Evaporation from the grapevine canopy and soil surfaces

Isa A. M. Yunusa

Department of Primary Industries, Rutherglen Research Institute, RMB 1145,
Rutherglen, Vic 3685, Australia

Abstract

In most commercial vineyards, canopy expansion is restricted by the rigid trellis systems and so only a small fraction of solar radiation is intercepted. This results in low rates of water use by vines compared to crops with fully closed canopies. Several studies in the recent past have, however, suggested that the small fractions of solar radiation intercepted by the canopy may not be constraining water use, because of additional energy transferred to the canopy from the exposed soil surface. It is shown in this review that this may not be the case under the hotter and drier conditions of the inland grape-growing districts of Australia, where the vines use their stomates to control evaporation through the canopy (E_c). In this environment, substantial proportions of the energy absorbed by leaves tend to be stored in the canopy, which may be up to 4 °C warmer than the surrounding air during daytime. A daily rate for E_c of 1.5 mm (approximately 12 litres per vine) was found over two seasons, from which the amount of water required by the grapevines for the growing season was estimated to be 210 mm (2.1 megalitres/ha). This constituted 47% of the total seasonal water-requirement for the whole vineyard of 450 mm (4.5 megalitres/ha). The latter was based on a crop factor (K_c) of 0.3 for a typical drip-irrigated vineyard at Merbein in the north-west of Victoria. The rest of E is accounted for by evaporation from the soil surface (E_s), most of which occurs just outside the canopy edge, especially on the northern side of the vine rows following rainfall and/or irrigation. Estimates of seasonal E could be up to 1.5 fold higher than 450 mm under full-cover irrigation systems or in the presence of cover-crops. It is concluded that aspects of irrigation water management developed in the Northern Hemisphere should only be applied with caution to the inland grape-growing regions of Australia, where the vine appears highly parsimonious in its water use.

Introduction

Water is increasingly a key determinant of profitability of viticulture in many parts of Australia. Water requirements for vineyards depend on several biological, environmental and management factors. In the absence of run off, water applied to and stored in the soil is either used for evaporation through the surfaces of plants and soil (E), or is drained (Dr) either to ground water or lower depths of the soil beyond the reach of roots:

$$\Delta S = E + Dr \tag{1}$$

where ΔS is change is soil-water storage. The Dr component is generally lost to the production system, but may raise the watertable which may be saline and could contribute to salinity problems. It is generally difficult to split E between that which occurs through soil (E_s), and that through plant canopy (E_c) or transpiration, especially in tree crops and grapevines that sparsely cover the ground area. It is however, important to quantify the two components, E_s and E_c, because management determines the degree of canopy cover in these crops, and hence, the extent to which the crop and soil intercept sunlight. New flow-sensing technologies are now commercially available allowing E_c to be monitored with comparative ease in woody species.

Drip irrigation and other techniques that deliver water close to root systems have provided a saving in costs in addition to reducing off-farm impacts. By minimising both the wetted area of the surface and the profile of the soil, these techniques minimise E_s. This is especially important in vineyards where interception of solar energy by the canopy is poor, with the majority transmitted to the soil surface, and where E_s can account for up to 70% of E (Lascano et al. 1992; Heilman et al. 1994; Yunusa et al. 1997a). In this paper, partitioning of E between E_s and E_c is re-evaluated using published and some unpublished data to illustrate that water use by vines can differ between districts with seemingly similar weather conditions.

Soil evaporation (E_s)

The rates and magnitude of E_s are determined by soil water contents and radiant energy incident on the soil surface. Ritchie (1972) described a two-stage evaporation process by which the first stage commences soon after the soil surface has been wetted, and proceeds at a rate determined by the atmospheric conditions. During this first stage, also termed the energy-dependent stage, E_s may approach potential evaporation (E_{pot}) and is thus sensitive to the degree of soil surface shading either by crop canopy or mulching. The second phase comes into effect once free moisture at the soil surface dries out, and its rate is dependent on soil-water content and the ability of the soil to transfer moisture to the surface, i.e. the unsaturated hydraulic conductivity of the soil. Soils generally are not able to transfer water to the surface at a rate high enough to meet the evaporative demand, hence E_s in the second stage is generally less than E_{pot}. The stage-two process, however, can prevail for extended periods resulting in substantial loss of soil water.

