Transpiration of table grape (*Vitis vinifera* L.) trained on an overhead trellis system under netting

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Abstract

The quantification of transpiration and corresponding basal crop coefficients is crucial for appropriate irrigation scheduling of drip irrigated crops. Besides basal crop coefficients already published, there is the announcing need for setting values for the new growing practices such as cropping under netting. In this paper, measurements of unstressed table grape transpiration and basal crop coefficients under netting have been performed. Vineyards of two seedless cultivars (Crimson and Autumn Royal) were trained on an overhead trellis system which permitted the ground cover to reach values up to 90%. Two campaigns of mid-season measurements were performed using one of the heat pulse techniques available (that known as the Tmax approach). Obtained values for average seasonal daily transpiration ranged between 3.9 and 4.4 mm day^{-1}, for both cultivars, depending on the period considered. Weekly averages of the basal crop coefficients, from mid-May to end-September, ranged from 0.47 to 0.87. A polynomial equation was fit to the measured basal crop coefficients as a function of fraction of thermal units. After further validation for other cultivars with different cumulative thermal requirements, this equation could be considered helpful for farmers as a practical estimate of the table grape basal coefficient under the netting.

Introduction

Table grape (*Vitis vinifera* L.) is a profitable crop in semiarid regions of Spain achieving great yields and very high fruit quality (Blanco et al. 2010). Table grape vineyards encompassed 19,500 ha in Spain, second in Europe behind Italy (OIV, 2006). Most vineyards (82%) are irrigated (Anuario de Estadística Agroalimentaria 2008).

Due to the water shortage in semiarid areas, knowledge of crop water requirements (i.e. evapotranspiration, ET) is paramount for adequate irrigation scheduling and management. Crop evapotranspiration (ET_c) depends upon environmental conditions, crop characteristics (such as trellis system and planting density), ground cover fraction, and cultural practices (such as fertilization and irrigation management). Seasonal table grape ET_c has been reported to range between 687 mm and 1,350 mm for Mediterranean climate in California (Williams et al. 2003; Williams and Ayars 2005), semiarid climate in Israel (Netzer et al. 2009), arid Mexican climate (Rodríguez et al. 2010) and for Spanish Mediteranean (Moratiel and Martínez-Cob, 2012).

ET_c is often estimated as the product of the reference crop evapotranspiration (ET_o) and a crop coefficient (K_c): $ET_c = K_c ET_o$ (Allen et al. 1998). The ET_o reflects the effect of the meteorological conditions on the evapotranspiration process and must be estimated from meteorological data recorded at a standard reference weather station using the FAO Penman-Monteith approach. The K_c includes all features of the cropping systems: species, crop architecture, management, etc. (Allen et al., 1998). The K_c is estimated as a function of crop growth stage, canopy height, local climate, plant architecture, ground cover fraction, and crop management among others. Allen et al. (1998) showed procedures to estimate K_c as a single crop coefficient or as a dual crop coefficient, i.e. as the sum of two components, basal crop coefficient (K_{cb}) due to transpiration, and evaporation coefficient (K_e) due to soil evaporation: $K_c = K_{cb} + K_e$. Allen and Pereira (2009) applied the procedures described by Allen et al. (1998) to present tabulated values of both K_c (single approach) and K_{cb} (dual approach) as a function of several ground cover fractions for different horticultural and orchard crops.

Recently, the use of insect-proof netting has widespread in orchard crops to reduce pesticide applications, radiative load during summer and hail and bird damage. The netting has a relatively low cost compared to total production costs in these orchard crops. Netting might have an important effect on microclimate and crop water requirements. Some authors have studied the effect of netting on the microclimate of different horticultural crops such as sweet pepper (Tanny et al. 2003; Möller et al. 2004; Möller and Assouline 2007) and banana (Tanny et al. 2006; Tanny et al. 2010). For sweet pepper, a 38% decrease of evapotranspiration due to reduced incoming solar radiation and wind speed has been reported (Möller and Assouline 2007). In the banana screenhouse experiment a reduction of radiation between 8-25% was reported, depending on cleanness and aging of the polyethylene screen. Also, it is shown that presence of a screen reduces the velocity statistics responsible for turbulent transport and the effective roughness of the surface.

There is little information about the effect of netting on crop water use in table grapes. Rana et al. (2004) studied the effects of different types of netting (uncovered, thin net and thin plastic film) on table grape ET (cv. Italia) with a complete ground cover. Their results present calculated mid-season K_c values for unstressed table grape vineyards of 1.0 for the uncovered vineyard, 0.9 for the thin net cover, and 0.86 for the thin plastic film. These values must not be considered K_c as defined by Allen et al. (1998) but as 'adjusted' K_c that contain the reduction as the consequence of the netting. Moratiel and Martínez-Cob (2012) studied the simultaneous effect of the netting and a black-plastic mulching on the K_c of 'Red Globe' table grape grown under a gable trellis system. They estimated weekly K_c values (adjusted for the effects of the netting and the mulching) ranging between 0.64 and 1.2 along the season, while the average adjusted K_c values during mid and end-season stages were 0.79 and 0.98, respectively. Moratiel and Martínez-Cob (2012) estimated a netting coefficient (0.65) representing the reduction effect of the netting on K_c. The works of Rana et al. (2004) and Moratiel and Martínez-Cob (2012) include all the effects of the netting on the K_c as this coefficient, as defined by Allen et al. (1998), should reflect the different characteristics of the cropping system.

Frequently, table grape vineyards are trained on an overhead trellis system which leads to an almost full ground cover shading. This, and the use of netting in drip irrigated table grapes grown in semiarid regions, cause that transpiration represents most of the total ET during mid-season stages due to minimum soil evaporation because wetted soil surface areas are shaded (Allen et al. 1998), and to the low rainfall that generally occurs during that stage. Therefore, the quantification of transpiration becomes crucial for appropriate irrigation scheduling of such drip irrigated crops. To our knowledge, no previous works have been reported on the effect of the netting on table grape transpiration.

The aim of this research was to determine the transpiration of two seedless cultivars of table grape, Crimson and Autumn Royal, grown under the semiarid conditions of the central Ebro River Valley in Spain. These vineyards were trained on an overhead trellis system and grown under netting. Measurements were carried out along two campaigns during the mid-season stage and the corresponding basal crop coefficients (K_{cb}) were obtained. It was aimed that these K_{cb} include all effects of the netting on the transpiration through a “netting coefficient” (K_{ne}) so this coefficient can allow scheduling irrigations of this cropping system (table grape grown under an overhead trellis system and netting) following the guidelines proposed in Allen et al. (1998).

Material and methods

Site and crop

The study was conducted on a commercial table grape vineyard at the farm Santa Bárbara, in Caspe (Zaragoza, NE Spain) during 2008 (15 July to 30 September) and 2009 (15 May to 30 September). The geographical coordinates of the farm are 41º16’ N latitude, 0º02’ W longitude, and 147 m elevation above the sea level. The long-term annual average meteorological conditions in the area are described in Martínez-Cob and Faci (2010). According to this reference annual precipitation is 315 mm; mean air temperature is 14.9 °C; minimum air relative humidity is 41%; mean global solar radiation is 185 W m^{-2}; mean wind speed at 2 m above ground is 3.1 m s^{-1}; the annual reference evapotranspiration is 1,392 mm.

The 4.0 ha commercial table grape vineyard was divided in two experimental subplots, each with a different cultivar: A) Crimson; B) Autumn Royal; both cultivars were grafted on Richter 110 rootstock. This vineyard was surrounded by other table grape vineyards (Blanco et al. 2010; Moratiel and Martínez-Cob 2012). Row direction was approximately northwest to southeast. The vineyard was trained on an overhead trellis system, and was covered with a net made of a thread warp of high-density polyethylene (Criado and López, Almería, Spain) to protect the vines from hail, birds, and insects. This netting was transparent with individual pores of 12 mm^2 (2.2 mm x 5.4 mm) and was placed at a height of 3.0 m above ground level just above the canopy level. The vineyard had a slope of 1%. The soil at the 'Crimson' subplot was sandy except for the upper 0.1 m (sandy loam), and was classified as Xeric haplogypsid, sandy, mixed (gypsic), thermic. The soil at the 'Autumn Royal' subplot was sandy loam and classified as Xeric calcigypsid, coarse loamy, mixed (gypsic), thermic (Soil Survey Staff, 1999, 2006). Nevertheless, the uppermost soil layer in-between rows (about 0.1 m) were used to create a ridge where the plants were established. The ridge was directly beneath the vines in each row; its dimensions were 0.5 m in width and 0.4 m in height. Thus the actual texture within the root zone was sandy loam in both vineyards. Table 1 lists some of the physical and chemical properties of these soils that were determined at the laboratory from soil samples taken at two trial-pits opened in the vineyard.

