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Crop water parameters of irrigated wine and table grapes to support water productivity analysis in the São Francisco river basin, Brazil

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ABSTRACT

Energy and water balance parameters were measured in two commercial vineyards in the semiarid region of the São Francisco river basin, Brazil. Actual evapotranspiration (ET) was acquired with the Bowen ratio surface energy balance method. The ratio of the latent heat flux to the available energy, or evaporative fraction (EF), was 81% on average for two growing cycles in wine grape and 88% for two growing seasons in table grape. Energy partitioning in this last vineyard was higher due to microsprinkler irrigation conditions and greater soil cover promoted by the overhead horizontal trellis systems. The accumulated ET from pruning to harvest in wine grape was 438 and 517 mm for the first and second growing cycles, respectively. Table grape consumed less water than wine grape (393 and 352 mm for the first and second growing seasons, respectively) due to shorter crop stages. Beneficial transpiration (T) was 89 and 81% of total ET for wine and table grape, respectively. Brazilian semiarid climate allows 2.5 production cycles per year for vineyards. The yield was in average of 6183 kg ha^{-1} for two cycles of wine grape and 11,200 kg ha^{-1} for one short growing season of table grape, corresponding to a bio-physical water productivity per unit ET of 1.06 kg m^{-3} (or 1.02 L wine m^{-3}) and 3.18 kg m^{-3}, respectively. Table grape showed a significantly higher economic water productivity (US\$ 6.51 m^{-3}) than wine grape (US\$ 0.93 m^{-3}). These values are much favorable than for staple crops.

1. Introduction

Irrigated crops in the semiarid region of São Francisco river basin in Brazil consist mainly of fruit crops, such as grapes, mangos, bananas and guavas. The average rainfall in this region is 570 mm $year^{-1}$, and the rainy period is concentrated from January to April. The reference evapotranspiration (ET_o) is around 1600 mm $year^{-1}$. The monthly average air temperature varies between 24 and 30 °C only. Under such high evaporative atmospheric demand and low and irregular rainfall, irrigation becomes necessary for commercial agriculture.

The vineyards growing under these permanently warm conditions exhibit an agronomic behaviour being different from the temperate climates. While in these last climates, a typical winter season induces dormancy in grapes, the continuous physiological processes in the semiarid region of Brazil are accelerated and the propagation is very fast allowing the first production after 1.5 years.

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With proper irrigation and cultural management practices, the farmers in São Francisco valley can produce grapes and wine in any time of the year, allowing on average 2.5 production cycles per year and the harvests in periods with higher prices, although for seedless table grapes, the rainy period is avoided due to the direct damage to the fruits and the high occurrence of diseases.

Crop water productivity (CPW) – or its equivalent water use efficiency for irrigated crops – represents the fresh fruit or wine production per unit of water applied or consumed. It is preferred to analyse CPW in terms of consumptive use because it includes also non-irrigation sources of water, such as rainfall, seepage and soil moisture changes.

The amount of applied water is partitioned into evapotranspiration and deep percolation. Actual evapotranspiration (ET) represents the water that is vapourized and not longer available to downstream users of a river basin. Percolated water can be recycled, and should therefore not be ascribed to the production of a certain irrigated crop.

The term "water productivity" reflects the link between production of an intended good and its resource input (Molden and Satkhivadivel, 1999; Kijne et al., 2003; Bos et al., 2005; Molden et al., 2007), having a more general basis than the term "water use efficiency", and makes it suitable to compare the economic performance with other water use sectors.

It is deemed necessary to study the energy and water balances of vineyards for understanding and predicting CPW (Bastiaanssen et al., in press). As wine and table grapes are cultivated in different trellis and irrigation systems in the São Francisco river basin, it is important to quantify various grape water parameters under these differences, being ET the most important of them.

ET from vineyards can be obtained accurately using weighing lysimeters (Evans et al., 1993; Williams et al., 2003; Williams and Ayars, 2005b), eddy correlation techniques (Oliver and Sene, 1992; Sene, 1994; Trambouze et al., 1998; Ortega-Farias et al., 2007) and the Bowen ratio energy balance method (Heilman et al., 1994, 1996; Rana et al., 2004; Yunusa et al., 2004).

These studies reveal a significant variation in water consumption due to different irrigation strategies and cultural practices. While certain farmers prefer the production of high quantities of berries, others like a high quality product introducing significant water stress levels by partial root zone drying and deficit irrigation.

The extrapolation of field measurements to irrigation schemes, regions and river basins are, therefore, cumbersome (Williams and Ayars, 2005b). With simultaneous measurements of ET and ET_o, it is possible to determine the crop coefficient (k_c) that normalizes ET for climatic influences. This coefficient reflects the canopy development and vineyard water status as the crop stages progress (Snyder et al., 1989).

As Brazil is a developing country on fast track with a growing export of fresh fruits and wines, on-farm water management in vineyards is the cornerstone for a productive use of scarce water resources at the basin scale. The objective of this study was the determination of water parameters related to ET such as crop coefficients, evaporative fraction, soil evaporation and canopy transpiration, bulk surface and canopy resistances and crop water productivity for wine and table grapes growing under different trellis and irrigation systems. Upscaling of these data sets is a good bio-physical basis for appraising the options for increasing total CPW at the regional scale.

2. Vineyards investigated

2.1. *Wine grapes with drip irrigation and vertical trellis*

The wine grape investigated stands at Vitivinícola Santa Maria farm near the town of Lagoa Grande in Pernambuco state (latitude 09°02′S; longitude 40°11′W). The cultivar is Petite Syrah, and the vineyard was 11 years old during the field investigation in 2002.

The plants are spaced at 1.20 m × 3.50 m, trained vertically to a bilateral cordon and spur pruned. The cordon wire was at a height of 1.6 m with no foliage wires (a sprawl type canopy developed). There was no cover crop between the rows, and they are oriented in a north–south direction. The shoots are allowed to grow freely over the wires. Vertical trellis systems in wine grape are preferred instead the overhead horizontal because it makes easier the mechanical practices.

The daily drip irrigated area of 4.13 ha was bordered on all sides by other wine grapes. There was one drip emitter between two plants in the rows at a discharge rate of $4\ \mathrm{L\ h^{-1}}$, suspended on the wire. Although it is common in many wine production areas not to irrigate vines at budbreak, or shortly thereafter, the irrigation manager started the irrigation soon after pruning with a fixed and large amount of water without quantifying the water demand.

The soil is sandy with a water retention capacity that increases with depth, presenting a cracked rock layer below 0.60 m evidenced by the time of installing the tensiometers.

Because the vineyard was pruned two times in 2002, the study involved two growing cycles during this year. The duration of the first growing cycle (GC1) was 132 days, elapsing from 7 February to 19 June 2002, while the second growing cycle (GC2) comprised 136 days, from 8 July to 22 November 2002. Grapes were picked to produce wine from both periods.

