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RESEARCH

Estimation of water requirements and Kc values of 'Thompson Seedless' table grapes grown in the overhead trellis system, using the Eddy covariance method

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Crop evapotranspiration (ETc) is essential for irrigation scheduling. The amount of water consumed can be estimated by multiplying the reference evapotranspiration (ET_0) by a crop coefficient (Kc); the value of Kc is usually obtained from FAO Paper nr 56. In table grapes (*Vitis vinifera* L.), Kc are obtained from experiments in vines trained on trellis systems; however in Chile, the most used is the overhead trellis system (parronal). Therefore, the objective was to determine water requirements and Kc values of a table grape orchard cv. Thompson Seedless trained on an overhead trellis system in Calle Larga (32º52'40" S, 70º37'45" W, 795 m a.s.l.), Aconcagua Valley, Chile, using the Eddy covariance method. During the 2008/2009 and 2009/2010 seasons, the instruments required for ET_0 and ETc measurement were installed on a 4 m tower above the soil (2 m above vine canopy). The ET_0 was estimated according to the FAO Penman-Monteith equation and ETc by the Eddy covariance method. The Kc was obtained by ratio between ETc and ET_0. The maximum ETc was 7 mm d^{-1} and total water consumption was 810 mm. The season maximum Kc value of 1.2 was obtained near harvest during the first season, and 20 d before veraison in the second season. The Kc increased linearly with the percentage of intercepted solar radiation (IRS) by the vine canopy at noon, suggesting that an equation to convert the IRS to Kc is more useful than Kc tabulated according to phenology. The equation obtained in this experiment was Kc = 0.012 IRS – 0.1029, R^2 = 0.85.

Key words: Energy balance, evapotranspiration, FAO Penman-Monteith, *Vitis vinifera*.

INTRODUCTION

The assessment of crop evapotranspiration (ETc) allows adjusting the water volume applied and irrigation frequencies to the effective needs of the crop, which increases irrigation efficiency. Unfortunately, ETc measurements for adult fruit trees are scarce (Williams et al., 2003b; García Petillo and Castel, 2007), even though the study of the processes of ETc can help model, predict, and increase crop yields (Moguel et al., 2001).

The ETc may be estimated based on studies of soil water balance in cultivated fields (Allen et al., 1998), by weighing lysimeters (Allen et al., 1998; Williams et al., 2003b; Williams and Ayars, 2005a), by method of mass transference or energy balance (Allen et al., 1998; Moguel et al., 2001; Teixeira et al., 2007; Conceição et al., 2008; Giambelluca et al., 2009), or Eddy covariance method (Martín de Santa Olalla y de Juan, 1993; Gomes, 2003; Paço et al., 2004; Barr et al., 2006; Conceição et al., 2008; Giambelluca et al., 2009) or using reference evapotranspiration (ET_0) weighted by a crop coefficient (Kc) (Allen et al., 1998; Ferreira et al., 2006).

Selecting the appropriate value of Kc, which should be used in a given moment, is not an easy task (Sellés et al., 2000). In the case of table grapes, Kc values have been estimated in trellis system not in an overhead trellis system, as table grapes are cultivated in Chile. In the last 30 yr many studies have estimated standard values and the temporal evolution of crop coefficients. However, it is always recommended to adapt them to the local climate, varieties, and management practices, especially in fruit crops, in which standard parameters may vary considerably from one area to another (Campos et al., 2010). Studies in citrus (Castel, 1997; García Petillo and Castel, 2007), apricot (Paço et al., 2004), pear (Conceição et al., 2008), and kiwi orchards (Silva et al., 2008) show that the Kc values obtained experimentally in local conditions may not be concordant with those proposed by FAO 56 (Allen et al., 1998).

The only Kc values available in the literature for table grapes come from lysimeter studies performed in California at orchards using the trellis system (Allen et al., 1998; Williams et al., 2003a; 2003b) and Williams and Ayars (2005a; 2005b).