The vineyard was irrigated with a drip irrigation system with one lateral in each row of vines with integrated self compensating emitters of a discharge of 2.2 L h^{-1}, spaced 0.5 m. A volumetric water meter was placed at the inlets of the two experimental vineyard subplots to register the irrigation depth applied to each cultivar. Daily drip irrigation from May to September was applied following the farm manager's criteria. These criteria were based on FAO Penman-Monteith estimations of ET_o, K_c values tabulated by Allen et al. (1998), and adjustments for ground cover fraction irrigation uniformity and leaching requirements. Other management practices (herbicide and fertilizer applications and pruning) were also conducted according to the farm manager's criteria. Herbicides were periodically applied between rows to control weeds. Vines were winter pruned. However, in 2009 an additional summer pruning of the shoots in a strip 0.5 m wide between vine rows was performed for the cultivar Crimson around veraison, to allow a better penetration of light in the canopy to enhance the berries quality and to increase color uniformity.

Transpiration measurements

Table grape transpiration was measured during the mid-season stage of the crop. For 'Crimson', data was recorded in two seasons: a) 2008 (15 July to 30 September); b) 2009 (15 May to 30 September). For 'Autumn Royal', measurements were taken only in 2009, from 15 May to 21 August. The heat pulse method was used (Green et al. 2003). Other authors have also applied this method to measure grape transpiration (Yunusa et al. 1997; Yunusa et al. 2004; Pereira et al. 2006; Fernández et al. 2008; Green 2008; Zhang et al. 2011). The heat pulse method can be applied using different approaches.

In this paper, that known as Tmax was chosen due to the relatively large xylem vessels of table grapes (Green et al. 2003).

The instrumentation for monitoring the sap flow was provided by Tranzflo (Palmerston North, New Zealand). During 2008, two vines of ‘Crimson’ were monitored using one set of probes per vine. During 2009, three vines of each cultivar were monitored using two sets of probes per vine. Each set of probes consisted of a line heater and two temperature probes, all of them of 1.8 mm diameter. Each set was installed into parallel holes drilled radially into the stem at heights of about 0.8-1.0 m above the ground. The temperature probes of each set were placed at 10 and 40 mm above the heater (Green et al. 2003). Each temperature probe had three thermocouples at 5, 10 and 15 mm depths.

One datalogger (CR3000 in 2008) or two dataloggers (CR23X in 2009, one for each cultivar) Campbell Scientific (Shepshed, UK) were used to activate the heater for 2 s each half hour. The pair of temperature sensors was used to monitor the subsequent changes in stem temperature at the three abovementioned depths. These changes occurred as the heat pulse propagated through the sapwood. The dataloggers interpreted the temperature signals after each heat pulse and determined the time until a peak temperature difference (t_M) was observed for each depth. Thus, for each set of probes and depth, a series of half-hour values of t_M were collected by the datalogger for further analyses. These analyses followed the procedure described by Green et al. (2003). Thus, corrected heat pulse velocity, V_c (cm h^{-1}) was calculated as:

$$V_C = a_0 + a_1 V_M + a_2 V_M^2 \qquad [1]$$

where: a_0, a_1, and a_2 are correction factors to take into account the effect of the installation wound width; chosen from tabulated values considering that wound width was 3.2 mm (Green et al. 2003); V_M, uncorrected heat pulse velocity (cm h^{-1}):

$$V_M = 3600 \frac{\sqrt{x_D^2 - 4\kappa_d t_M}}{t_M} \qquad [2]$$

where: x_D is downstream distance from line heater, 1.0 cm; κ_d is the thermal diffusivity estimated as 8.33 x 10^{-4} cm^2 s^{-1} at times when zero sap flow occurs (Green et al. 2003); in this paper, it was assumed that zero sap flow occurs if t_M = 300 s as this was the highest value recorded during the measurement period.

Next, the sap flow, J_s (cm h^{-1}) at each depth (5, 10 and 15 mm) was obtained as:

$$J_s = \left(k\, F_M + F_L\right) V_C \qquad [3]$$

where: F_M and F_L are the volume fractions of wood and water, respectively, and k = 0.441 is a factor related to the thermal properties of the woody matrix (Green et al. 2003). F_M and F_L were determined experimentally from wood samples taken from the monitored vines: three times during 2008 (1 August, 29 August and 3 October) and four times during 2009 (14 May, 2 July, 12 August and 21 October) (Table 2). The fresh weight of each wood sample was determined just right after taking it out. The dimensions (base radius and height) of the sample were also measured to determine the wood sample volume (V_T). Later, the sample was oven-dried to determine the mass of dry wood (m_M) and the mass of water (m_L) contained in the fresh sample. Then F_M and F_L were computed as:

$$F_M = \frac{m_M}{\rho_M V_T} \qquad [4]$$

$$F_L = \frac{m_L}{\rho_L V_T} \qquad [5]$$

where: ρ_M, is dry wood density taken as 1500 kg m^{-3} (Green, 2009) and ρ_L is water density taken as 1000 kg m^{-3}.

Finally, the half-hour volume sap flux, F (L h^{-1}) was determined integrating the J_s values at the three depths following the procedure described by Hatton et al. (1990) for which the radius of each vine at the cambium was required (Table 2). Daily transpiration values (mm day^{-1}) were obtained summing up the half-hour values and dividing by the surface area allocated for each vine (3.5 m x 2.5 m). During 2009, the F values of the two set of probes at each vine were averaged to get a single half-hour F value for that vine.

An assessment of the reliability of the experimentally derived transpiration data was performed by comparing them with the table grape (cv. Red Globe) evapotranspiration values recorded by the surface renewal method (SR) at a plot next to that of this study (Moratiel and Martínez-Cob, 2012). These evapotranspiration values were almost equal to transpiration particularly during summer (Moratiel and Martínez-Cob, 2012) as soil evaporation was highly reduced by a black plastic mulching. The SR method has already proven its accuracy on a wide range of crops with different canopy architectures and management conditions, including vineyards (Paw U et al. 2005, Castellví and Martínez-Cob, 2005; Castellví et al. 2006, 2008; Spano et al. 2008; Castellví and Snyder 2009, 2010). Moratiel and Martínez-Cob (2012) provide a detailed description of the surface renewal measurements. This assessment was only performed for year 2008 as the Red Globe evapotranspiration data was collected for 2007 and 2008.

Experimental basal crop coefficients (K_{cb_exp}) under the netting were obtained as: $K_{cb\_exp} = Tr/ET_o$, where Tr is the daily transpiration and ET_o is the daily reference evapotranspiration, computed using the FAO Penman-Monteith method (Allen et al. 1998). The daily meteorological variables (wind speed, solar radiation, air temperature, and relative humidity) for ET_o calculation were recorded at a standard weather station, located over grass following Allen et al. (1998) guidelines. It was located about 1 km north from the vineyard ('grass weather station'). This station belongs to a network named SIAR installed and managed by the Spanish Ministry of Rural and Marine Environment (http://www.mapa.es/siar/). It should be noted that these K_{cb_exp} values are adjusted basal crop coefficients that take into account the effect of the netting. It was assumed that this management practice would reduce the vineyard transpiration and the K_{cb} compared to a similar vineyard managed without that management practice. Thus, these K_{cb_exp} values would represent the optimum (potential) transpiration of the crop under the netting.

Additional measurements

A standard meteorological station was installed at the Crimson experimental subplot (in-situ). It consisted of a pyranometer (Kipp & Zonen, CM3), a switching anemometer (Vector instruments, A100R), and an air temperature and relative humidity probe (Vaisala, model HMP45C). All sensors were installed above the canopy, just below the netting. The measurements of the in-situ station were compared to those recorded at the ‘grass weather station’ (SIAR). The average ratios of each variable at both stations were used to estimate the netting effect on “reference” evapotranspiration following the procedure described in detail in Moratiel and Martínez-Cob (2012).

