fig. 9). The agreement was always good, despite significant changes in weather conditions that occurred during the measurement period. This good result provides added support to the model as a reliable tool for predicting E_p in the experimental orchard. The same goodness of fit was observed between prediction and measured sap flow in Asian pear trees (Fig. 10). For the well-irrigated tree (middle graph), model predictions matched the actual E_p values throughout the experimental day. As expected, model outputs for the deficit-irrigated tree (bottom graph), were much lower than corresponding model outputs for the case of non-limiting soil water conditions ("Modeled 1" in the figure). When the model was run using actual stomatal conductance values measured throughout the day, the simulated

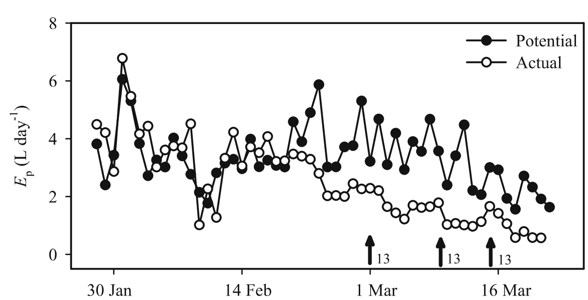

Fig. 7 Vine water use (E_p) for the T4 treatment (30% ET_c), estimated from sap flow measurements (Actual) and with the model of Pereira et al. (2006) for non-limiting soil water conditions (Potential). The days in which water was supplied by irrigation are marked with arrows; the number close to each arrow is the number of litres supplied per plant. No rainfall was recorded in the shown period

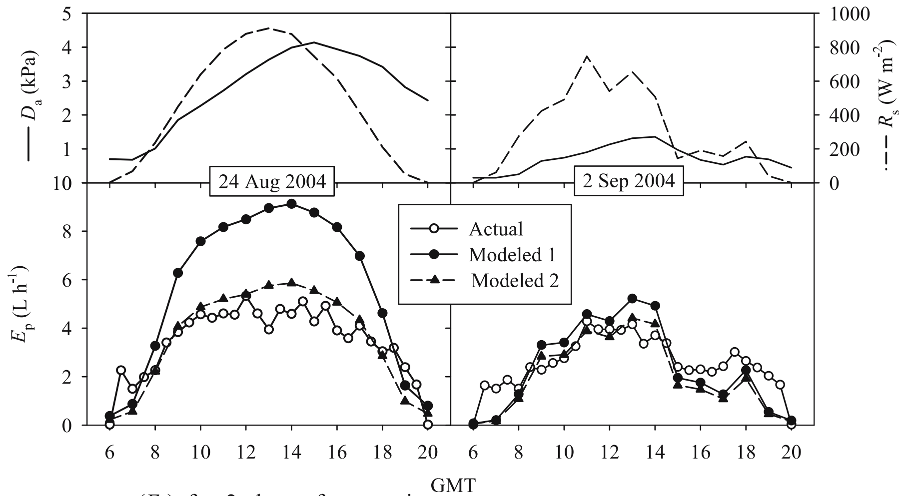

Fig. 8 Olive tree water use (E_p) for 2 days of contrasting atmospheric demand. Data refer to an olive tree under a PRD treatment. The average soil water content was similar on both days (relative extractable water was 0.51 on August 24 and 0.57 on September 2). The E_p values were estimated from sap flow measurements (Actual) and with the model for olive described in the "Materials and methods" section, both for non-limiting soil water conditions (Modeled 1) and for the actual soil water contents (Modeled 2). D_a Vapour pressure deficit of the air, R_s solar global radiation, *GMT* Greenwich mean time. See text for details on the measurements