Soil water lost through E_s can be substantial in vineyards following irrigation, especially with full-cover or flood systems that wet large proportions of the soil surface. Irrigating at long intervals is designed to minimise the length of time the soil surface remains wet. The small area of the soil surface wetted with drip irrigation generally limits stage-one evaporation, although such irrigations tend to be more frequent, so some of this saving is off–set by the total time that the soil surface along the drip-line remains wet. Stage-two process may also be substantial even some distance away from the drip line, due to lateral sub-surface redistribution of soil water, which occurs in response to the gradient in water potential between the profile under the drip-line and that away from the point of water application. Measurements in six-year-old, drip-irrigated grapevines at Merbein in 1995 (I.A.M. Yunusa, R.R. Walker and P. Lu, unpublished data) showed a uniform wetness of the soil profile across the vineyard (Fig. 1) implying that stage-two E_s is also likely to be uniform across the vineyard. This result suggested that E_s can, therefore, be substantial even with the drip-irrigated system, despite application of water being limited to only small areas.

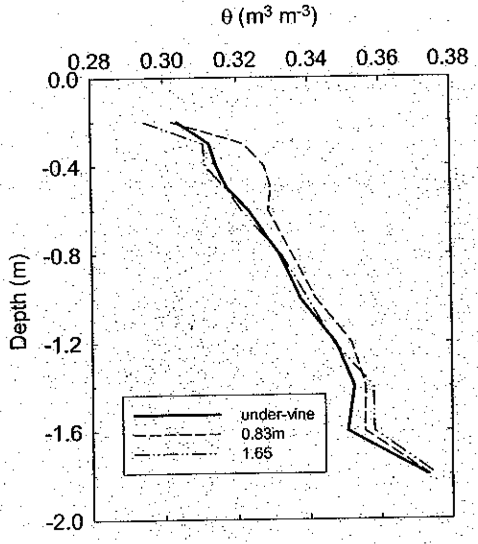

Figure 1. Volumetric water content (θ) for the soil profile beneath the vine and at 0.82 m and 1.65 m distances into the inter-row space in February 1995 at Merbein. Position 1.65 m corresponds to mid-inter-row. Source: I.A.M. Yunusa, R.R. Walker and P. Lu (unpublished data)

Several schemes have been described in the literature for determining E_s in the field using either micrometeorological methods (Shuttleworth and Wallace 1985), soil hydrology (Tanner and Jury 1968; Van Bavel and Hillel 1976) or weighing lysimeters (Rose et al. 1966), or their combination in various forms. Lysimetry is considered to provide the most precise estimates of E_s, with microlysimetry often used to determine loss of water from the surface beneath crops. The technique involves taking intact soil cores with metallic or plastic cylinders, ranging in diameter of between 80 and 200 mm, and in length of between 50 and 300 mm. These are installed beneath the canopy or in the open, and are repeatedly weighed to obtain E_s (Boast and Robertson 1982), and have been used in vineyards by Trambouze et al. (1998).