The Bowen ratio surface energy balance method was used to measure the partition of net available energy into sensible and latent heat fluxes. The sensors were installed at the centre of the plot. The gradients of air temperature and vapour pressure above the crop were calculated by using wet and dry thermocouples of cupper/constantan at 0.5 and 1.5 m above the canopy.

The surface albedo ($\alpha = R_R/R_G$) was measured through incident (R_G) and reflected (R_R) global solar radiation acquired with pyranometers faced up and down (model Eppley, Rhod Island, USA). The net radiation (R_n) was measured at 1 m over the canopy with two net radiometers (model NR-Lite, Kipp & Zonnen, Delft, The Netherlands), each one installed above a row of plants.

The soil heat flux (G) was obtained with four heat flux plates (HFT3-L, REBS, Radiation and Energy Balance Systems, Seattle, WA and Hukseflux, Delft, The Netherlands) at 0.02 m soil depth and 0.50 m from the plants. Two plates were burried at the west and the other two at the east side of two rows of plants.

Wind speed was measured with anemometers (03101, R.M., Young wind Sentry, Michigan, USA) at two levels, i.e. 1.0 and 2.0 m above the canopy. Air temperature and relative humidity at 0.5 m above the canopy were obtained with a probe from Vaisala (model HMP 35A, Helsinki, Finland), inside the shelter at the first level of the thermocouples.

Soil moisture profiles were weekly monitored with tensiometers located between the drip emitters and the vine trunks. The sampling depths were 0.2, 0.4 and 0.6 m considered to represent the effective root zone for vineyards in local soil and cultural conditions (Bassoi et al., 2003). Tensions were converted into soil moisture by using laboratory measurements of soil water retention curves. Applied water by irrigation was obtained by simple weekly readings of water meters attached to the drip pipes.

2.2. *Table grapes with microsprinkler irrigation and overhead horizontal trellis*

The table grape plot is located at Vale das Uvas farm near the town of Petrolina, Pernambuco state (latitude 09°18′S; longitude 40°22′W). The cultivar is the Superior Seedless and the vineyard was only 2 years old at the start of the measurement campaign.

The plants are spaced at 3.5 m × 4.0 m, with the rows oriented in the usual north–south direction. The vineyard has an overhead horizontal trellis system at 1.80 m height. The cover crop consists of a mixture of legumes and grasses, and was incorporated into the soil after budbreak.

The plot investigated is 5.13 ha, surrounded by other table grapes. The grapes were daily microsprinkler irrigated, with one in-line microsprinkler between two vines on the ground at a discharge rate of 44 L h^{-1} which wetted 70% of the soil surface. As in wine grape, the farmer started the irrigation soon after pruning with large amount of water, thereby promoting high rates of direct soil evaporation and cover crop transpiration at initial stages.

The soil is also sandy throughout the vertical profile, but its water retention capacity does not increase with depth. Water holding capacity is higher in the upper soil layer (0–20 cm) due to high organic matter content.

The measurements involved two growing seasons (GS1 and GS2), during the same period but in different years: both from 8 July to 7 October, in 2002 and in 2003. The duration of the growing seasons were 90 days only, being extremely short as compared to vineyards in California and Australia among others. The grapes were brought to the export market at the end of GS2 in 2003.

The crop was left resting between the two seasons to avoid possible direct damage in fruits and high incidence of fungi diseases due to rainfall. The plants were not girdled nor sprayed with gibberellic acid and the leaves were not removed from fruit zone. At the stage of vegetative growth, non-fruitful shoots and lateral shoots growing in the fruiting zone were removed and at fruit growth stage, the berries were protected with a white cover from direct solar radiation.

The same method, measurement procedures and equipment's manufacturers as for wine grapes were set up for table grapes with few differences. Two net radiometers were installed, with one instrument at 1 m over the canopy and the other at 1 m above the ground surface to measure intercepted radiation by the canopy. Two heat flux plates (model HFT3-L, REBS, Radiation and Energy Balance Systems, Seattle, WA) were used, one at the east and the other at the west side of two rows of plants.

Air temperature and relative humidity near the leaves was measured by a probe (SKH 2013, Sky instruments LTD, Llandrindod Wells, UK) installed in the arm of the datalogger's shelter at 0.5 m bellow the trellis system and only one level anemometer was installed at 1.0 m above the canopy.

Soil moisture profiles and applied water by irrigation were weekly monitored with tensiometers located between the emitters and the vine trunks along two rows at same soil depths as for wine grapes and with water meters in microsprinkler pipes.

3. Methodology

The energy balance equation of a vineyard can be expressed by means of bulk energy and heat fluxes:

$$R_n - \lambda E_v - G - H_v = 0 \quad (1)$$

where R_n is the net radiation, λE_v the latent heat flux from the vineyard, H_v the sensible heat flux from the vineyard and G is the soil heat flux. λE_v was obtained by a partitioning parameter:

$$\lambda E_v = \frac{R_n - G}{1 + \beta} \quad (2)$$

where β is the Bowen ratio:

$$\beta = \gamma\left(\frac{\Delta T}{\Delta e}\right) \quad (3)$$

and γ (kPa °C^{-1}) is the psychrometric constant, ΔT (°C) the temperature gradient measured by the dry thermocouples and Δe (kPa) is the vapour pressure gradient measured by the difference between dry and wet thermocouples over the height interval above the canopy surface.

The actual evapotranspiration (ET) was derived from the latent heat of vaporization (λ), density of water and λE_v. As a first approximation, an ET of 1 mm day^{-1} is equivalent to λE_v of 28 W m^{-2}. With measured values of R_n and G and estimations of λE_v, the sensible heat flux from the vineyards (H_v) was obtained as a residual in Eq. (1).

The ET_o was calculated in this study following FAO-56 standardized guidelines (Allen et al., 1998), using weather data from an automatic agrometeorological station near the table grape plot (at a distance of 200 m), also equipped with a pluviometer to measure rainfall. The crop coefficient (K_c) was obtained as ET/ET_o. For the further separation of ET into transpiration (T) and soil evaporation (E), the dual crop coefficient approach of FAO-56 was used with the basal crop coefficients (K_{cb}) and soil evaporation coefficients K_e ($K_e = K_c - K_{cb}$):

$$T = K_{cb} ET_o \quad (4)$$

$$E = K_e ET_o \quad (5)$$

Initial and end values of K_{cb} were derived from the values at the lower envelope of daily measured K_c at these stages when foliage development is minimal. The mid-stage K_{cb} values have been taken from Allen et al. (1998). Tabulated values for mid-stage K_{cb} are 0.80 for table grape and 0.65 for wine grape which were adjusted for the our specific weather conditions:

$$K_{cb} = K_{cb}(\text{tabular}) + \{0.04(u_2 - 2) - 0.004(\text{RH}_{min} - 45)\}\left\{\frac{h_v}{3}\right\}^{0.3} \tag{6}$$

where u_2 and RH_{min} are, respectively, the averaged wind speed and minimum relative humidity at the agrometeorological station (at a height of 2 m) and h_v (m) is the mean plant height for the mid-stage periods.