Soil volumetric water content was measured at 0.1, 0.2 and 0.3 m depth with two frequency domain reflectometry (FDR) probes (Enviroscan, Sentek, Pty Ltd. South Australia). Each sensor of the probe has its own factory calibration and following the manufacturer`s user manual, these probes were normalized at the laboratory before installation. With the probe inside the access tube, readings of the sensors were performed in the air and in a normalization chamber filled with water. The readings of each sensor in the air and in the water chamber were input in the datalogger for the configuration of the commercial calibration equation of each sensor to convert the readings into volumetric soil water content. The probes were installed within the crop row at 0.5 and 1.25 m from a central vine, to obtain values of the soil water content in the area wetted by the emitters. Soil water content readings were continuously taken each hour. The relatively important percent of gravel (Table 1) precluded the measurement of soil water content deeper than 0.5 m. Nevertheless, most of rooting activity of crops under drip irrigation is commonly found within the upper 0.4-0.5 m soil layer (Steven and Douglas, 1994; Fernandez and Moreno, 1999; Soar and Loveys, 2007; Searles et al., 2009). As a consequence, readings deeper than 0.3 m were not taken. More details about these readings can be found in Blanco et al. (2010).

Phenological stages by visual observation, canopy cover evolution by digital photography, and yield at harvest were also recorded. Pictures of ground cover were taken with a digital camera (Olympus, model µ810, China). The camera was set on the ground and focused upwards to capture a quarter of the space that belongs to a vine (1.25 × 1.75 m). The images were processed with the GIMP program (available at www.gimp.org). The program transforms the picture into black pixels that represent leaves and branches while the white ones reflect clear screen. After calculating the black and white pixels and presenting them on histogram, a value of the percentage of the black pixels which represents the shaded ground cover was derived (Blanco et al. 2010).

Thermal units (TU) were estimated using the University of California Statewide Integrated Pest Management Project's website (http://www.ipm.ucdavis.edu/WEATHER/index.html). Thermal units were calculated using the single sine method with a lower threshold of 10 °C from budbreak up to harvest. Finally, stem water potential was measured at solar noon in 3-5 exposed leaves per vine for each cultivar during three different dates during 2009. The exposed leaves were sealed in foil laminate bags to prevent overheating by the sun and to allow leaf water potential to equilibrate to that of the stem. Measurements were made using a Scholander pressure chamber (M3115, ICT, Armidale, Australia).

Results and discussion

Meteorological conditions, phenology and water status

Figure 1 shows the weekly totals of precipitation and the weekly averages of air temperature, vapour pressure deficit and wind speed at 2 m above ground recorded at the nearby SIAR station from 15 May to 30 September for both seasons. Precipitation was higher for 2008 (122 mm) than for 2009 (74 mm). The largest difference between both seasons occurred for the period from 15 May to 18 June during which 53.9% of the total seasonal precipitation was recorded for 2008 but only 16.6% for 2009. Weekly total precipitation exceeded 10 mm only for two weekly periods during 2009 but for six weekly periods for 2009. Warmer temperatures for 2009 were observed for 17 of the 20 weeks included in the period from 15 May to 30 September. In general, the largest differences between both seasons occurred during the period from 15 May to 18 June. Vapor pressure deficit (VPD) was higher for 2009, 0.4 kPa in average. The highest differences were observed for the period from 15 May to 18 June and for mid-August. The 2009 season was only slightly windier (0.2 m s^{-1} in average) than the 2008 season. The highest differences occurred during May and mid-July. Summarizing, the 2009 season was drier, warmer and the evaporative demand was higher. Thus the total season ET_o estimated at the SIAR station for the period from 15 May to 30 September was 938 mm for 2009 and 842 mm for 2008.

Some differences in the phenology of the studied cultivars were observed for both years (Table 3). For ‘Crimson’, despite a later budbreak, the 2009 season was about one month shorter than that for 2008. The season length for ‘Autumn Royal’ from budbreak to harvest during 2009 also was sharply shorter (35 days) than that for ‘Crimson’. The measurements taken in this study started around three weeks before veraison in 2008 and about 1-2 weeks before flowering in 2009. The different phenology observed for ‘Crimson’ for both seasons was due to the warmer conditions of 2009 for the period from 15 May to 30 September (Figure 1). These warmer conditions for 2009 led to a higher cumulative TU value for ‘Crimson’ from budbreak to harvest: 2,381 °C for

2009 and 2,245 °C for 2008. The cumulative TU values before 15 May indicate that early spring was colder for 2009 and this would explain the later budbreak for 'Crimson'. But, as the 2009 season was warmer since the end of May (Figure 1), the cumulative TU for 'Crimson' exceeded that for 2008 and then the development of 'Crimson' fastened compared to 2008. As a consequence, flowering dates were similar for both years, while veraison and harvest dates occurred sooner for 2009. A similar behaviour was observed for 'Autumn Royal' (Table 3) its shorter season length as compared to 'Crimson' is also reflected in a lower value of cumulative TU value from budbreak to harvest (2,140 °C).

Figure 2 shows the evolution of ground cover fraction (i.e. fraction of the soil being shaded by the crop canopy) along both 2008 and 2009 seasons. Most of the measurements were taken for a ground cover fraction above 70-80%, i.e. during the mid-season stage as defined by Allen et al. (1998), except for those during May, taken during the last part of the development stage. For both cultivars and seasons, ground cover fraction started to decline slightly after reaching a maximum value of 90% around mid-August (day of the year, DOY, 230; TU, 1400 °C) (Figure 2). For 'Crimson' during 2009, the decline in ground cover fraction was slightly higher because the farm's manager made a leaf clearance at the beginning of August in the middle area between rows to improve colour uniformity of the berries.

For the period from 15 May to 30 September, the irrigation amounts applied for 'Crimson' for 2009 (532 mm) were higher than for 2008 (446 mm) as a consequence of the meteorological conditions (warmer and drier for 2009) (Table 4). The largest differences were observed for May to July when the differences between the meteorological conditions among the two seasons were largest. The irrigation amounts applied for ‘Autumn Royal’ for 2009 (581 mm) also were higher than those applied for ‘Crimson’ for the same season (Table 4). The daily irrigation of ‘Autumn Royal’ was generally split in two moments (night and noon) as the farm’s manager believed that this practise would reduce the potential berry cracking problem that may appear with sudden supplies of great amounts of water (Blanco et al. 2010).

Figure 3 shows the evolution of hourly soil water content along the measurement periods during 2008 and 2009 for both cultivars. These values must be considered as relative instead of absolute according to the manufacturer. There was a strong daily fluctuation in this variable due to the daily drip irrigation. In general, the limits of these fluctuations kept around similar values along the season (Figure 3). Just after the irrigation, there was a sudden increase of the soil water content reaching the upper limits. Later, there was a smoother decrease of that variable as water infiltrated into the soil, was absorbed by the crop, and drained out the root zone. Some drainage was required to keep the soil salinity within the current values (Table 1). These fluctuations were larger at 0.1 m, i.e. near soil surface, and shorter at 0.2 and 0.3 m. There was a period (second half of June 2009) with a lack of daily fluctuations due to maintenance and repairing of the irrigation pump system. Therefore, these values suggest that the crop was sufficiently watered and did not suffer water stress, i.e. the measured transpiration values correspond to a cropping system under optimal conditions. For 2009, the mid-day stem water potential values recorded at three different dates (5 August, 2 September and 2 October for ‘Crimson’; 16 July, 26 August and 2 September for ‘Autumn Royal’) ranged from -0.41 to -0.88 MPa for ‘Crimson’ and from -0.49 to -

0.61 MPa for ‘Autumn Royal’. These values were below the threshold values for setting water stress for table grapes (Patakas et al. 2005; Williams and Baeza 2007).