Microlysimetry was used at Merbein in 1995 to monitor E_s at several positions under the drip line and at a distance of 0.83 m on either side of the drip line and at midway between vine rows, under various soil-water conditions (Fig. 2) (I.A.M. Yunusa, R.R. Walker and P. Lu, unpublished data). E_s for the day following a 12 mm rainfall on 14 February was highest along the drip line (0.83 m either side of the vines), especially on the northern side where exposure to direct solar radiation caused rapid rates of water loss from the soil surface. By contrast, the soil surface on the southern side of the vines was shaded and dried out gradually at low rates of E_s (Fig. 2a), i.e. the soil on this side switched into the stage-two process later than on the northern side. A similar pattern in E_s distribution was observed during frequent irrigation periods (Fig. 2c), suggesting that substantial amounts of water were lost through the soil surface even with drip irrigation. During extended dry periods with neither rainfall nor irrigation, E_s was predominantly in stage two and was therefore similar at all positions (Fig. 2b).

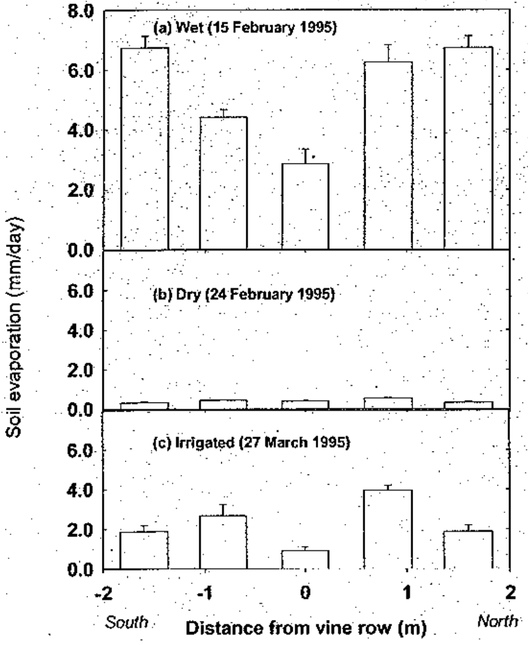

Figure 2. Soil evaporation (E_s) measured with microlysimeters in a drip-irrigated vineyard for (a) wet, (b) dry and (c) irrigated days at Merbein, Australia. The left-hand side of the graphs corresponds to the south of the vine rows, and the right-hand side to the north. Measurement positions were 0 (under-vine), 0.83 m north and south, and 1.65 m (mid-interrow). Standard errors of means are shown on each bar. Source: I.A.M. Yunusa, R.R. Walker and P. Lu (unpublished data).

It should be noted that E_s at the respective measurement positions were not additive for determining water loss for the whole vineyard, since they were not hydrologically independent. Mean E_s for the vineyard on each of the three days was 4.5 mm on 15 February, 0.4 mm for 24 February and 2.4 mm for 27 March; the corresponding E_{pot} (Monteith and Unsworth 1990) for those days was 9.6, 12.8 and 3.7 mm respectively. E_s at 0.83 m on either side of the vine rows was similar over the long term (Table 1). This is because Yunusa et al. (1994) showed in a previous study that an initial short phase for stage one was always followed by relatively high rates of stage-two, as found on the northern side of the vines. However, the pattern was reversed for the southern side of the vine rows. E_s was generally highest at 0.83 m distance (long edge of canopy) that was wetted through surface redistribution during irrigation, while it was restrained by canopy shading under the vine and by a dry soil surface mid way between the rows (Table 1). Daily E_s for the vineyard averaged 1.34 mm during the measurement period. This was much higher than the 0.55 mm for rainfed vineyards in France (Trambouse et al. 1998), where the soil surface remained dry for most of the time except in rainy periods, i.e. the situation was similar to the dry period at Merbein (Fig. 2c).

Table 1. Average rates for daily E_s measured with microlysimeters at various positions relative to the vine rows in a drip-irrigated vineyard between January and March 1995 at Merbein. Source: I.A.M. Yunusa, R.R. Walker and P. Lu (unpublished data).