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There are almost no studies in Chile on table grape (*Vitis vinifera* L.) evapotranspiration. Tosso (1976) and Tosso and Torres (1986) estimated Kc values for table grape. However, the methodology used was not the most exact and only its utility for future research was considered, with values that should be confirmed or corrected. The most frequently used source are the Kc values proposed in FAO paper nr 56 (Allen et al., 1998) where Kc values for table grapes are tabulated according only to the phenological stages without consideration of training systems. In the USA the trellis system is of widespread use in table grape crops and hence, FAO56 uses this training system for its recommendations. In Chile, by contrast, the most common system is the overhead trellis. Thus the objective of this study was to determine ETc and Kc in different phenological stages of 'Thompson Seedless' table grapes grown in overhead trellis. Additionally, the Kc values obtained were correlated with solar radiation interception to obtain a simple method of Kc estimation.

MATERIALS AND METHODS

Experimental site

The experiments were performed in a commercial vineyard of 'Thompson Seedless' table grapes grafted on 'Harmony' rootstock (8-yr old), and conducted on an overhead trellis system, located in Valparaíso Region (32°52'40" S, 70°37'45" W, elevation 795 m a.s.l.), Chile; during 2008-2009 and 2009-2010 seasons. Trials were performed in the central part of a 150 ha field planted with table grapes in overhead trellis. The study zone had a surface area of 7 ha; grapes were planted at 3.5 × 1.75 m. Drip irrigation was used, with one line per plant row and 4 L h^{-1} emitters spaced at 1 m. The yield of the plantation in the last 3 yr averaged 28 t ha^{-1}. The soil is a Fluventic Haploxerolls (Mollisol), 1 m depth, with a clay loam texture in all depths. The climactic conditions (monthly average temperature, rainfall, and pan evaporation) during the study period are presented in Table 1.

Soil water content measurement

The variation in soil water content was measured continuously in both seasons, using one FDR probe (Frequency Domain Reflectometry, Agrilink, AquaSpy, San Diego, California, USA), placed near the tower, with sensors at 10, 20, 30, 40, 50, 60, 80, and 100 cm depth.

Determination of intercepted solar radiation

To determine the solar radiation intercepted by the table grape orchard we measured, every 2 wk, the flux density of photosynthetically active incident radiation over (PAR_i) and under the orchard (PAR_{bd}) with a ceptometer (AccuPAR, Decagon Devices, Washington, USA). Data were measured in six quadrants of six plants each (three plants per row) in the experimental area. Fifteen measurements were made for each quadrant; five in each row and five between rows. Measurements were made at solar zenith every 2 wk. Mean values in μmol photons m^{-2} s^{-1} were expressed as percentages using:

$$ISR = \left[1 - \left(\frac{PAR_{bd}}{PAR_i}\right)\right] \cdot 100$$

where IRS is the percentage intercepted solar radiation, PAR_{bd} is the flow of photosynthetically active radiation under the vines and PAR_i is the flow of photosynthetically active radiation above the vines, both measured in μmol photons m^{-2} s^{-1}.

Measurement of energy balance components and crop evapotranspiration

The sensible heat flux (H) and the latent flux (LE) were measured with the method of Eddy covariance. To do this, a 4-m tower (2 m above the crop) with a sonic anemometer (Windmaster Pro, Gill Instruments, Hampshire, UK) and an open pass gas analyzer of CO_2/H_2O (OP-2, ADC Bioscientific Ltd., Hoddesdon, UK), oriented in the dominant wind direction (SW), were installed. Fetch length for the dominant wind was 250 m and it was at least 100 m in every orientation. The frequency of measurements was 10 Hz averaged over 30 min. Data were recorded on a CR-1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA). The processing of data and corrections

Table 1. Monthly average temperature, rainfall and pan evaporation during 2008/2009 and 2009/2010 season.

Month	2008/2009 season			2009/2010 season		
	Monthly average temperature	Monthly rain	Monthly pan evaporation	Monthly average temperature	Monthly rain	Monthly pan evaporation
	°C	mm m^{-1}		°C	mm m^{-1}	
May	13.20	65.8	51.0	13.9	0.8	46.1
June	10.80	34.3	27.8	10.4	89.2	25.1
July	9.40	27.8	31.0	9.8	13.0	32.4
August	10.90	87.0	38.0	11.8	69.8	36.4
September	13.70	12.0	78.8	12.0	10.4	58.2
October	16.20		129.0	17.3		135.3
November	20.20		175.5	17.7		161.9
December	21.40		210.3	20.4		222.0
January	22.40		231.1	21.7		217.7
February	21.33		186.0	20.7		169.9
March	20.80		169.0	19.7		123.2
April	18.00		114.6	15.9		80.3