In average, the ratios of solar radiation, wind speed, air temperature and relative humidity at the Crimson subplot to the corresponding variables at the SIAR station were 0.865, 0.153, 1.014 and 1.027, respectively. Using these ratios to ‘correct’ the meteorological values recorded at the SIAR station, the ratio of the ‘corrected’ ET_o to that originally computed was 0.67 in average (Figure 4). Therefore it can be considered that that value, 0.67, can be used as a rough estimation of the reduction coefficient for evapotranspiration due to netting (K_{ne}). Moratiel and Martínez-Cob (2012) got a similar value, 0.65; both nettings were similar at the close ‘Red Globe’ vineyard grown under similar netting. Möller and Assouline (2007) reported a 38% reduction (i.e. a reduction coefficient of 0.62) of sweet pepper evapotranspiration due to reduced incoming solar radiation and wind speed because of the netting. It is also interesting to note that the ratio of solar radiations at both stations indicate that, in average, the netting reduced incoming solar radiation by about 13.5 %, i.e. the netting reflected and absorbed about 13.5 % of the incoming solar radiation.

Thus assuming that transpiration is almost equal to evapotranspiration in these types of table grape vineyards because of the high ground cover fraction, it could be possible to state that the netting would reduce transpiration by about 30 to 35% although this figure should require further research due to the rough comparisons discussed in the previous paragraph. However the aim of this paper was to get appropriate crop coefficients for the studied cropping system such that they could be applied following the guidelines by Allen et al. (1998). Remind that the ET_o must be computed from meteorological variables recorded at reference stations. In addition, for the particular cropping system studied in this work, $ET_c = ET_o K_c K_{ne}$. Assuming that soil evaporation is minimal for this cropping system due to the high ground cover fraction, $ET_c \approx Tr$ (being Tr, crop transpiration) and $K_c \approx K_{cb}$ in this case. Then the above expression can be rewritten as $Tr = ET_o(K_{cb}K_{ne})$ such that the experimental basal crop coefficients obtained in this paper would represent the 'adjusted' K_{cb} due to the netting. This statement is only valid once the ground cover fraction becomes 70 % or higher (Figure 2), i.e. for the mid-season and late-season crop growing stages. The effect of the netting on basal crop coefficient during early stages would require further research.

Transpiration

Table 5 shows several statistics (mean, median, coefficient of variation, and percentiles 25 and 75 %) that allow the comparison of the transpiration measurements within the same plant and between plants of the same cultivar. The measurement period actually available for each probe was used for these comparisons. These results show some differences between the values recorded by the two probes of the same plant; in general, the probes facing south recorded higher values. There was also variability noted between plants of the same cultivar likely due to factors such as differences in trunk diameter and actual ground area corresponding to each plant. Because of the growing pattern of vines that makes almost impossible to adequately distinguish single crop canopies, the same ground area was assigned to each vine. For later analyses, the values of each plant were averaged to get a single data set for each cultivar. In the case of 'Autumn Royal', only two plants were averaged from 20 June to

21 August 2009. Because of electronic failure of the sap flow equipment, transpiration values for ‘Autumn Royal’ since 22 August to the end of the measurement period were lost.

There was a good agreement between our experimental results (Crimson transpiration) and the Red Globe evapotranspiration values obtained at a neighbor vineyard (within the same commercial farm) by Moratiel and Martínez-Cob (2012). Figure 5 shows the seasonal evolution of the daily values of both variables. There was a general agreement particularly during summer when soil evaporation was minimized by the black plastic mulch used in the Red Globe vineyard and there was a little amount of rain (Figure 1). The difference observed at the beginning of the measurement period was due to the precipitation occurring on May 2008 increasing soil evaporation. Figure 6 shows that there was a good linear relationship between Crimson transpiration and Red Globe evapotranspiration (coefficient of determination, 0.73). The simple linear regression equation depicted on Figure 6 was used to ‘adjust’ our transpiration values and then to compute ‘adjusted’ basal crop coefficients. Table 6 shows the differences between the experimental and the adjusted K_{cb} values for the year 2008 when both Crimson transpiration and Red Globe evapotranspiration were measured. Those differences were minimal, around ±3%. These results suggest that our transpiration values were reliable and can be considered appropriate to obtain accurate basal crop coefficients for the studied cropping system.

Figure 7 shows the evolution of the measured daily table grape transpiration values and the estimates of ET_o calculated from the recorded meteorological variables at the nearby SIAR station. In general terms, the trends of these lines were similar for both years. The highest values of measured transpiration and estimated ET_o were observed during mid-summer (July and August) when the evaporative demand was higher due to the general meteorological conditions (temperature and VPD). During 2009, the measured transpiration values of both table grape cultivars were quite similar. For the period from 15 May to 21 August 2009, the average measured transpiration was 4.4 mm day^{-1} for 'Crimson' and 4.3 mm day^{-1} for 'Autumn Royal'; transpiration totals for that period were 426 mm and 439 mm, respectively. Nevertheless, 'Autumn Royal' showed slightly lower transpiration values than 'Crimson' at the beginning of the measurement period (Figure 7) due to the later start up of the development stages in 'Autumn Royal' (Table 3). Later 'Autumn Royal' showed slightly higher transpiration values than 'Crimson' because it reached slightly higher maximum ground cover fraction (Figure 2) and it also received slightly higher irrigation dose (Table 4). For 'Crimson', the differences between both seasons, 2008 and 2009, were also small for the period from 15 July to 30 September: averages were 4.0 mm day^{-1} for 2008 and 3.9 mm day^{-1} for 2009. Despite the different meteorological conditions in 2008 and 2009, the differences in transpiration for 'Crimson' between both seasons for the period from 15 July to 30 September were practically negligible because the main differences among meteorological conditions were observed during May and June (Figure 1). The maximum weekly averages of the measured transpiration values were 4.7 mm day^{-1} (in 2008) and 4.8 mm day^{-1} (in 2009) for 'Crimson', and 5.3 mm day^{-1} (in 2009) for 'Autumn Royal'.

The transpiration values measured in this paper are not directly comparable to those reported in previous works (Netzer et al. 2009; Williams and Ayars, 2005) because the variables are different (transpiration and evapotranspiration). In addition, average values for ‘Crimson’ in 2008 and ‘Autumn Royal’ in 2009 cannot be adequately compared with averages reported in those works for measurements periods being much longer than ours. Nevertheless, note that most transpiration measurements in this work were done for a ground cover fraction above 80%. Soil evaporation occurs mostly at the wetted and sun exposed fraction of the soil surface (Allen et al. 1998), the air ventilation was highly reduced due to the netting, and precipitation was low, therefore, reduced soil evaporation should be expected. The seasonal average transpiration recorded for ‘Crimson’ (2009 season, May to September) in this study was 4.0 mm day^{-1}; discarding the netting effect, an average value of 6.0 mm day^{-1} would have been obtained, quite close to the average evapotranspiration values reported by Netzer et al. (2009) and Williams and Ayers (2005). These authors studied the water use of table grape vineyards under semiarid climate and similar canopy architecture, with high ground cover fraction above 80 %.

Basal crop coefficient

The weekly averages of K_{cb_exp} obtained in this paper for ‘Crimson’ (seasons 2008 and 2009) and ‘Autumn Royal’ (season 2009) for the mid-season stage are presented as a function of the fraction of cumulative thermal units (FTU), i.e. the ratio of cumulative TU at a given week to the total cumulative TU at harvest (Figure 8). In general, the values of K_{cb_exp} for ‘Crimson’ were similar for both seasons; during the period from 15 July to 30 September, K_{cb_exp} ranged from 0.55 to 0.82 for 2008 and from 0.54 to 0.87 for 2009 while the average K_{cb_exp} was 0.65 for both seasons. Likewise, values for ‘Crimson’ and ‘Autumn Royal’ for 2009 also were similar; during the period from 15 May to 21 August, K_{cb_exp} ranged from 0.54 to 0.67 for ‘Crimson’ and from 0.47 to 0.75 for ‘Autumn Royal’, while the respective average K_{cb_exp} values were 0.59 and 0.60. In average, considering together the three cultivar-season data sets, these values showed a gradual increase from about 0.50 at the beginning of the measurement period to about 0.60 at mid-June when a FTU value of about 0.35 was reached (Figure 8). From mid-June to mid-August, values of K_{cb_exp} were fairly stable, around 0.60. Later, an additional increase of the K_{cb_exp} values was observed up to the end of the measurement period, reaching values of about 0.90. This later increase of K_{cb_exp} was only observed for ‘Crimson’ as no data was available for ‘Autumn Royal’ after mid-August.