Position	E_s (mm d^{-1}) (mean ±se)
Under-vine	1.0 ± 0.16
0.83m north	1.6 ± 0.25
0.83m south	1.5 ± 0.28
Mid-interrow	1.3 ± 0.18

Transpiration (E_c)

This is the component of the E that contributes directly to fruit production. It is a process that is primarily driven by:

(a) Proportion of radiant energy intercepted by the canopy
(b) Humidity of the air
(c) Transport mechanism – *viz.* turbulence and wind
(d) Availability of water in soil

Of these four, only energy interception and water supply can be readily manipulated by the grower and thus provide opportunities for enhancing water-use efficiency and/or grape quality. These factors are considered briefly further in the following sections.

Radiant energy

Many studies (e.g. Lascano et al. 1992; Sene 1996) have associated the parsimonious use of soil-water by grapevines with the small fraction of radiant energy intercepted by the canopy. Manipulating energy interception by enlarging the canopy through widening the width of the trellis, fertilisation and/or rootstock choices may not always be desirable as it may have undesirable consequences on fruit quality and also restricts access within the vineyard. Daily rates of E_c of between 0.8 and 2.2 mm have been reported for irrigated vines of different canopy size in North America (Lascano et al. 1992; Heilman et al. 1994) similar to 1.6–2.2 mm for rain-fed vines in Europe (Trambouse and Voltz 2001). These upper limits were higher than the 0.8–1.2 mm found for drip-irrigated vines in inland Australia (Yunusa et al. 1997a, 1997b). Studies by Heilman et al. (1994, 1996) in the southern United States, however, showed that the vines acquire additional energy emanating from the exposed surface of the soil and its transfer to the canopy. This additional energy then enhanced transpiration, so that E_c could be in excess of radiant energy directly intercepted by the vine. To understand this phenomenon, water use by vines should be considered in terms of their energy balance components. Available radiant energy (R_n) incident on the vineyard surface is either used directly to evaporate moisture as latent heat (λE), or stored in the soil (G), or is given off as sensible heat (H) by the intercepting surface:

$$R_n = \lambda E + H + G \qquad (2)$$

The soil surface is the major source of H in vineyards, but it can also be generated from the canopy. A framework similar to eqn (2) can be applied to that fraction of energy absorbed by the vine canopy (R_{nc}):

$$R_{nc} = \lambda E_c + H_c \qquad (3)$$

where the subscript *c* applies to vine canopy. In the studies of Heilman et al. (1994, 1996) they found that H accounted for up to one third of the energy used for E_c. This is a phenomenon that has been reported in other field-crops planted in wide rows, and sometimes termed the *clothesline effect*. By this process energy originating from the exposed soil surface is advected to the canopy under unstable conditions to enhance crop water-use (Johnson et al. 1981; Graser et al. 1987; Sojka et al. 1988). However, data in Table 2 suggest that this process may not be important in enhancing water use by the grapevine at Merbein. Despite the similarity in R_n at Lamesa and at Merbein, λ

E was lower, while H was higher, at the latter compared to the former location (Table 2). At Lamesa, λE_c was in excess of R_{nc}, meaning that the vine must have gained energy from H transferred to the canopy to support transpiration. This process is discussed further later.

Table 2. Comparison of daily averages of the components of energy balance for irrigated grapevines during the mid part of growing seasons at Merbein, Australia (34° 13'S, 142° 2'E) and Lamesa, USA (33° 30'N, 102°W)

Energy component ($MJ\ m^{-2}$)	Lamesa (5 –8 June 1991)	Merbein (15 –20 Feb. 1996)
	Whole vineyard	
R_n	15.4	14.1
λE	8.4	6.1
H	3.4	6.3
G	3.6	1.2
	Vine canopy	
R_{nc}	2.5	4.9
λE_c	3.7	2.9
H_c	1.2	2.0
$\lambda E_c:R_{nc}$	1.48	0.59
λE_s ($\lambda E-\lambda E_c$)	4.7	3.2

Sources: Merbein from I.A.M. Yunusa, R.R. Walker and P. Lu (unpublished data) and Lamesa from Heilman *et al.* (1994).