were done with the software Eddysoft (Meteotools, Max Planck Institut für Biochemie, Germany). Latent flux was corrected as proposed by Webb et al. (1980); for H corrections proposed by Schotanus et al. (1983) and Liu et al. (2001) were used. The crop evapotranspiration was derived from LE, dividing LE by the latent heat of vaporization of water (2.44 MJ kg^{-1}). The footprints for the two seasons were 34 m for 50% and 230 m for 90%.

Net solar radiation (Rn) was measured with a net radiometer (NR2, Delta-T Devices, Cambridge, UK) installed in the same tower. We also installed in the ground two soil heat flux plates (HFP01, Hukseflux Thermal Sensors, Delft, The Netherlands) at 7 cm depth, one over the row at 3.5 m from the tower and the other in the next row. To determine the heat flow in the soil (G) we measured the absorption or liberation of heat in the soil above the plates with four copper-constantan thermocouples; two above the row and two in the next row, at 2 and 6 cm depth, which measured the variation in soil temperature.

The values of LE, H, G, and Rn were used to verify the closure of the energy balance and thus validate the Eddy covariance measurements. Measurements may be considered valid when the closure error does not exceed 20% (Wilson et al., 2002). Linear regressions of the energy used in heat transport (LE + H) against the effective amount of energy available (Rn - G) were estimated. The closure error of each regression, expressed as a percentage, was calculated as 100 × (1 - slope).

Calculation of reference evapotranspiration and Kc values

Reference evapotranspiration was calculated with the Penman-Monteith FAO equation (Allen et al., 1998); thus in the instrument tower we also measured net radiation (NR2, Delta-T Devices, UK), temperature (T), relative air humidity (HR) (humidity and temperature probe HMP50, Intercap, Vaisala, Vantaa, Finland), and wind velocity (u) (wind sensor WM-IIIA, Climatronics Corporation, Bohemia, New York, USA). All these measurements were done every 30 min.

Crop coefficient values were calculated weekly as the quotient between the average ET measured by eddy covariance and the average ET_0.

RESULTS AND DISCUSSION

Soil water content and intercepted solar radiation

Soil water content at field capacity (FC) was 280 mm m^{-1}. The mean water content during the period was 276 mm m^{-1} (Figure 1). The water in the profile remained close to FC in both seasons. This assures that plants did not have water deficit, thus stomata were completely open and