This later increase of K_{cb_exp} after mid-August does not mean that ‘Crimson’ transpiration increased as it can be seen on Figure 8. The lower atmospheric evaporative demand after mid-August led to a decrease of both transpiration and ET_o. However, the decrease of transpiration was slower than that of ET_o leading to that increase of K_{cb_exp}. This behavior was likely due to several factors. When ET_o is low, a small energy supply, for instance from canopy or soil, may enable an increase in the crop coefficient (Testi et al. 2006). The summer pruning in mid-August increased the amount of leaf area exposed to direct sunlight and allowed a better air circulation within the canopy. Williams and Ayars (2005) reported that leaf area exposed to direct sunlight determines more the water use of a grapevine than the total amount of leaf per vine. Finally, the intense metabolic activity occurring after veraison may have contributed to make the transpiration decrease slower as compared to that of ET_o after that phenological stage.

Williams and Ayars (2005) showed a relatively similar pattern for the crop coefficient (K_c) curve of ‘Thompson Seedless’ table grape under semiarid climate, i.e. a gradual increase and a plateau from end-June to end-August. However, they did not show a later increase of the K_c curve as no data was presented after that date. Williams and Ayars (2005) published an average plateau K_c value of about 0.90 for a ground cover fraction of 80% although this average K_c value increased up to about 1.25 for the short period when the authors raised the canopy curtain to increase shaded area. Also for semiarid climates, Netzer et al. (2009) showed K_c values continuously increasing up to values of about 1.30 for ‘Superior Seedless’ table grape due to a concomitant increase of leaf area index even after harvest (which occurred about 1.5-2.0 months before than harvest date observed in this paper). The K_c values of Netzer et al. (2009) showed even a slightly increase when the leaf area index had already started to decline. The K_c values of those two works can not directly be compared to the K_{cb_exp} values obtained here as they represent two different variables: evapotranspiration and transpiration, respectively. Nevertheless, the soil evaporation term of evapotranspiration should be small for table grapes with ground cover fractions reaching values of 80% and above. Discarding the reduction coefficient due to the netting, the seasonal average K_{cb_exp} obtained in this work would have been relatively close to those reported by Netzer et al. (2009) and Williams and Ayars (2005).

On the other hand, Allen and Pereira (2009) listed tabulated mid-season values of K_{cb} = 1.05 for table grapes for a ground cover fraction above 70%. The average windspeed and minimum relative humidity recorded during the mid-season at the SIAR station were used to correct the tabulated K_{cb} following Allen et al. (1998) and Allen and Pereira (2009). After multiplaying by K_{ne}= 0.67, the K_{cb} values for this cropping system (mid-season) estimated using FAO procedure were about to 0.73 to 0.76 slightly higher than the K_{cb_exp} measured during the mid-season in this work. Allen and Pereira (2009) did not provide any further information (trellis system, distance between vines, climatological conditions) that could help to explain such a difference. Rana et al. (2004) reported a crop coefficient reduction of only 14% for table grape 'Italia' under thin plastic netting. This netting was different to that of this study and this could be the reason for this lower reduction effect of the netting.

The coefficient of determination (R^2) of the polynomial fit to the measured K_{cb_exp} values was relatively high (about 69%) indicating that a relatively great proportion of the variability observed for K_{cb_exp} was explained by FTU (Figure 8). This value of R^2 was slightly lower than those reported in previous works where curves of crop coefficient versus TU or FTU were obtained (Steele et al. 1996; Martínez-Cob 2008). It should be expected that FTU can not completely explain the variability of K_{cb} as crop development is highly but not completely affected by thermal units; other climatic, plant, soil and management factors should be considered to estimate crop coefficient curves. Other variables, such as ground cover fraction and leaf area index have also shown to be appropriate to develop crop coefficient curves (Allen and Pereira 2009; Netzer et al. 2009; Williams and Ayars 2005, among others). These variables are easy to measure by scientific groups and to describe quite well crop development. But these variables are not readily available for farmers for routinely use in irrigation scheduling. Variables such as thermal units are more suitable for the purpose of routinely estimation of basal crop coefficients by farmers because it can be easily obtained from the air temperature records of standard weather station networks. The use of FTU is preferred over the use of TU as it allows a general application of the crop coefficient curve across cultivars requiring different TU totals from emergence or budbreak to harvest or physiological maturity (Amos et al. 1989). The polynomial curve displayed on Figure 8 should be limited to the late development and mid-season stages. In addition it is only valid for cropping conditions (particularly netting) similar to those of this study. The reduction in transpiration and K_{cb} due to the netting would require further studies to determine more appropriate reduction coefficients. Likewise, this equation should be still validated for other cultivars requiring different cumulative thermal units from budbreak to harvest.

Conclusions

Similar transpiration and basal crop coefficients (K_{cb_exp}) were measured in this paper for both studied cultivars, Crimson for two seasons (2008 and 2009) and Autumn Royal for one (2009). Most of the differences in meteorological conditions in both years were observed from May to June, and as most of the measurements were carried from July to September, only slight differences were observed between the transpiration rates of both cultivars. For the corresponding shared measurement periods, average transpiration values for ‘Crimson’ and ‘Autumn Royal’ for 2009 were 4.4 and 4.3 mm day^{-1}, respectively, while average transpiration values for ‘Crimson’ for 2008 and 2009 were 4.0 and 3.9 mm day^{-1}, respectively. Likewise, for the corresponding shared measurement periods, values of K_{cb_exp} for ‘Crimson’ and ‘Autumn Royal’ ranged from

0.54 to 0.67 (average 0.59) and from 0.47 to 0.75 (average 0.60), while values of K_{cb_exp} for 'Crimson' for 2008 and 2009 ranged from 0.55 to 0.82 (average 0.65) and from 0.54 to 0.87 (average 0.65), respectively. The shorter development length and the slightly higher ground cover fraction of 'Autumn Royal' would explain the small differences among these two cultivars. Additionally, these results point out that the presence of netting system has reduced the transpiration rates. Further research would be required to obtain more accurate reduction coefficients due to netting.

A polynomial equation was fit to the measured basal crop coefficients as a function of fraction of thermal units. This equation could help farmers to easily estimate the table grape basal coefficient under the netting. However this equation should be limited to the late development and mid-season stages and similar conditions of this study. This equation still needs validation for other cultivars with different cumulative thermal requirements from budbreak to harvest.

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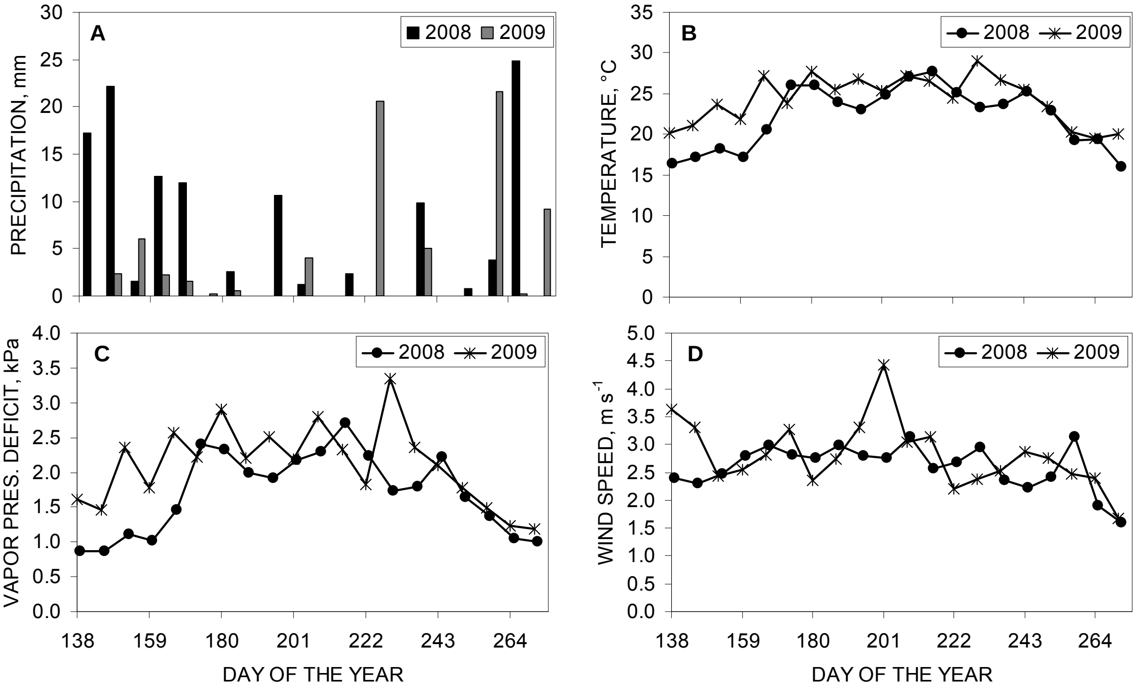

Figure 1. Weekly meteorological conditions during 2008 and 2009 (15 May to 30 September) recorded at a standard weather station over grass located 1 km from the vineyard. A, total precipitation; B, mean air temperature; C, mean vapour pressure deficit; and D, mean wind speed at 2.0 m above ground.