values of E_p ("Modeled 2" in the figure) were closer to the measured sap flow. However, the model tended to overestimate sap flow early in the morning, and underestimate it later in the day. This is not surprising, since the tree's capacitance is expected to cause a lack of agreement between the tree transpiration and the sap flow measured in the trunk, at those times of the day. The continuation of sap flow late into the night, even after the stomata have closed, has been observed by others (Green and Clothier 1988). We conclude that such sap flow is most likely due to a re-filling of the water lost from the tree's different organs, such as fruit, leaves, and branches, rather than direct evaporation from the leaves. By the time of 2030 h, the average leaf water potential (Ψ_{leaf}) of the deficit-irrigated tree had increased to −1.1 MPa (from −1.9 MPa at noon) compared to a value of −0.2 MPa recorded for the well-watered tree. It is worth noting that a value of −0.2 MPa is a typical pre-dawn value for the non-stressed trees in this study. Thus, the deficit-irrigated tree was likely to be under a moderate water stress with sap flow continuing well into the night. In contrast, the well-watered tree had become fully rehydrated by the end of the day and so little sap flow occurred beyond 2030 h as a consequence.

The delayed onset of sap flow in the early morning, relative to the calculated transpiration losses, was most likely favoured by the very low soil moisture conditions (REW=0.09) experienced by the Asian pear trees. The average soil water content measured in the lysimeters on the morning of November 18 was just θ=0.07 m^3 m^{-3}, and this equates to a mean soil water potential of about <−0.8 MPa for this B horizon of the Manawatu fine sandy loam (Clothier et al. 1977). Little or no sap flow would be expected until the plant water potential was reduced (i.e. becomes more negative) below the threshold set by the soil water potential. At pre-dawn times and at 0800 h, the leaf water potential ψ_{leaf} of the deficit-irrigated tree was only slightly less than

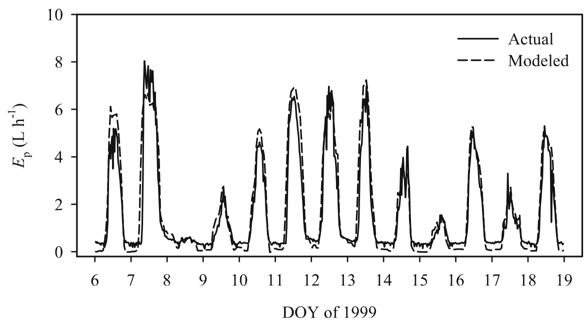

Fig. 9 Apple tree water use (E_p) for non-limiting soil water conditions, both estimated from sap flow measurements (Actual) and with the Penman–Monteith equation adjusted for the orchard conditions (Modeled). See text for details on the measurements

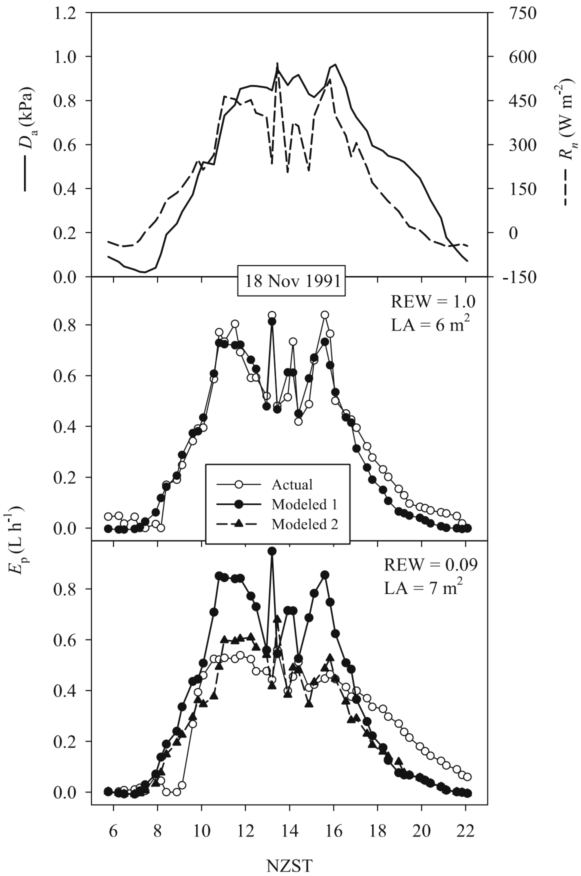

Fig. 10 Asian pear tree water use (E_p) both under non-limiting (*central graph*) and limiting (*bottom graph*) soil water conditions, estimated from sap flow measurements (Actual) and with the Penman–Monteith equation: data marked as "Modeled 1" are potential transpiration values estimated for non-limiting soil water conditions; data marked as "Modeled 2" are the outputs of the equation after input the actual stomatal conductance values recorded on that day in the deficit irrigated tree. D_a Vapour pressure deficit of the air, R_n net radiation, *REW* relative extractable water, *LA* tree leaf area, *NZST* New Zealand standard time. See text for details on the measurements