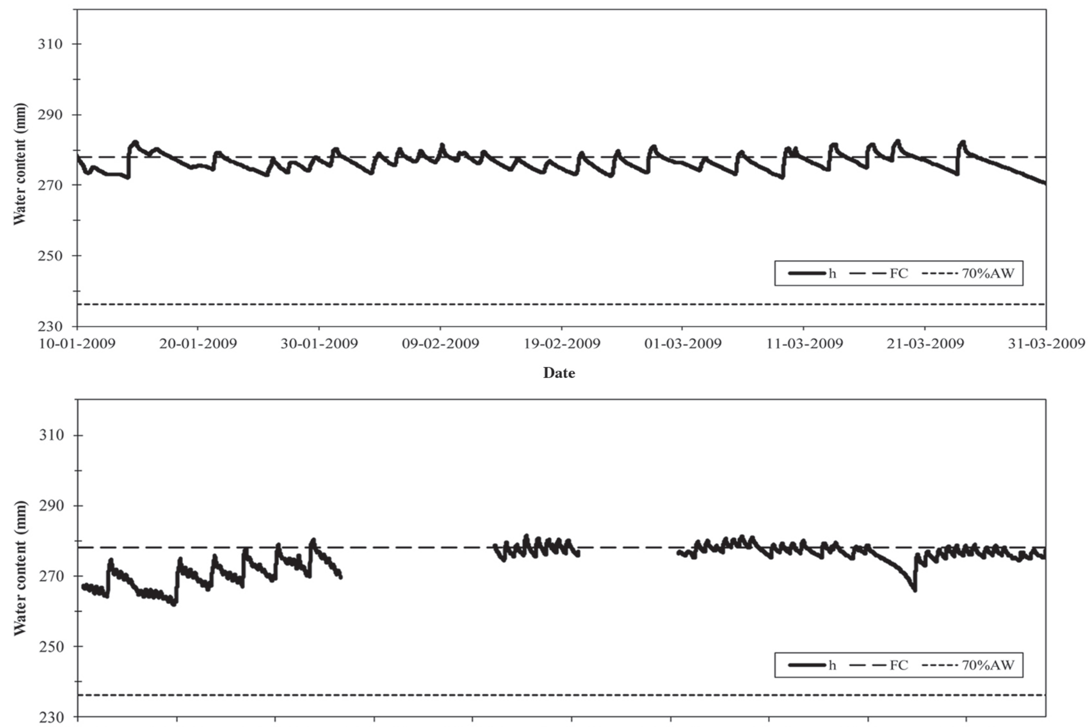


Figure 1. Variation in water content (h) in the soil profile during the 2008-2009 (above) and 2009-2010 (below) seasons. Dashed lines indicate field capacity (FC) and watering threshold (70% AW).

transpiring at their maximum potential. Possible problems of aeration provoked by the high soil water content were discounted, since the commercial yield of the orchard (28 t ha^{-1}) and the condition of the plants did not indicate any symptom related to excess soil water.

Figure 2 shows the variation in IRS during the season. Both seasons had similar behavior, at the moment of berry set the IRS was around 75%; the maximum IRS (112 d after bud break, DAB) occurred close to veraison.

Energy balance components, crop evapotranspiration, and crop coefficient

The closure error of energy balance was close to 40% from bud break until vines intercepted 40% of solar radiation (45 DAB). The closure error decreased as the season advanced and leaf area increased, which is reflected in closing errors less than 20% after IRS reached 40%. At the end of the season, this error reached 2% (Figure 3). As a consequence, measurements may be accepted as valid from the time the vines intercepted 40% of solar radiation, since that moment on the closure error did not exceed the 20% limit, proposed by Wilson et al. (2002) for validation of measurements using the Eddy covariance method. Figure 4 shows that in the first season ETc was less than ET_0 from bud break to 147 DAB. From this day until 167 DAB, the ETc was greater than ET_0. From 168 DAB to the end of the growth period ET_0 was again greater than ETc. In the second season, from bud break to 90 DAB ETc was less than ET_0. From 91 DAB until 112 DAB ETc was greater than ET_0. Mean maximum ETc (Figure 4) in both seasons was 7 mm d^{-1}, which is very close to the values reported for the same variety by Williams et al. (2003a) and Williams and Ayars (2005a; 2005b), which were 6.6, 6.75, and 6.99 mm d^{-1}, respectively. Total water consumption (810 mm) was also similar to the values reported in these studies.

The maximum calculated Kc in both seasons was 1.2 (Figure 5); however, this was reached in different stages. In the first season it occurred close to harvest, while in the second season it happened 20 d after veraison. Comparing our results to the proposal of FAO Paper nr 56 (Allen et al., 1998) (hereafter called FAO Kc values), in the first season the FAO Kc values underestimate local water needs of 'Thompson Seedless' grapes between 28 and 84 DAB, and beginning with 140 DAB. According to the values we obtained in the second season, local Kc values were underestimated by the tabulated FAO Kc values from 28 DAB until the end of the season. Because of the variation found, Kc was estimated using the values obtained in both seasons (Eddy, Figure 5), with the following result:

$$Kc = \frac{1.07}{(1 + 0.54e^{-0.05DAB})}, \quad R^2 = 0.84$$

where, Kc is the crop coefficient and DAB is days after bud break.