Divide λE or λE_c by 2.45 to obtain E or E_c in mm.

An underestimation of λE_c could not have been the reason for λE_c being less than energy intercepted by the canopy (R_{nc}) at Merbein, since the sapflow system used was calibrated (Yunusa et al. 2000), and was also satisfactorily compared against another sapflow monitoring technique (Lu et al. 2002). The result at Merbein could be associated mostly with micrometeorological conditions, especially the degree of moistness of the atmosphere and/or presumably the low stomatal conductance.

Air humidity

The moistness of air determines its drying-power. Dry air generally has a greater drying capacity than a moist one. Humidity also influences the response of the plant to environment by controlling the degree of opening of the stomates (pores on leaf surfaces that form the pathway through which water is lost to the atmosphere, and through which CO_2 enters the leaves). For the purpose of these exchanges, the air-moistness is considered in terms of its vapour pressure deficit (D), which is the partial pressure exerted by the water vapour molecules in comparison to the partial pressure they exert if the air was saturated at the same given temperature. Plants are generally sensitive to D, such that grapevines tend to shut their stomates as air gets drier, often observed around mid-day (Loveys 1984). This happens even though soil-water may be readily available (Lange and Meyer 1979; Larsen et al. 1989). Conductance of water-vapour through the canopy of irrigated grapevines declines rapidly once D exceeds 1.0 kPa in inland Australia (Lu et al. 2003). Once stomates close, R_{nc} may not be entirely dissipated through λE_c, but remains stored in the canopy, which then becomes hotter than the surrounding air (Table 2) and makes the canopy a significant source of H.

Transport mechanism

Wind conveys vapour away from the evaporating surface to maintain the gradient between the surface and the air, which then ensures continuous loss of water vapour (Monteith and Unsworth 1990). The characteristics of the prevailing wind that have a profound influence on E_c are its speed and humidity. For instance, the capacity of the wind to absorb moisture is generally inversely related to its humidity so that dry winds tend to have greater drying power than a moist one. A relatively moist wind may, however, sustain E_c since they are less likely to induce stomatal closure, as described above. In the study of Heilman et al. (1994) that was introduced above, the stomatal conductance was much higher than was observed at Merbein (Table 3). This was due in part to a comparatively lower D at Lamesa than at Merbein. The resulting high rates of E_c at Lamesa cooled the canopy below the temperature of the surrounding air by as much as 5°C. Conversely at Merbein, stomatal conductance was low and the canopy was warmer than the ambient air by up to 4.7 °C, irrespective of the rootstock.

The foregoing, therefore, suggests that weather conditions at Lamesa are more conducive for dissipating heat through λE_c, which could be enhanced by a net transfer of H to the canopy, compared to inland Australia. This is consistent with values for the decoupling factor (Ω), which sets the relative importance of aerodynamic forces in driving E_c (McNaughton and Jarvis 1983). A lower Ω at Merbein (Table 3) suggested that the E_c was controlled less by radiation than by D at this site, compared to Lamesa where the prevalent weather conditions appear to be more conducive to sustaining high rates of transpiration . The 4-year averages of key weather variables show that Lamesa is generally warmer and windier, but more humid (has lower D) than Merbein. Daily averages for the main weather variables at Merbien were 1.27 kPa for D, 36.1 MJ for radiation, 2.6 $m\ s^{-1}$ for wind, and 20.1 °C for mean temperature. The corresponding values at Lamesa were 1.40 kPa, 23.0 MJ, 3.43 $m\ s^{-1}$ and 23.6 °C, respectively (Table 3). Long-term weather data (Fig. 3) show that Lamesa is generally more humid (average D= 1.27kPa) and windier, than Merbein (D=1.44kPa) from mid-season onwards. This suggests that the second half of the growing season at Lamesa, with declining D (Fig. 3d), wind speed (Fig. 3b) and, hence, evaporative demand (Fig. 3e), tends to be more favourable to sustaining high rates of transpiration than at Merbein. It is probable that the prevailing wind at Lamesa brings in moist air to account for the relatively low D, while the high wind speeds increase the potential for the transfer of H to the canopy. Therefore, transpiration may be less likely to be moderated by the physiological control mechanisms of the vine at Lamesa than in the drier environment at Merbein.