One key parameter in ET processes is the aerodynamic resistance (r_a) that describes the turbulence of the atmosphere, and is related to the roughness of the land surface. The surface roughness parameters of the vineyards were estimated from the flux profile relationships.

The atmospheric surface-layer similarity theory was used (Stull, 1988; Monteith and Unsworth, 1990) applying universal integrated stability functions of temperature (Ψ_h) and momentum (Ψ_m) for relating fluxes to atmospheric state profiles and surface properties (Businger et al., 1971).

The friction velocity, u_* (m s^{-1}), which is a velocity scale related to mechanically generated turbulence, was calculated from two-level (z_1, z_2) wind speed measurements (u_1, u_2):

$$u_* = \frac{k(u_2 - u_1)}{\ln[(z_2 - d)/(z_1 - d)] - \psi_m((z_2 - d)/L) + \psi_m((z_1 - d)/L)} \tag{7}$$

The aerodynamic resistance, r_a (s m^{-1}), between the surface roughness and the canopy level from where atmospheric state variables are measured was calculated as:

$$r_a = \frac{\ln[(z_1 - d)/z_{0h}]}{ku_*} - \psi_h \tag{8}$$

The surface roughness length for moment transfer (z_{0m}) that together the roughness length for heat and vapour transfer ($z_{0h} = 0.1\, z_{0m}$) controls u_* and r_a was obtained from:

$$z_{0m} = \frac{z_1 - d}{\exp((ku_1/u_*) + \Psi_m)} \tag{9}$$

In Eqs. (7)–(9), u_1 and u_2 are the wind speed values at heights z_1 and z_2 (2.6 and 3.6 m for wine grapes and 2.8 and 3.8 m for table grapes), d is the zero plane displacement height (2/3 of the mean canopy height), k is the von Karman's constant (0.41) and L is the Obukhov length, which was obtained by an iterative numerical method starting with a value of 10^6 m.

The wind speed in table grapes was measured only at 2.8 m. The values at 3.8 m, necessary for solving u_* in Eq. (7), were estimated by means of H_v and field measurements of ΔT considering initially neutral conditions solving r_a in the following equation:

$$H_v = \rho_a c_p \frac{\Delta T}{r_a} \tag{10}$$

where ρ_a and c_p are the air density and air specific heat at constant pressure.

The first values for u_* were then calculated by Eq. (8) using the height levels of 3.8 and 2.8 m. The resulted values of u_* were used in Eq. (7) to obtain the wind speed at 3.8 m (u_2). These calculations were performed first without using the stability correction terms Ψ_h and Ψ_m.

The latent heat flux from the canopy (λE_c) was acquired from transpiration fluxes (T). The continuous measurement of net radiation over and under the canopy made it possible to obtain the energy available to the soil surface (R_{ns}) for table grape, as well to derive the amount absorbed by the canopy ($R_{nc} = R_n - R_{ns}$). With known values of λE_v, λE_c and r_a, the bulk surface (r_s) and canopy (r_c) resistances were estimated inverting the general Penman–Monteith equation (Farah, 2001):

$$\lambda E_{v,c} = \frac{s_a(\text{AE}) + \rho_a c_p(\text{VPD})/r_a}{s_a + \gamma(1 + (r_{s,c})/r_a)} \tag{11}$$

where $\lambda E_{v,c}$ is the latent heat flux from the vineyard (subscript 'v') or from the canopy (subscript 'c'); s_a (kPa °C^{-1}) is the slope of the saturated vapour pressure curve, AE is the available energy (($R_n - G$) or ($R_n - R_{ns}$)), ρ_a (kg m^{-3}) is the moist air density, c_p (J kg^{-1} K^{-1}) is the air specific heat at constant pressure, VPD (kPa) is the vapour pressure deficit and γ (kPa °C^{-1}) is the psychrometric constant and $r_{s,c}$ (s m^{-1}) is the bulk surface (subscript 's') or canopy (subscript 'c') resistance to water vapour transport.

The leaf area index (LAI) was derived for table grape with the values of intercepted radiation (Teixeira and Lima Filho, 1997) and consideration of the inversion of Beer's law:

$$\text{LAI} = 0.17 - 1.24 \ln\left[\frac{R_{ns}}{R_n}\right] \tag{12}$$

Crop water productivity (CWP) is commonly expressed in yield per unit of applied water, including rainfall and irrigation (Peacock et al., 1977; Araujo et al., 1995; Srinivas et al., 1999). In this study, it was calculated as:

$$\text{CWP}_{\text{ET,T,IRR}} = \frac{Y_{act}}{W_{\text{ET,T,IRR}}} \tag{13}$$

where the subscripts ET and T denote the water fluxes by evapotranspiration and transpiration, respectively; the subscript IRR denote the amount of water supplied by irrigation and Y_{act} is the actual yield of wine or fruits. Following Droogers et al. (2000) and Bos et al. (2005), the economic indicators used were the standard gross value of production (wine and grapes) over the irrigation supply ($\text{CPW}_{\$\_IRR}$) and over evapotranspiration ($\text{CPW}_{\$\_ET}$) and transpiration ($\text{CPW}_{\$\_T}$).

4. Results and discussion

4.1. Soil moisture and weather conditions

The values of soil moisture (SM) are shown in Fig. 1. SM at 20 cm depth showed more variations with time, than at deeper soil layers in both vineyards. This is an expected result because of the dynamics of infiltration and subsequent depletion by root water uptake and soil evaporation.