that of the well-watered tree (−0.27 vs. −0.13 MPa, and −0.57 vs. −0.39 MPa, respectively). However, by about 1000 h the values of ψ_{leaf} had declined to −1.72 MPa in the DI tree compared with −0.97 MPa for the OI tree. Sap flow began some time between 0930–1000 h, i.e. about the same time when ψ_{leaf} became less than the estimated water potential of the bulk soil.

Discussion

When determining the total transpiration of woody plants from sap flow measurements, scaling errors associated with the measurement can be substantially reduced if the radial pattern of sap flow is determined across the entire sapwood depth (Wullschleger and King 2000; Nadezhdina et al. 2002). Typically sap flow is fastest towards the outer xylem regions (Cermak and Nadezhdina 1998) but that is not always the case. Analysing the shape of the sap flow profile has been reported by some researchers as a useful way of scheduling the need to irrigate. This was the case in previous work that we did in our experimental olive orchard, as reported by Fernández et al. (2001). In that work there were clear changes in the profile shape that corresponded to times when the trees were under mild water stress due to insufficient water in the root-zone soil. More recently, Nadezhdina et al. (2007) reported that the shape of the sap profiles, recorded in both the trunk and branches of olive trees, changed in response to soil water content. They observed a decrease in sap flow in the outermost xylem when the water content in the top soil layer decreased. Their findings are at odds with our own results shown in Figs. 1, 2, 3, 4. In our work we could find no consistent changes in the radial pattern of sap flow profiles as a result of water stress in any of our experimental plants. Our results, in fact, clearly suggest that the shape of the sap profile is consistent under a wide range of soil moisture levels. Therefore, an analysis of the shape of the flow profile alone does not appear to be a reliable indicator for scheduling the onset and need for irrigation.

Nadezhdina et al. (2007) hypothesized that different parts of the stem xylem are connected with roots exploring different volumes of soil with different water conditions. Others acknowledge the upwards connection of xylem to the branches and leaves of the plant (Tyree and Zimmermann 2002), and this too can account for large spatial variation in measured sap flow. Either way there are likely to be differences in the radial patterns of sap flow at different locations around the tree stem at different radial depths into the sapwood. In the data presented here there was a lack of consistency in the response of the radial sap flow pattern. The greatest sap flow values were recorded close to the cambium in most cases, but in a few occasions a change in the water stressing conditions gave rise to the greatest values occurring deeper into the xylem.

The second indicator for irrigation scheduling, i.e. the transpiration ratio (TR) obtained by dividing the measured sap flow in a target plant by the corresponding sap flow in a similar-size plant growing under non-limiting soil water conditions, appeared to be a more useful irrigation scheduling tool, at least for grape (Fig. 5) and olive (Fig. 6) that were tested here. Nonetheless, widespread application of this approach in commercial orchards may be limited by the need to have "well-irrigated" plants as a reference. Apart from the need to modify the irrigation system around those plants, they may also be overirrigated and exhibit different growth habits and behaviours. For example, over watering could lead to those plants becoming non-representative, due to a lack of oxygen in the rootzone, of a nitrogen deficiency because of excessive leaching losses, etc. (Goldhamer and Fereres 2001). Also, well-irrigated plants may develop much larger leaf areas resulting in higher water use than by other plants in the orchard.

Another limitation of the TR approach is that full irrigation may not be required to maximise fruit yield or quality. For example, the 'Picual' olive trees studied by Moriana et al. (2003) demonstrated a curvilinear response of yield to irrigation, both for fruit and oil production. Decreasing productivity was observed when irrigation application approached that of maximum crop water requirements. A similar result was reported by Grattan et al. (2006) and Berenguer et al. (2006) in a super high tree-density olive orchard. In both studies production was maximised by using irrigation amounts of between 70–75% of ET_c, while the best oil quality was obtained from trees irrigated using between 33–40% of ET_c. An appropriate deficit irrigation approach can produce better fruit compared with a full irrigation treatment on grapevines. This is because growth is reduced (less pruning required), yield is not affected and fruit quality may improve (de Souza et al. 2003, 2005; dos Santos et al. 2003).