Table 3. Typical leaf characteristics for grapevines, and weather variables for the days of measurements, at Merbein in Australia and at Lamesa in USA during the mid part of the growing season (The vines at Merbein were variety Sultana either on their own-roots or on Ramsey rootstock)

Variables[1]	Merbein[2]		Lamesa
	Own- rooted	Ramsey	
Peak leaf area per plant (m^2)	16.5	28.4	4.7
Peak groundcover (%)	30	45	11
Stomatal conductance (g_s) (mm s^{-1})	3.2	2.4	20.0
Leaf–air temperature (°C)	4.7	4.5	-5.0
Air temperature (°C)	20.1		25.2
Vapour pressure deficit (VPD)	1.2		1.0
Wind speed (m s^{-1})	2.5		2.5
Average coupling factor (Ω)	0.13		0.53

[1] r_s and leaf temperature measured on 17 February 1995 at Merbein, and between 5 and 8 June 1992 at Lamesa; Data for Merbein from Yunusa et al. (1997) and I.A.M. Yunusa, R.R. Walker and P. Lu (unpublished data), and for Lamesa from Heilman et al. (1994).

[2] Differences in LAI, peak groundcover, g_s and leaf-air temperature between Sultana on own roots and Sultana on Ramsey significant at $P < 0.001$.

Soil moisture

Transpiration is sensitive to availability of soil water, and conductance of water vapour through the stomata (g_a) is often restricted at low levels of soil-water availability. Trambouze and Voltz (2001) observed declines in E_c from grapevines once soil-water availability dropped below 90% of field capacity. This may not be critical in many irrigated vineyards, where supply of soil water is often kept at relatively high levels. However, manipulation of water supply is becoming an important tool for achieving high water use efficiency for fruit yield and quality.

Techniques such as Regulated Deficit Irrigation (RDI) and partial rootzone drying (PRD) are being applied in order to minimise water use and to improve grape quality.

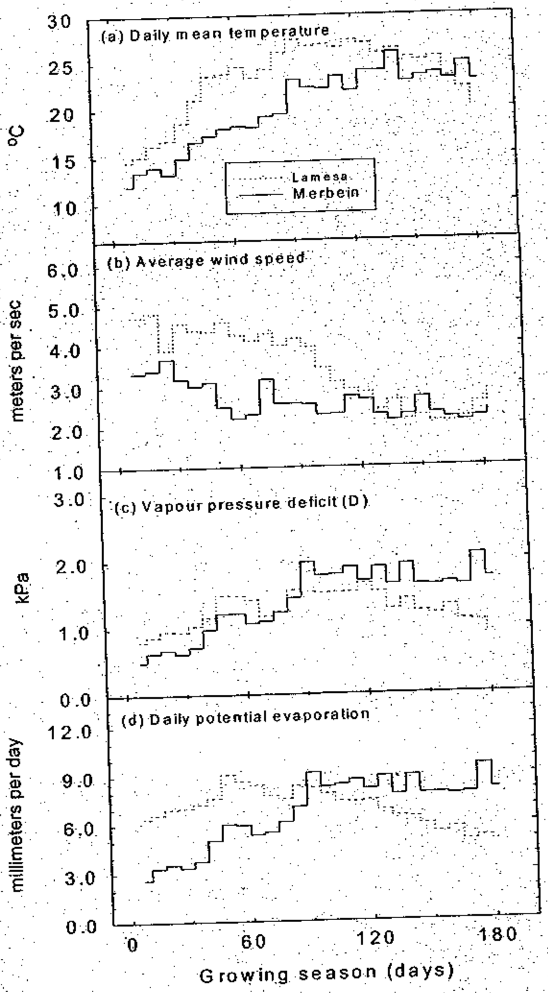

Figure 3. Weekly averages for selected meteorological variables for Merbein, Australia, (1994–1998) and Lamesa, USA (1996–2000). Start of growing season taken as 1 September at Merbein and 1 April at Lamesa. Sources: Merbein weather data from CSIRO Plant Industry, Merbein; Lamesa weather data (http://lubbock.tamu.edu/irrigate/et/archive.html)