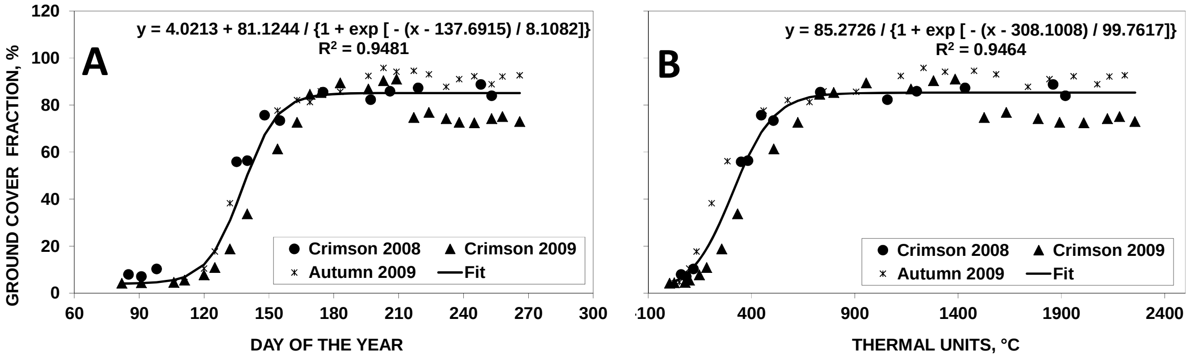

Figure 2. Measured values of ground cover fraction (i.e. the fraction of soil shadowed by the crop canopy) for cultivars 'Crimson' (seasons 2008 and 2009) and 'Autumn Royal' (season 2009), as a function of (A) day of the year and (B) thermal units

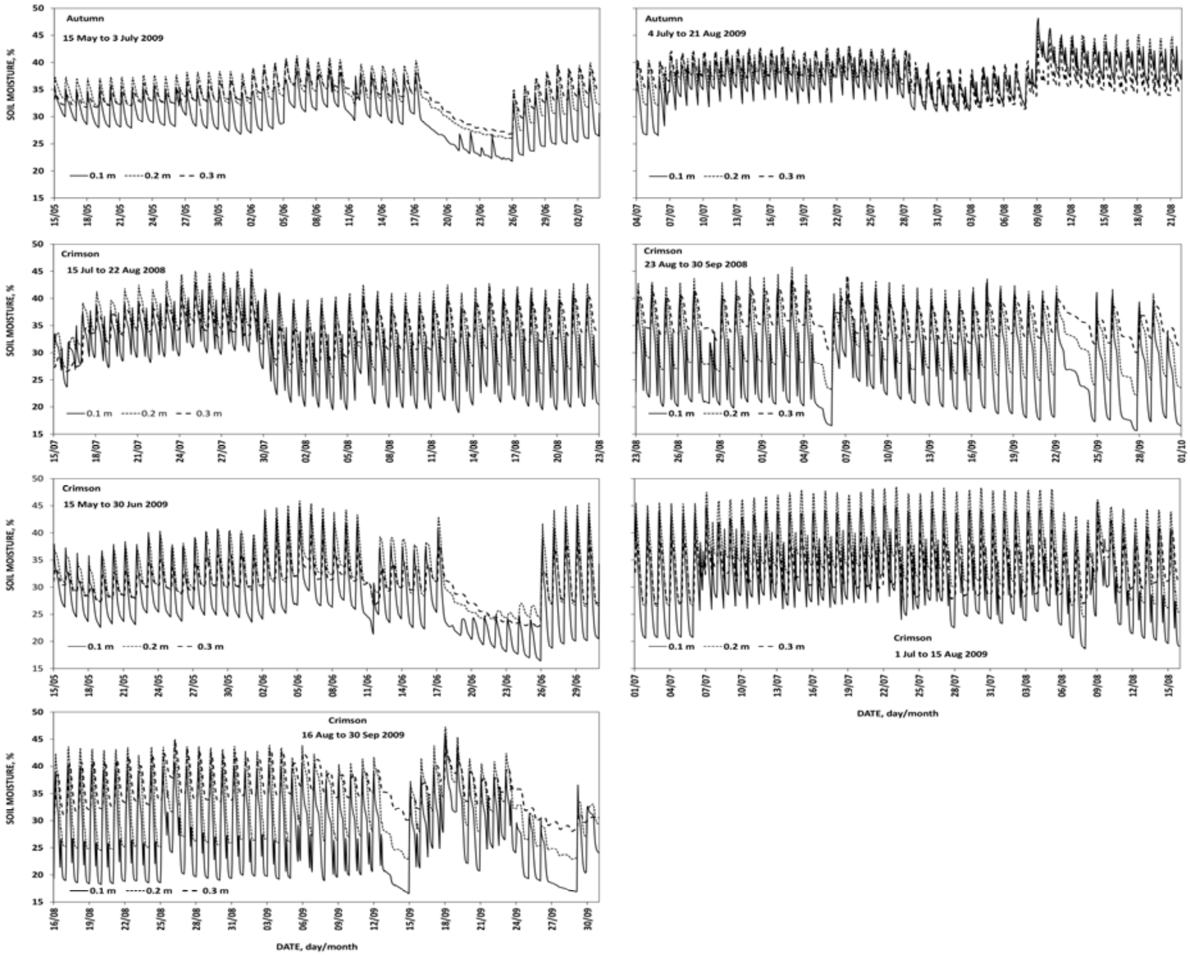

Figure 3. Hourly soil water content values recorded at different depths during the measurement periods for 2008 (cultivar 'Crimson') and 2009 (cultivars 'Crimson' and 'Autumn Royal'). Values are the averages of two access tubes installed at 0.5 and 1.25 m from the central vine.

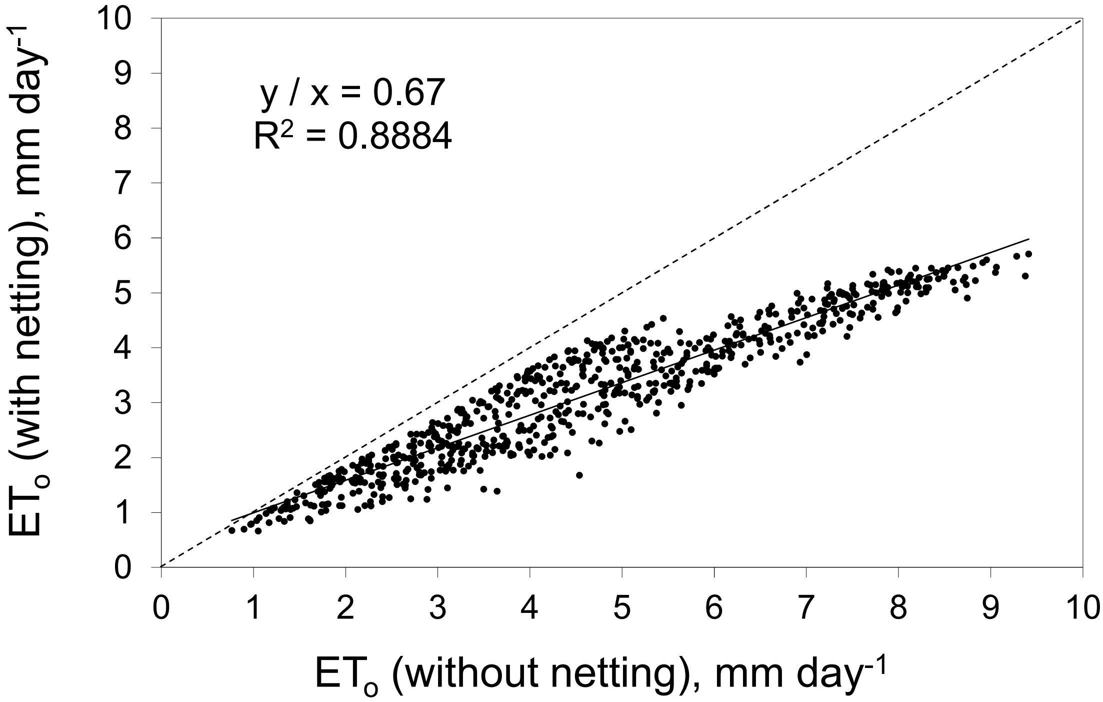

Figure 4. Comparison between the reference evapotranspiration (ET_o) estimated using the meteorological variables recorded at the SIAR station ("ET_o without netting") and the ETo estimated by 'correcting' those meteorological variables by their corresponding ratios to the recorded values at the 'Crimson' station ("ET_o with netting").