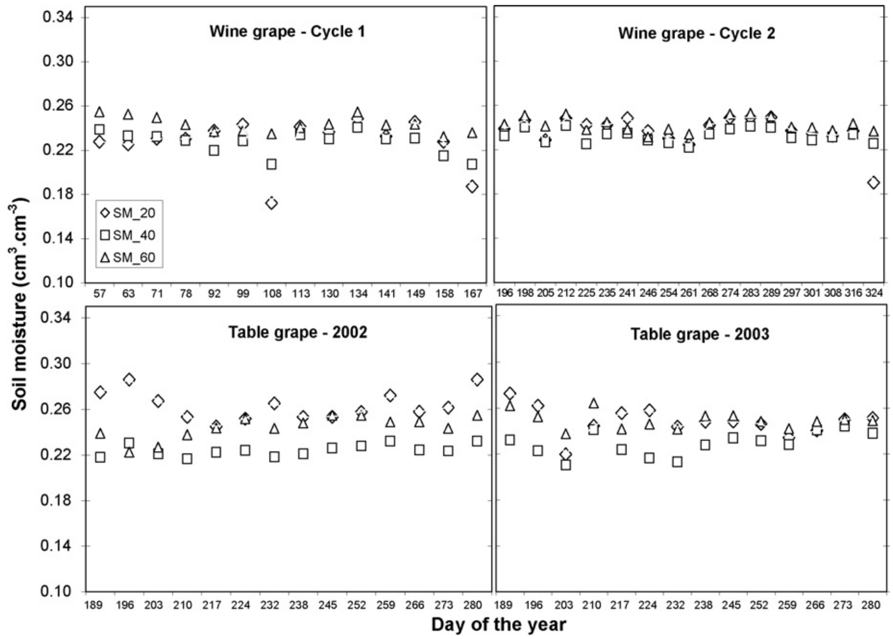

Fig. 1 – Soil moisture (SM) at different depths (20, 40 and 60 cm), during the growing cycles of 2002 of wine grape and for the growing seasons of 2002 and 2003 of table grape.

The maximum values of SM in the wine grape were found at 60 cm depth pinpointing that moisture assembles in the lower root zone and is not easily drained away. This could be related to the increasing retention properties and reduced permeability at this soil depth. For table grape, the values are over against that maximal at 20 cm, which reveals typical free drainage conditions. SM varied during most days between 0.19 and 0.29 $cm^3\,cm^{-3}$ in both vineyards, which is similar to the range those from Ortega-Farias et al. (2007) in Chile.

A regular soil moisture trend line reflects a constant supply and removal of irrigation water. Water excess can arise if supply exceeds removal by root water uptake, what in wine grape, could adversely affect the production and quality of wine. This excess not only enhances the loss of scarce water resources but also valuable nutrients can be leached out from the root zone.

July and October are the coldest and the warmest months of the year, respectively. The difference between the values of air temperature (T_a) near the canopies and at the routine agrometeorological station was small (see Fig. 2a and b). The seasonal average near-canopy T_a in wine grape was with 26.5 °C, slightly higher than the 25.2 °C for table grape. The lower values in the last vineyard can be ascribed to the higher soil cover caused by the overhead trellis system and micro-sprinkler irrigation.

The higher values of wind speed (W) in the study region normally happen during the driest period, between August and October, with longer term values reaching 3.0 m s^{-1} in September. The lowest values occur during the rainy period with monthly average of 1.6 m s^{-1}. The daily variations of W over the vineyards and at agrometeorological station are depicted in Fig. 2c and d. During 2002 and 2003, averaged daily values were above 0.8 m s^{-1} and lower than 3.0 m s^{-1} for both vineyards. The above-canopy wind speed measurements accounted for 80% of those from the station, which can be ascribed to differences in surface roughness.

The high values of T_a together with the dryness of the air induce high vapour pressure deficit (VPD) conditions outside the rainy period. The monthly averaged relative humidity in the region ranges from 55 to 70%. The 24 h averaged values of VPD for the study period are plotted in Fig. 2e and f. Moister air near the canopy can be attributed to irrigation that raises the air humidity. This effect was greater in microsprinkler irrigation system of table grape than for the drip irrigation in wine grape.

According to Fig. 2g and h, global solar radiation (R_G) decreased in the first half of the year of 2002 and increased during the second halves of the years 2002 and 2003. ET_o followed R_G. Higher values of R_G in the second half of 2002 established a slightly higher value for T_a and ET_o, in comparison with the same period in 2003. ET_o was 4.4 and 5.0 mm day^{-1} on average for the first and second halves of 2002, while it was 4.1 mm day^{-1} during the second half of 2003. The total rainfall during the first half of 2002 was 41.4 mm, and in the second half of the same year, it was 49.3 mm. It rained only 17.3 mm during the growing season of table grape in 2003.

4.2. *Energy partitioning*

The values of the components of the energy balances – and the latent heat flux from the vineyard (λE_v) in particular – varied according to R_G. The diurnal variation of these components for the period of measurements is depicted in Fig. 3. Maximum midday λE_v were around 400–500 W m^{-2} for both vineyards.

The fluxes had a very smooth behaviour during daytime hours, with an exception for G in wine grape, which presented