The foregoing discussion on how micrometeorology and soil water influence transpiration has shown that prevailing climate factors could explain, to a large extent, the differences in E_c reported for grapevines in the literature. From studies at Merbein discussed above, a daily rate of E_c was found to be 1.5 mm d^{-1} (12.4 litres/vine/day) in 1995 (Yunusa et al. 1997a) and 1996 (Table 2) (I.A.M. Yunusa, R.R. Walker and P. Lu, unpublished data). This was lower than the upper rates of 2.2 mm day^{-1} from vines with canopies smaller than those at Merbein, and growing in the cooler and moister environments of North America (Lascano et al. 1992; Heilman et al. 1994). Cool conditions also tend to prevail in grape-growing areas of southern Europe, where summers experience considerable rainfall and E_{pot} rarely exceeds 6.0 mm d^{-1} (Sene 1996; Trambouse and Voltz 2001). The ratio E_c/E_{pot} at Merbein during several periods of measurements in the two seasons averaged 0.15. This suggested a seasonal grapevine water requirement of 210 mm or 2.1 megalitres based on the 5-year average (1994–1998) for total E_{pot} of 1517 mm for the growing season (September–April). Differences in water use and water requirements could also be due to varietal differences between both scions and rootstocks.

Whole vineyard water-use and water requirement at Merbein

Water requirements are generally low for drip-irrigated vineyards where both E_s and E_c are generally conservative. This was evident by the measurements made at Merbein between January and March in 1995 (Yunusa et al. 1997a) and between January and March in 1996 (I.A.M. Yunusa, R.R. Walker and P. Lu, unpublished data) where daily rates of E are generally between 1.8 and 3.2 mm d^{-1} (Fig. 4a). These rates were lower for 1995 (average 1.74 mm day^{-1}) when E was obtained by separate measurements of E_s with microlysimeters and E_c with a sapflow system, compared to 1996 (2.49 mm day^{-1}) when the Bowen Ratio Energy Balance technique was used. It appears more probable, however, that the differences in rates between the two years were associated with a greater evaporative demand in 1996, when daily rate of E_{pot} averaged 7.5 mm compared to 6.9 mm in 1995 (Fig. 4b). These values were remarkably similar to 1.8–3.5 mm d^{-1} reported for 11-year-old vines planted in a 2.4 m grid in southern France (Trambouze et al. 1998), but generally higher than the average of 1.6 mm d^{-1} in a previous study at Merbein (Yunusa et al. 1997a). In the previous study, Yunusa et al. (1997a) estimated E_s to be less than 0.8 mm d^{-1} during the January–March period, compared to 1.34 mm d^{-1} measured with microlysimeters (Table 1).