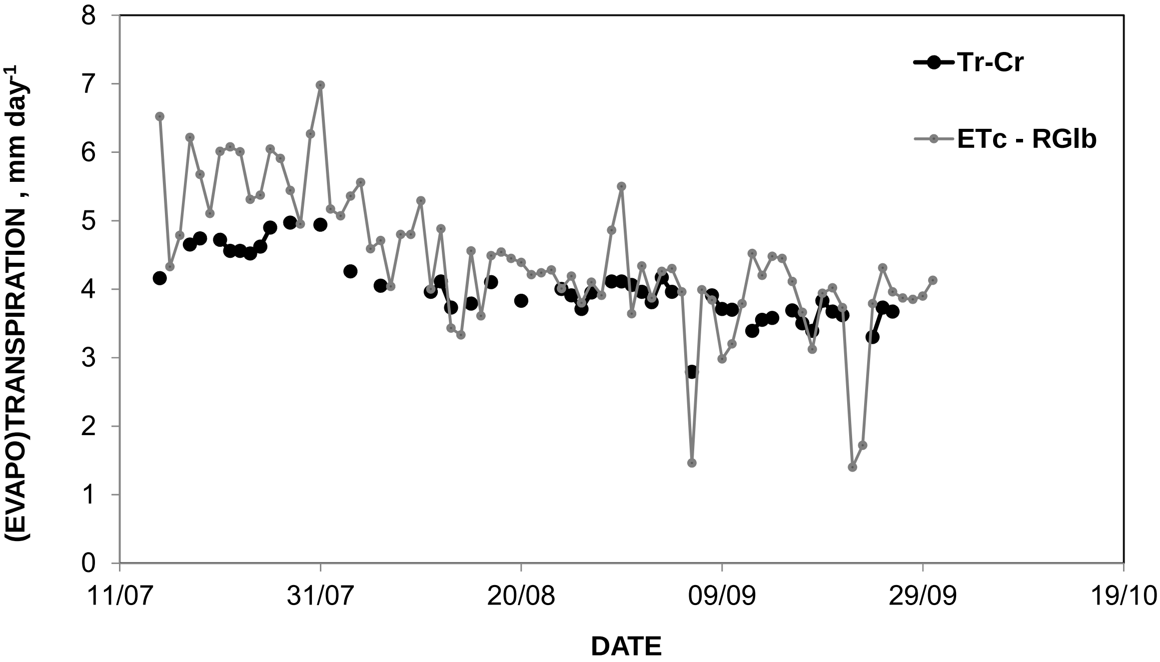

Figure 5. Evolution of Crimson daily transpiration (Tr-Cr) and Red Globe daily evapotranspiration (ETc-RGlb) during 2008 measuring season.

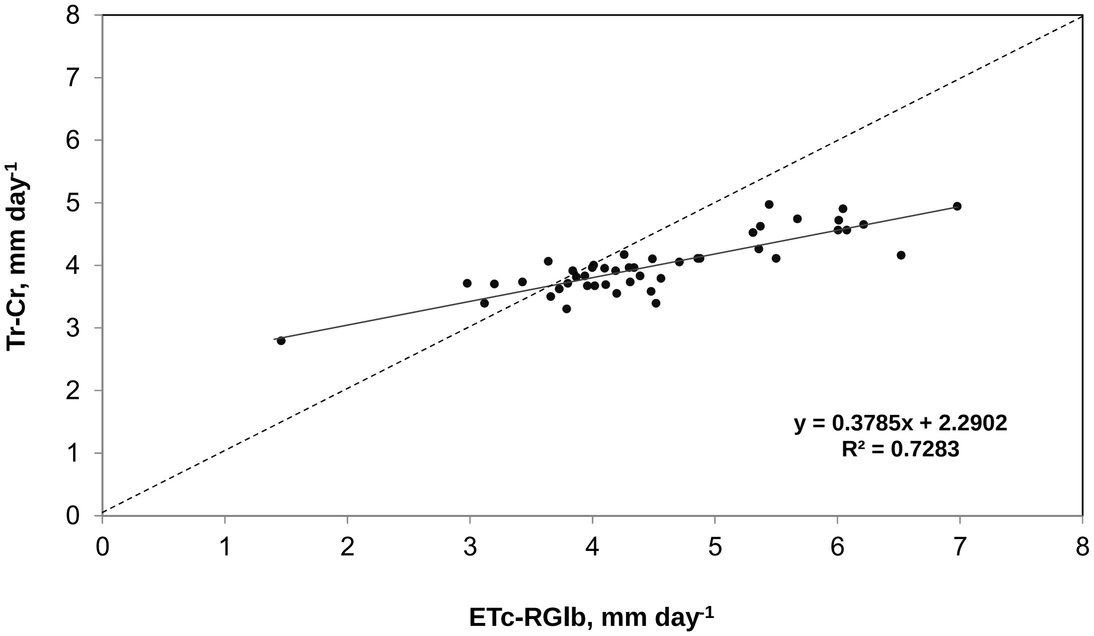

Figure 6. Analysis of regression between Red Globe daily evapotranspiration (ETc-RGlb) and Crimson daily transpiration (Tr-Cr) values for 2008 measuring season.

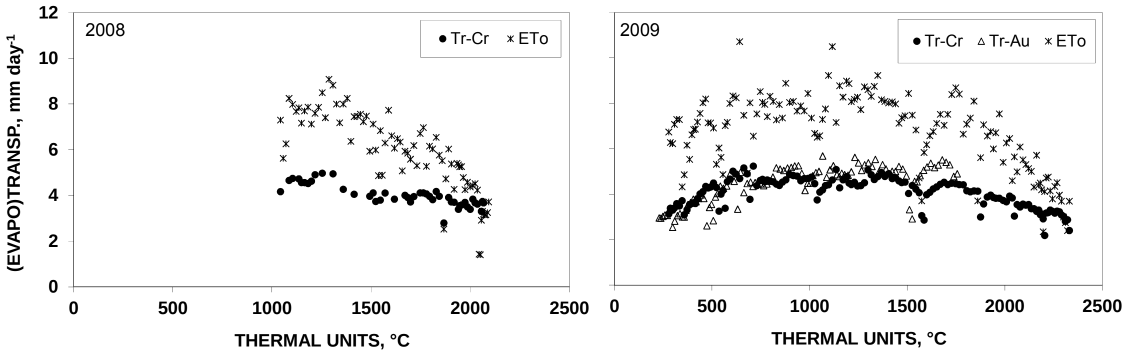

Figure 7. Daily values of measured table grape transpiration under the netting for cultivars ‘Crimson’ (Tr-Cr) (seasons 2008 and 2009) and ‘Autumn Royal’ (Tr-Au) (season 2009) and estimated reference evapotranspiration (ET_o) as a function of cumulative thermal units.