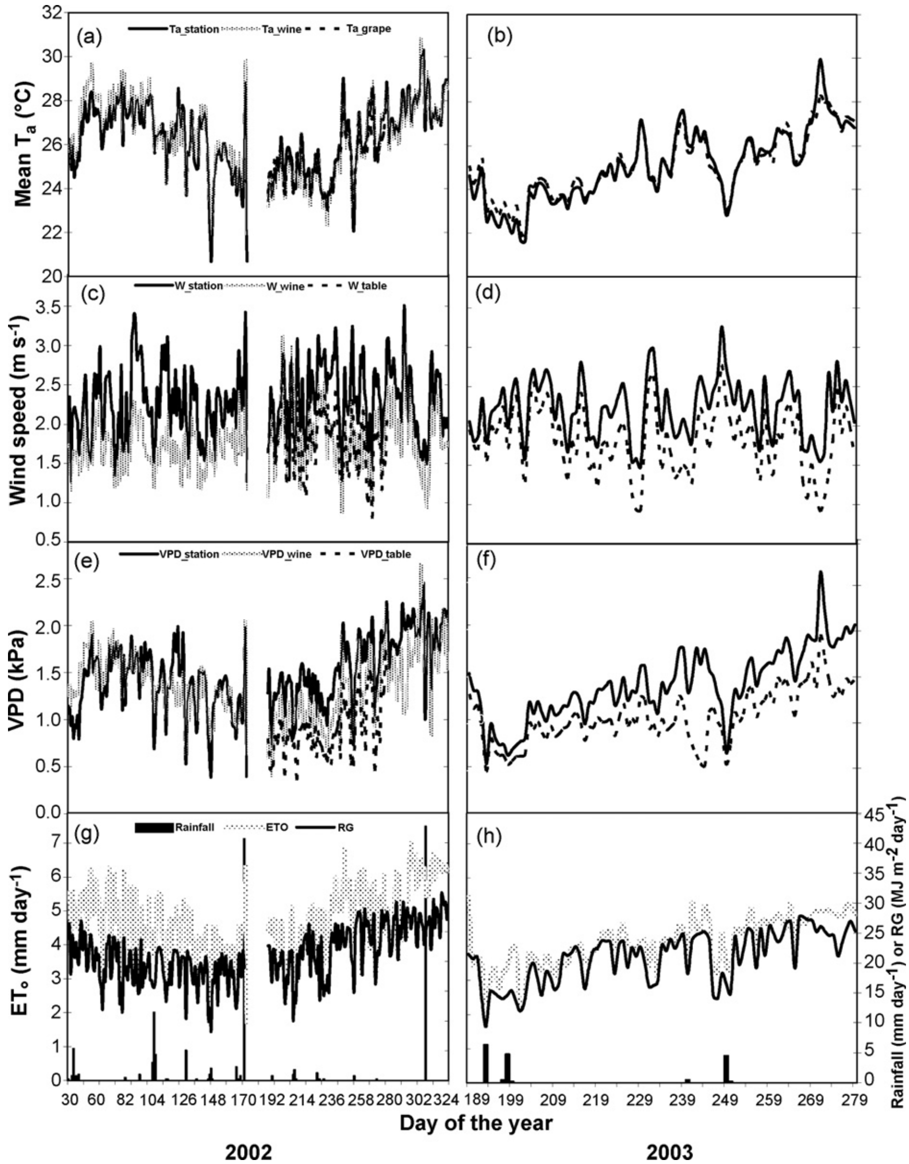

Fig. 2 – Daily values of weather variables during the study period in 2002 and 2003 from agrometeorological station (station) and near the canopies of wine grape (wine) and table grape (table): (a and b) mean air temperature (T_a); (c and d) wind speed (W); (e and f) vapour pressure deficit (VPD); (g and h) incident global solar radiation (R_G), reference evapotranspiration (ET_o) and rainfall.

midmorning and midafternoon peaks and lower values at midday due to the canopy architecture, what is in agreement with Heilman et al. (1994).

Daily averages of energy balances components for wine grape in 2002 are presented in Table 1. R_n was on average 46% of R_G for both growing cycles. A fraction of approximately 50% is in agreement with earlier crop science radiation studies (e.g. Makkink, 1957; Oliver and Sene, 1992).

The sensible heat flux from the vineyard (H_v) accounted for 18% of R_n for both growing cycles of wine grape, being a modest heat flux. During the first cycle, the daily averaged G was negative because heat was released from the warm soil body. The opposite situation occurred during the second cycle. The largest portion of R_n was converted into λE_v, which represented around 83 and 78% of R_n in the first and second growing cycles, respectively, corresponding to an evaporative fraction ($EF = \lambda E_v/(R_n - G)$) around 81%.

Daily averages of energy balance components for table grape in 2002 and 2003 are presented in Table 2. R_n represented a fraction of 55% of R_G, being higher than for wine grape; the overhead trellis and microsprinkler irrigation system promote lower both, albedo and longwave emission, increasing R_n. The measured albedo in wine grape in the actual study varied between 0.19 and 0.24. These values are higher than for microsprinkler irrigated table grape (0.18–0.23) reported by Azevedo et al. (1997).

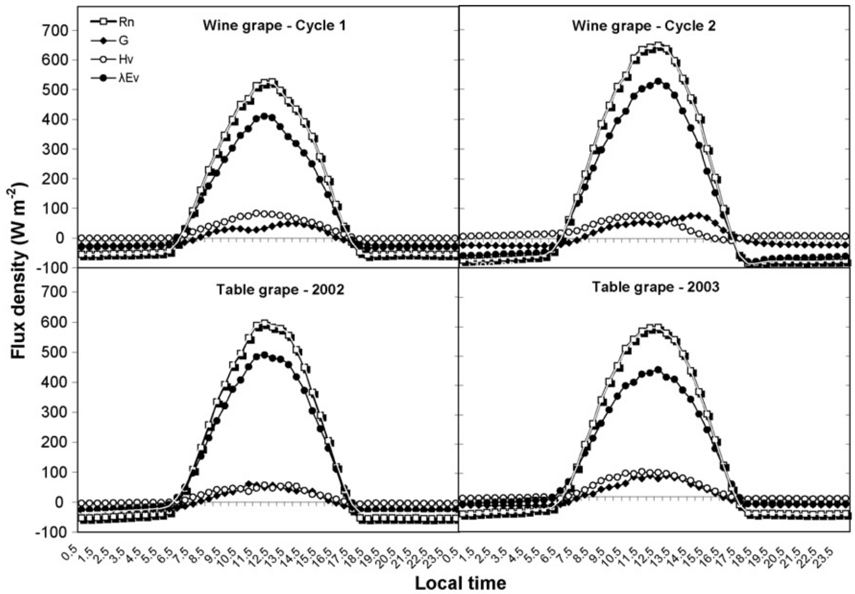

Fig. 3 – Diurnal averages for the energy balance components during the growing cycles of wine grape in 2002 and for the growing seasons of 2002 and 2003 for table grape: net radiation (R_n); latent heat flux from the vineyard (λE_v); sensible heat flux from the vineyard (H_v) and soil heat flux (*G*).

Near-neutral conditions predominated above the table grape, with H_v representing around 12% of R_n. The averaged G was negative during both seasons, accounted for only 1% of R_n. The largest portion of R_n was also partitioned into λE_v which representing 91 and 87% of R_n in 2002 and 2003, respectively, corresponding to a mean EF of 88%. Higher values of energy partition as λE_v are explained by moister both, microclimatic and soil conditions in table grape than in wine grape.

According to Scott et al. (2003), evaporative fraction also reflects the moisture conditions in the root zone. High EF values reveal that the crop is not water stressed, and that the soil is wet, what is confirmed from Fig. 1.

Differences in the partition of the energy balance with different trellis and training systems in vineyards were also reported by Novello et al. (1992), Heilman et al. (1996), Katerji et al. (1994) and Rana et al. (2004).

Table 1 – Daily averages of the energy balance components for wine grape crop at Lagoa Grande, PE, Brazil for the first growing cycle (GC1) from 07/02 to 19/06 and for the second growing cycle (GC2) from 08/07 to 21/11, both in 2002: net radiation (R_n), latent heat flux from the vineyard (λE_v), sensible heat flux from the vineyard (H_v), soil heat flux (*G*) and evaporative fraction (EF) are presented

DOY	R_n (MJ m^{-2} day^{-1})	λE_v (MJ m^{-2} day^{-1})	H_v (MJ m^{-2} day^{-1})	G (MJ m^{-2} day^{-1})	EF
GC1					
057	11.69	9.20	2.09	0.40	0.81
077	10.63	8.34	2.00	0.29	0.81
097	10.01	8.13	1.91	−0.01	0.81
117	10.07	8.35	2.14	−0.42	0.80
137	9.65	8.16	1.91	−0.42	0.81
157	8.05	7.17	1.64	−0.76	0.81
170	7.45	6.62	1.57	−0.73	0.81
Mean	9.65	8.00	1.89	−0.24	0.81
GC2					
208	8.59	6.48	1.69	0.42	0.79
228	9.43	6.98	1.80	0.65	0.80
248	11.67	9.63	1.71	0.33	0.85
268	12.59	9.73	2.18	0.68	0.82
288	12.69	9.64	2.43	0.62	0.80
308	14.06	11.39	1.92	0.74	0.86
325	14.32	11.23	2.42	0.67	0.82
Mean	11.91	9.30	2.02	0.59	0.82

(DOY) day of the year.