The third approach evaluated in this work was the use of computer models to estimate the potential water use E_p from the prevailing weather conditions. Such an approach would avoid the limitations of using well-irrigated plants as a reference, as mentioned in the previous paragraph. The use of models to estimate transpiration both at the plant and orchard level is not new (see review in the Introduction of the paper by Pereira et al. 2006). Results from our modelling exercises reinforce the dual potential of measurements and models to aid with irrigation scheduling. Firstly, the method is useful when the grower has access to daily climate data, needed to better define plant water use, and has confidence in the calculation procedures. Secondly, models can help the smart growers choose an appropriate deficit irrigation approach: results presented in Figs. 8 and 10 illustrate how models can be useful tools to estimate water consumption for a wide range of soil water conditions. Such information can then be combined with model estimations of the crop performance vs. the soil water content (see Fernández et al. 2007, for an example with olive trees).

Worldwide growers and industries are embracing technology and riding the knowledge wave as they seek to develop sustainable production systems. It is clear, however, that not all growers will use complicated models such as those based on the Penman–Monteith equation presented here. Instead, more user-friendly equations validated for particular orchard conditions, such as that by Pereira et al. (2006), could have a greater impact on the use of computer-based tools for scheduling irrigation. That will only happen in commercial orchards if easy methods can be found for determining leaf area development. Prospects for the development of simple leaf-area estimators are promising: both the point quadrant method (see example for grapes in van der Velde et al. 2006) and the gap photographic fraction method (see example for olive and other fruit trees in Phattaralerphong et al. 2006) can provide reliable measures of plant leaf area and they require little time and effort.

An additional problem arises when model calculations of E_p are compared with measured sap flow. In heterogeneous orchards, spatial variability in plant size and density within the orchard means that the number of instrumented trees required to get a sound measure of orchard water use climbs to unaffordable levels (Naor and Cohen 2003; Naor et al. 2006). Once again, technological advances are coming to the rescue and will, eventually, minimize this problem. For example, remote sensing of canopy 'green leaf area' and canopy temperature, via fixed camera or satellite imagery, can already identify problem areas and may also help to select representative sites within the orchard. Such advance could also reduce significantly the number of instrumented trees (Naor 2006; Sepulcre-Cantó et al. 2006).

Conclusions

In contrast to what has been suggested by other authors, as well as by previous work we have done in some of our orchards, the shape of the sap velocity profiles does not appear to be a reliable indicator for scheduling irrigation. The use of the transpiration ratio, as defined from the ratio between the actual daily water use divided by the potential daily water use of similar plants under non-limiting soil water conditions, appears to be a useful tool for irrigation scheduling. However, when the potential water use is estimated with well-irrigated plants, problems related to overirrigation e.g. hypoxia, and nutrient leaching to name a few, may develop easily. If that happens then those plants are not a good representation of the orchard. In addition, well irrigated plants may not be appropriate as reference plants because, in some cases, plant form and function may be altered. A deficit irrigation strategy is sometimes an advantage over full irrigation, especially in olive, grapes, and other species in which high levels of water in the soil can actually decrease fruit quality.

Computer modelling offers an alternative approach to estimate the potential plant water use, i.e. the use of a validated model for local orchard conditions, appears to be more promising. The reliability of the calculations rests on good knowledge of plant leaf area. The impact that the transpiration ratio method may have for scheduling irrigation in commercial orchards will depend, first, on the development of simplified models able to give reliable values, even when relying on a larger number of empirical inputs. This is the case of the model of Pereira et al. (2006) developed for grapevines. It will further depend on the availability of user-friendly methods both for estimating some of the input variables of the model, e.g. the time course of leaf area development, and for reducing the number of instrumented plants required for obtaining representative values for the whole orchard. Recent developments in both aspects make us optimistic on an increasing use of the mentioned approach in commercial orchards.

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