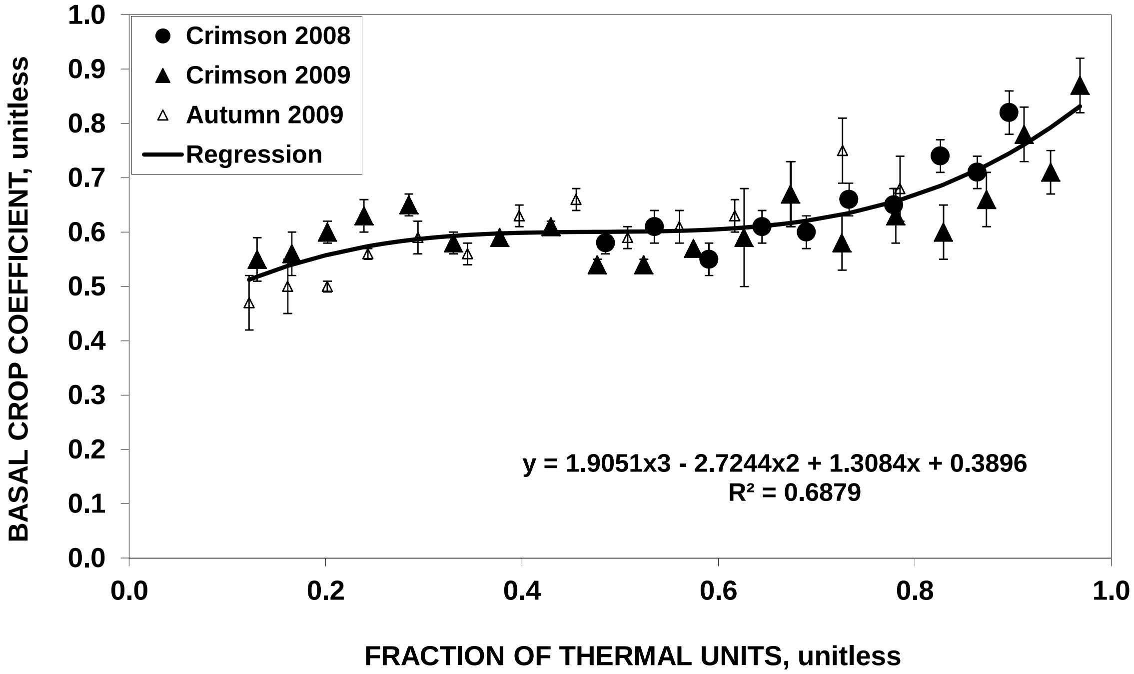

Figure 8. Weekly averages of measured basal table grape coefficient under the netting for cultivars 'Crimson' (seasons 2008 and 2009) and 'Autumn Royal' (season 2009) as a function of fraction of thermal units.

Table 1. Physical and chemical properties of the soils in the studied vineyards. STC, USDA soil texture classification; GE, percentage of particles above 2 mm; SBD, soil bulk density; FC, field capacity; WP, wilting point; SAT, saturation water content; MO, organic matter; ECe, electrical conductivity.

Cultivar	Depth (m)	STC	GE %	SBD Kg m^{-3}	FC % [a]	WP % [a]	SAT % [a]	MO %	ECe dS m^{-1}
Crimson	0.00 - 0.10	Sandy loam	3	1441.3	37.5	14.4	53.3	2.30	4.06
	0.11 - 0.39	Sandy	10	1565.8	26.6	7.8	48.5	0.21	4.86
	0.40 - 0.70	Sandy	1	1522.7	7.6	< 1.0	45.7	< 0.01	2.54
Autumn	0.00 - 0.26	Sandy loam	10	1468.7	39.7	13.2	54.3	2.24	2.94
	0.27 - 0.76	Sandy loam	10	1564.7	39.1	11.0	53.2	0.70	1.83

[a] Expressed as volumetric water content

Table 2. Volume fractions of wood (F_M) and water (F_L) (averages and standard deviations), and radius at the cambium, determined for each cultivar, vine and year.

	Fraction	Year	Vine 1	Vine 2	Vine 3
Crimson	F_M	2008		0.274 ± 0.016	0.276 ± 0.032
		2009	0.305 ± 0.017	0.301 ± 0.022	0.293 ± 0.013
	F_L	2008		0.461 ± 0.127	0.467 ± 0.050
		2009	0.516 ± 0.039	0.521 ± 0.031	0.539 ± 0.030
	Radius (cm)	2008		3.58	3.55
		2009	3.06	3.70	3.43
Autumn Royal	F_M	2009	0.332 ± 0.026	0.336 ± 0.028	0.338 ± 0.009
	F_L	2009	0.527 ± 0.047	0.501 ± 0.045	0.514 ± 0.022
	Radius (cm)	2009	2.66	2.68	3.46

Table 3. Phenological stages of the studied cultivars during 2008 and 2009. Values between brackets represent cumulative thermal units since (°C) budbreak.

Cultivar	Year	Budbreak	Flowering	Veraison	Harvest
Crimson	2008	5 March	20 May	7 August	20 October
		(0)	(382)	(1433)	(2245)
	2009	23 March	20 May	22 July	5 October
		(0)	(333)	(1281)	(2381)
Autumn Royal	2009	8 April	28 May	15 July	16 September
		(0)	(377)	(1123)	(2140)

Table 4. Monthly irrigation amounts (mm) applied from 15 May to 30 September for each cultivar and season.

Cultivar	Year	May	Jun	Jul	Aug	Sep	Total
Crimson	2008	20.7	85.0	145.5	122.8	71.7	445.7
	2009	44.6	117.5	181.2	126.1	63.1	532.5
Autumn Royal	2009	50.5	134.4	192.2	122.9	80.8	580.8

Table 5. Statistics parameters for the comparison of the transpiration measurements within the same plant and between different plants of the same cultivar.

	Crimson 2008(a)		Crimson 2009(b)			Autumn 2009(d)		
Parameter	Vine 1	Vine 2	Vine 1	Vine 2	Vine 3	Vine 1	Vine 2	Vine 3
Mean	4.1	3.9	3.2	5.1	3.8	3.7	3.4	3.6
Median	3.9	4.0	3.1	5.3	3.9	3.6	3.4	3.5
CV	14.8	8.3	17.2	18.8	15.1	16.7	15.6	23.0
Percentile 25	3.6	3.7	2.8	4.3	3.3	3.2	3.0	2.9
Percentile 75	4.2	4.1	3.6	5.9	4.3	4.0	3.8	4.0

	Crimson 2009(b)						Autumn 2009					
	Vine(*) 1~~N~~ ~~Vine 1S~~		Vine 2~~N~~ ~~Vine 2S~~		Vine 3~~N~~ ~~Vine 3S~~		Vine 1~~N(c)~~ ~~Vine 1S(c)~~		Vine 2~~N(d)~~ ~~Vine 2S~~		Vine 3~~N(c)~~ ~~Vine 3S~~	
Parameter	N	S	N	S	N	S	N(c)	S(c)	N(d)	S	N(c)	S
Mean	2.5	3.8	4.8	5.4	3.8	3.8	4.2	3.5	2.5	4.3	5.6	-
Median	2.6	3.7	5.0	5.6	3.8	4.0	4.2	3.6	2.4	4.3	5.7	-
CV	18.2	21.7	20.3	18.4	36.2	16.1	46.9	47.0	43.5	44.0	30.9	-
Percentile 25	2.1	3.1	3.9	4.7	3.4	3.3	3.9	3.2	2.2	3.7	4.4	-
Percentile 75	2.9	4.5	5.7	6.1	4.3	4.3	4.6	3.8	2.6	4.9	6.6	-

(a) 15 Jul to 30 Sep 2008; (b) 15 May to 30 Sep 2009; (c) 15 May to 21 Aug 2009; (d) 15 May to 19 Jun 2009

(*) Symbols N and S are used to distinguish measurements taken at north and south side of the same plant.

Table 6. Weekly averages of basal crop coefficients for Crimson during 2008: a) experimental values (K_{cb_exp}); and b) adjusted using the linear regression in Figure 6 (K_{cb_adj}). DOY, middle day of the year for each week.

DOY	K_{cb_adj}	K_{cb_exp}	Difference
200	0.59	0.58	0.01
207	0.58	0.61	-0.03
214	0.55	0.55	0.00
221	0.59	0.61	-0.02
228	0.60	0.60	0.00
235	0.65	0.66	-0.01
242	0.64	0.65	-0.01
249	0.73	0.74	-0.01
256	0.74	0.71	0.03
263	0.85	0.82	0.03