Table 2 – Daily averages of the energy balance components for table grape crop at Petrolina, PE, Brazil from 08/07 to 06/10 of the first growing season (GS1) in 2002 and for the second growing season (GS2) in 2003: net radiation (R_n), latent heat flux from the vineyard (λE_v), sensible heat flux from the vineyard (H_v), soil heat flux (G) and evaporative fraction (EF) are presented

DOY	R_n (MJ m^{-2} day^{-1})	λE_v (MJ m^{-2} day^{-1})	H_v (MJ m^{-2} day^{-1})	G (MJ m^{-2} day^{-1})	EF
GS1					
204	9.73	9.00	0.78	−0.06	0.92
219	10.29	9.19	1.20	−0.10	0.88
233	10.25	9.33	1.17	−0.25	0.89
249	12.79	11.66	1.24	−0.11	0.90
264	13.09	11.96	1.40	−0.27	0.89
280	13.32	12.20	1.12	0.00	0.92
Mean	11.58	10.56	1.15	−0.13	0.90
GS2					
204	7.35	6.75	0.76	−0.17	0.90
219	9.49	8.40	1.40	−0.32	0.86
233	10.82	9.50	1.71	−0.39	0.85
249	11.70	10.24	1.88	−0.41	0.85
264	12.50	10.29	2.07	0.14	0.83
280	13.76	11.66	1.70	0.40	0.88
Mean	10.94	9.47	1.58	−0.12	0.86

(DOY) day of the year.

4.3. Evapotranspiration, transpiration and soil evaporation

For the first growing cycle of wine grape (GC1), the average 24-h λE_v of 8.00 MJ m^{-2} day^{-1}corresponded to an ET of 3.3 mm day^{-1}. This value is similar to Heilman et al. (1996) in Texas (3.6 mm day^{-1}) who also used a Bowen ratio system for measuring ET. During the second growing cycle (GC2), the average 24-h λE_v increased to 9.30 MJ m^{-2} day^{-1} being equivalent to 3.8 mm day^{-1}. The accumulated ET values were 438 and 517 mm, respectively, for GC1 and GC2, showing the seasonal effects (Table 3).

The average daily λE_v values of 10.56 and 9.47 MJ m^{-2} day^{-1} for table grape represented ET of 4.4 mm day^{-1} in 2002 and 3.9 mm day^{-1} in 2003, respectively. Higher daily ET values than in wine grape are due to the microsprinkler irrigation system, high soil cover and the transpiration from the cover crop of legumes and grasses at initial stages. Consequently, the crop coefficients are higher and resistance values are lower than for wine grape (Table 3). As the growing period of table grape is around 90 days only, the seasonal crop water consumption is with a mean value of 372 mm lower than for wine grape (478 mm).

A review of international literature about water use in vineyards showed that the average ET rate from nine international field experiments is 3.0 mm day^{-1} (Oliver and Sene, 1992; Evans et al., 1993; Heilman et al., 1996; Yunusa et al., 1997, 2004; Trambouze et al., 1998; Williams et al., 2003; Rana et al., 2004; Williams and Ayars, 2005a). The mean values of daily water consumption obtained in our study are, in general, greater than those from literature, however, Williams and Ayars (2005a) reported similar daily values of ET for cv. Thompson Seedless in Sao Joaquin Valley of California, when there was neither gibberellic acid (GA3) application nor

Table 3 – Water use parameters for wine and table grapes: reference evapotranspiration (ET_0); actual evapotranspiration (ET); transpiration (T); soil evaporation (E); crop coefficients based on ET (K_c), T (K_{cb}) and E (K_e); aerodynamic (r_a), surface (r_s) and canopy (r_c) resistances; leaf area index (LAI)

Variable	Wine grape GC1	Wine grape GC2	Table grape GS1	Table grape GS2
Duration (days)	132	136	90	90
ET_0 (mm)	586	671	435	382
ET(mm)	438	517	393	352
T (mm)	385	462	312	293
E (mm)	53	56	81	59
ET (mm day^{-1})	3.3	3.8	4.4	3.9
K_c	0.75	0.77	0.90	0.92
K_{cb}	0.66	0.69	0.72	0.77
K_e	0.09	0.08	0.18	0.15
r_a(s m^{-1})	114	109	63	66
r_s (s m^{-1})	131	125	64	82
r_c(s m^{-1})	–	–	49	89
LAI	–	–	0.70	1.60

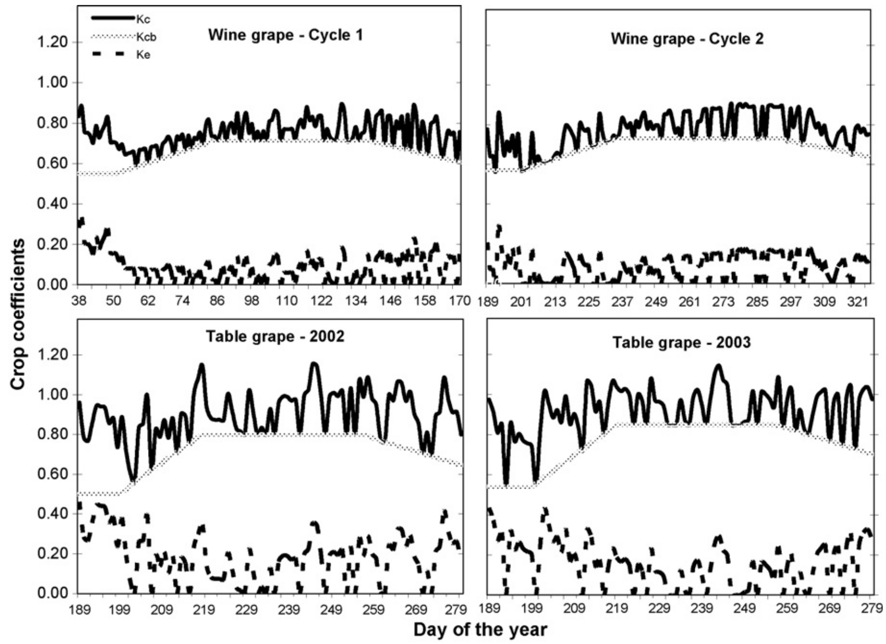

Fig. 4 – Seasonal variation of crop coefficients in vineyards during the growing cycles of 2002 of wine grape and for the growing seasons of table grape in 2002 and 2003: crop coefficients based on evapotranspiration (K_c), transpiration (K_{cb}) and soil evaporation (K_e).

trunk girdling, comparing with our 3-years-old Superior Seedless.