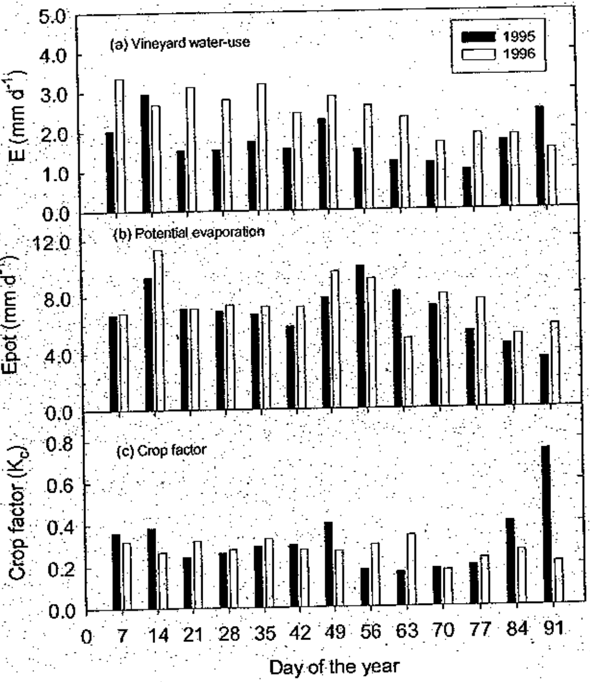

Figure 4. Weekly averages for (a) vineyard water use, (b) potential evaporation, and (c) crop factor, at Merbein. E was determined as the sum of separate measures of soil evaporation and transpiration in 1995 (Yunusa et al. 1997a) and determined with a Bowen ratio energy balance technique in 1996 (I.A.M. Yunusa, R.R. Walker and P. Lu, unpublished data).

Estimations of water requirement for irrigated crops are commonly based on a crop factor (K_c), or the ratio of E to E_{pot} for a given period or for the whole season. The data presented in Fig. 4 covered almost one half of the seasons, and the mean values for K_c were 0.32 in 1995 and 0.29 in 1996. An average value of 0.31 for K_c would therefore be appropriate for this site, and was used to estimate seasonal water requirement of 450 mm (4.5 megalitres/ha) for a typical drip-irrigated vineyard from a 5-year average of 1450 mm for the seasonal E_{pot}.

Conclusion

It is demonstrated here that water use by grapevines and the vineyard as a whole is strongly influenced by the environment. Hot and dry conditions prevalent in inland Australia during the growing season exert considerable restraint on stomatal conductance thereby limiting transpiration, despite frequent irrigation. Soil evaporation is a major component of the evapotranspiration, accounting for up to 47% of the seasonal water use. Most of E_s occurs just outside the canopy edge especially on the northern side of the vine rows following rainfall and/or irrigation. Seasonal water-requirement was estimated to be 450mm (4.5 megalitres/ha) based on a K_c of 0.31 for a drip-irrigated vineyard at Merbein. It should be noted that with full-cover irrigation the estimates of E would be larger due to high rates of E_s from the whole surface of the soil that is wetted frequently, and may increase seasonal water requirement by up to 50%, more so with cover crops (Yunusa et al. 1997b).

Understanding of some of the issues discussed in this paper is still limited, and requires further study in order to develop practices for achieving sustainable irrigation water management. These include:

- Well defined protocols for the use of commercial sapflow sensor systems for a wide range of environments, especially calibration of these systems in the field. Once this technique can be used with a high degree of certainty, varietal differences in stomatal response to temporal and long term dynamics in weather and other environmental conditions can be characterised and modeled with relative ease. Most models currently in use do not adequately account for varietal or rootstock differences in response to a set of environmental conditions.
- The question of whether grapevines transpire water at night. Despite data indicating nocturnal E_c, (Green et al., Lu et al. and Petrie et al., this proceedings), further work is required to better characterize this phenonemon.
- Re-evaluation of the efficiency of above-ground trickle irrigation on medium and heavy textured soils. It is shown here that significant lateral redistribution of water both at the soil surface and within the profile occurs to support relatively high rates of E_s at locations distant from the drippers.
- Exploration of opportunities to convert water lost through E_s for some productive use, such as for cover crops that could provide mulch and enrich soil carbon.

In conclusion, lessons learnt from grapevine water-use in the Northern Hemisphere should be applied with caution to inland Australia where the vines tend to be highly parsimonious in their water use. These lessons may, however, be more readily applicable to cooler districts such as the King Valley or Southern Victoria and south-eastern South Australia.

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