On the other hand, as the growing seasons in our study area are shorter, the seasonal water consumption is lower. A recent water balance study in vineyards in South Africa (Roux, 2007) showed that the average value of seasonal ET for wine grape is 621 mm and for table grape is in the range from 519 to 827 mm. The length of the growing seasons in South Africa is between 6 and 8 months with only one harvest per year.

Actual evapotranspiration (ET) can be corrected for climatic influences by normalizing it with ET_o, producing the crop coefficients (K_c). The K_c values can be variable with the crop properties and stress conditions caused by water deficit and salinity. Under pristine conditions, maximum values can be taken, and they are often published in tables (e.g. Snyder et al., 1989; Consoli et al., 2006).

The behaviour of daily K_c is demonstrated in Fig. 4. Note that our actual growing conditions also include few non-pristine environmental circumstances. The K_c values at the initial and the end stages are highly related to the cover crop and irrigation. For wine grape, the mean weekly values in the first growing cycle were in the range from 0.65 to 0.82, while for the second they were from 0.63 to 0.87. For table grape, the mean weekly averaged K_c values for both growing seasons varied between 0.77 and 0.91.

The seasonal trend of crop coefficients K_{cb} and K_e are also depicted in Fig. 4. After multiplying these coefficients by ET_o, the transpiration (T) and soil evaporation (E) were obtained. On average, 89–90% of the total ET was used for T and 10–11% for E in wine grape. For table grape, 79–83% of ET was used for T and 17–19% for E (Table 3). Thus, microsprinklers have a higher portion of non-beneficial evaporation than drip systems.

4.4. *Intercepted radiation, leaf area index and resistances*

Data availability of R_n above and under the canopy for table grape allowed the calculation of intercepted net radiation (R_{ni}) and the estimation of leaf area index (LAI) for the two growing seasons following Eq. (12). The mean values of LAI were 0.70 during the first growing season and 1.60 for the second (Table 3) pinpointing a situation of a young maturing vineyard. The last value of LAI is close to that found by Rana et al. (2004) for table grapes in Italy and by Yunusa et al. (2004) for mature Sultana grapes, growing in a T-trellis system in Australia.

Klaasse et al. (2007) reported LAI values between 2.5 and 3.0 for the table grapes and around 1.0 for wine grapes, in Hex River Valley, West Cape Province (South Africa). According to Katerji et al. (1994), LAI for vineyards in rows with a dominant vertical plant structure present value around 0.70–0.80. There were no measurements of R_{ni} to allow LAI estimations in wine grapes in the actual study.

The seasonal variations of aerodynamic resistance (r_a) and the surface (r_s) and canopy (r_c) resistances are shown in Fig. 5. Averaged values are found in Table 3. In wine grape, the values of r_a stayed in the range from 78 to 170 s m^{-1}, while for table grape, the range was from 30 to 160 s m^{-1}. The lower r_a values in the last vineyard can be related to the aerodynamic smoother horizontal trellis systems. A higher LAI and soil cover cause a shelter effect (e.g. Verhoef et al., 1997).

The r_s values in wine grape were between 35 and 240 s m^{-1}. For table grape, the range was from 10 to 140 s m^{-1}. Heilman et al. (1994) found maximum values of r_s of 50 and 75 s m^{-1}. The canopy resistance (r_c) for table grape in both years stayed between 20 and 182 s m^{-1}. Assuming that the stomatal resistance (r_{st}) can be roughly estimated by ($0.5 \times \text{LAI} \times r_s$) as reported in several handbooks (Allen et al., 1998), the mean

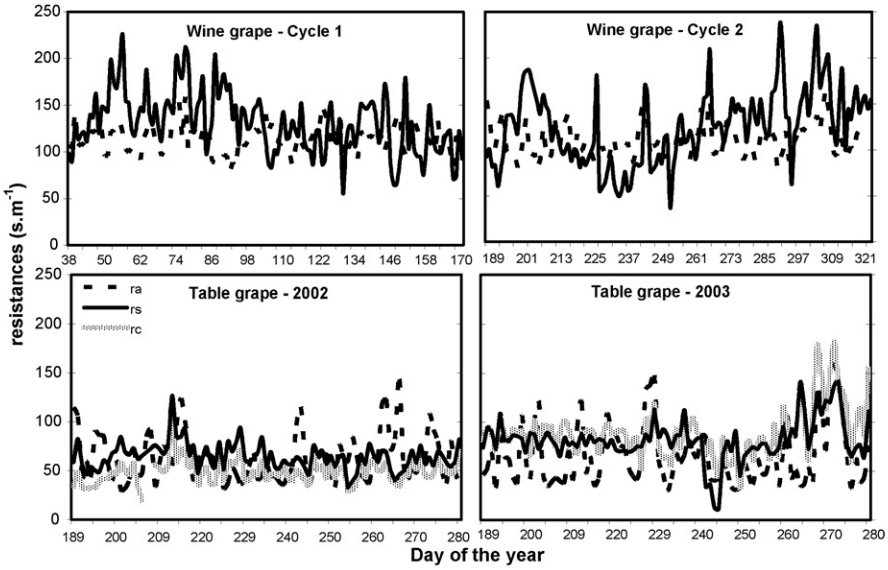

Fig. 5 – Seasonal trends of calculated aerodynamic (r_a), surface (r_s) and canopy resistances (r_c), during the growing cycles of wine grape and for the growing seasons of table grape in 2002 and 2003.

values of r_{st} become 22 and 66 s m^{-1}, for the first and second growing seasons, respectively (Table 3).

Winkel and Rambal (1990) described the stomatal response of different French vineyards. The minimum r_{st} was 73 s m^{-1} for Carignane, 93 s m^{-1} for Merlot and 114 s m^{-1} for Shiraz. According to them, the main reason for these differences could be attributed to different conditions of VPD, soil cover, soil moisture and evaporative demand. Ben-Asher et al. (2006) measured recently the r_{st} of grapes under saline irrigation conditions in Israel, and they showed minimum values of 135 s m^{-1}.

The low values of r_s, r_c and r_{st} in irrigated vineyards of semiarid conditions in Brazil are due to wet conditions for both, soil and air near the canopies. The magnitude of the differences between r_s and r_c in table grapes comparing the two growing seasons can be explained because for the younger vineyard in 2002, the lower intercepted radiation promoted the soil component to represent a relative large fraction of r_s (Fig. 5).

The accumulated values of ET_o and ET; T and E; together with the mean values of K_c, K_{cb} and K_e; r_a and r_s are shown in Table 3. For table grape, the averaged values of LAI and r_c are also presented. The different magnitudes of grape water parameters between the two vineyards are due to differences in crop stages, age and varieties, trellis and irrigation systems, soil cover and cultural management.

4.5. *Crop water productivity*

Only a few studies relate yields of grapes and wine to ET that is the true consumptive use of vineyards. Organizations responsible for irrigation management are interested in yield per unit applied irrigation water (CWP_{IRR}), as it is their duty to enhance yield through irrigation processes. The drawback is that not all irrigation water is used for generating crop production.

Large portion of applied irrigation water turns into percolation losses (Table 4). The values of percolation were computed as the differences between rainfall, irrigation and ET, and there are no corrections made for soil storage changes. It is worrisome to note that the percolation rates had the same magnitude as ET.

A summary of all crop water productivity parameters for both vineyards is presented in Table 4. Wine yield values (3300–6600 L ha^{-1}) are inside in what is expected to be normal practices in this region. The differences in yield of bottled wine between the first (3376 L ha^{-1}) and the second growing cycles (6514 L ha^{-1}) pinpoint seasonal effects. The first cycle was cloudier and duration of the days during the stages of flower and maturation of fruits were shorter than the in the second cycle.

Although the productivity for one cycle of wine grape is lower than in regions where the climate is temperate, the total production of two cycles in 1 year is in good agreement with for instance South Africa (Roux, 2007). Whereas the first cycle yielded an economical water productivity of 0.35, 0.70 and US$ 0.80 m^{-3} based on irrigation, ET and T, respectively, these values for the second growing cycle increased to US$ 0.62, US$ 1.15 and US$ 1.28 m^{-3}.

The yield in 2002 for table grape was not marketable. Only the growing season in 2003 was analyzed for productivity purposes. The yield of fresh table grapes (11,200 kg ha^{-1}) is in agreement with the public perception in the São Francisco river basin. At a double cycle, the yield could increase to 22.4 tonnes ha^{-1}. The CWP_{ET} values for marketable table grape (3.18 kg m^{-3}) were found to be lower than previous table grape studies with drip and furrow irrigation (Yunusa et al., 1997). Klaasse et al. (2007) reported a value of CWP_{ET} of 3.7 kg m^{-3} in South Africa.

The economic water productivity performance for table grape was US$ 2.77, US$ 6.51 and US$ 7.82 m^{-3}, for $CWP_{\$\_IRR}$, $CWP_{\$\_ET}$ and $CWP_{\$\_T}$, respectively. At an attractive market

Table 4 – Duration of growing seasons (*d*), market prices, gross return, yield (Y_{act}), actual evapotranspiration (ET), transpiration (*T*), irrigation (IRR), rainfall, percolation, crop water productivity (CWP) based on irrigation (IRR), evapotranspiration (ET) and transpiration (*T*) for wine (liters of wine) and table (kilograms of fruits) grapes

Variable	Wine grape GS1	Wine grape GS2	Table grape GS2
Period	7 February to 19 June 2002	8 July to 21 November 2002	8 July to 6 October 2003
Duration (days)	132	136	90
Market price	US$ 0.91 L^{-1}	US$ 0.91 L^{-1}	US$ 4.5 kg^{-1}
Gross return (US$ ha^{-1})	3070	5922	50,400
Y_{act} (kg ha^{-1})	4222	8143	11,200
Y_{act} (L ha^{-1})	3376	6514	na
ET (mm)	438	517	352
T (mm)	385	462	293
IRR (mm)	874	960	827
Rainfall (mm)	41	49	17
Percolation (mm)	477	492	492
CWP_{IRR} (kg m^{-3})	0.48	0.85	1.35
CWP_{ET} (kg m^{-3})	0.96	1.16	3.18
CWP_{T} (kg m^{-3})	1.10	1.76	3.82
CWP_{IRR} (L m^{-3})	0.39	0.68	na
CWP_{ET} (L m^{-3})	0.77	1.26	na
CWP_{T} (L m^{-3})	0.88	1.41	na
CWP_{IRR} (US$ m^{-3})	0.35	0.62	2.77
CWP_{ET} (US$ m^{-3})	0.70	1.15	6.51
CWP (US$ m^{-3})	0.80	1.28	7.82

price of US$ 4.5 kg^{-1}, the gross margin of production is in order of magnitude higher than for wine grape, however, the overall production costs for table grape are significantly higher; hence the differences in net income between table and wine grapes tend to be skimmed off. The difference between $CWP_{\$\_ET}$ and $CWP_{\$\_T}$ is higher for table grape than for wine grape, showing the better performance of drip system in comparison with microsprinkler irrigation.

Sakthivadivel et al. (1999) compared standardized value of production per unit of water consumed of various crops, including vineyards from the Sarigol and Alasehim irrigation schemes in Turkey. They reported economic water productivity of raisin grapes is with US$ 0.39 m^{-3} (Sarigol) and US$ 0.47 m^{-3} (Alasehim) lower than for table and wine grapes.

A gross return of several dollars per cubic meter of water depleted in vineyards of the semiarid region of São Francisco river basin is extremely high, and among the highest values of all crops in irrigated agriculture.

5. Conclusions

Albedo, evaporative fractions, beneficial/non-beneficial water consumption, aerodynamic resistance, bulk surface resistance and canopy resistance were derived from the field data set and compared with the international literature. The results allowed expressing water consumption from vineyards in more specific bio-physical parameters, rather than in crop coefficients that lump together other crop water parameters.

The seasonal evapotranspiration of table grape was less (352–393 mm) than for wine grape (438–517 mm). Water fluxes of grape crop in this semiarid region are essentially driven by solar radiation. The partitioning of available energy into latent heat flux in the two vineyards studied was found extremely constant throughout the crop stages due to a systematic over-irrigation that induces a continuous deep percolation flux. Microsprinklers increase the moisture content in soil and lower atmosphere, which turns the fraction of non-beneficial ET to 18%, comparing to 10% in drip systems.

The water productivity of vineyards is extremely high, both bio-physically with values exceeding 3 kg harvestable fresh product per unit of water depleted, as well as economically. The economic water productivity based on evapotranspiration ($CWP_{\$\_ET}$) exceed US$ 1 m^{-3} (for wine grape), up to US$ 6.51 m^{-3} (for table grape). It is interesting to note that the economic return of South African wine grapes and table grapes shows the opposite behaviour, with high values of $CWP_{\$\_ET}$ for wine grapes.

The crop water productivity analysis reveals that water is wisely used and creates a boost for the rural economy. Indeed, the Brazilian towns of Petrolina, PE and Juazeiro, BA, in low-middle São Francisco river basin, have tripled in terms of exports and job creation, and this is a good example of converting marginal savannah land into a booming rural development; however, the irrigation management requires full attention as significant percolation adversely affects environments in terms of rising water tables and return flow of polluted water to the river.

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