If the values published in FAO Paper nr 56 are used to calculate the ETc, the real water consumption of table grapes would be underestimated in the trial conditions from 28 DAB onwards. The maximum Kc value would

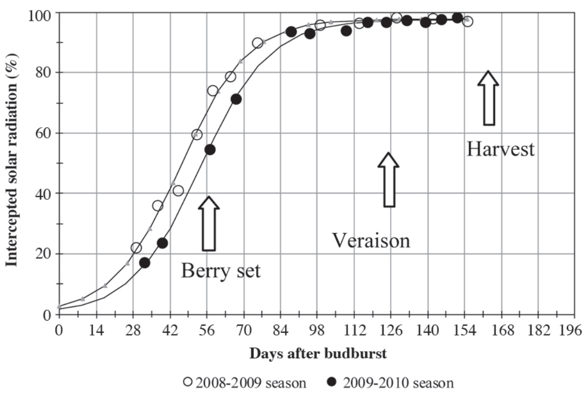
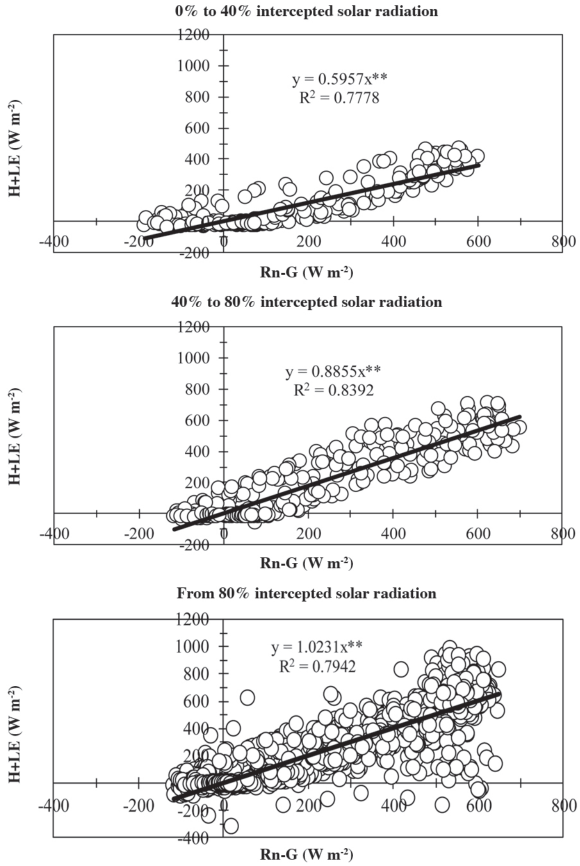


Figure 2. Intercepted solar radiation by the plantation during the 2008-2009 and 2009-2010 seasons. Arrows indicate the times of berry set, veraison, and fruit harvest.



**Highly significant regressions ($p < 0.01$).
Rn: net radiation; G: soil heat flux; LE: latent heat flux; H: sensible heat flux.

Figure 3. Energy balance closure with different percentages of solar radiation intercepted by the orchard (0-40%, 300 data; 40-80% 560 data; > 80%, 1020 data). The closure error of each regression is represented as 100 × (1 - slope).

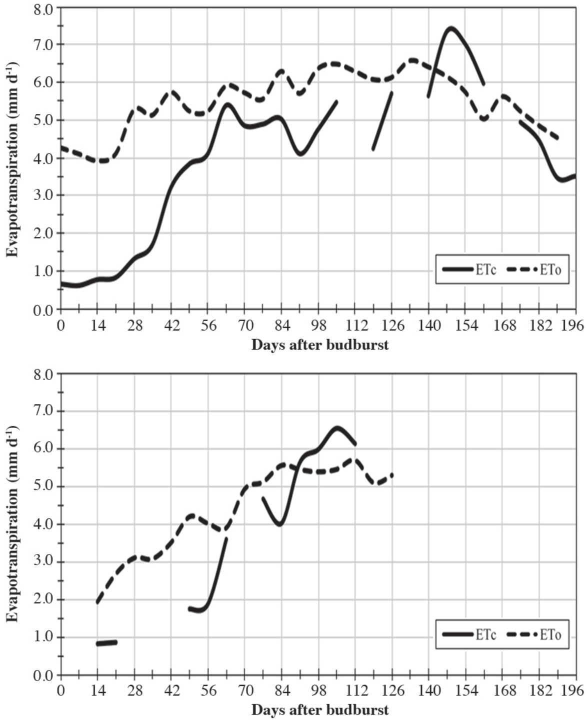


Figure 4. Seven-days averages of crop evapotranspiration (ETc) of the grape orchard and of reference evapotranspiration (ET_0) during the 2008-2009 (above) and 2009-2010 (below) seasons. The blank spaces in data indicate periods of malfunctioning of the sonic anemometer.

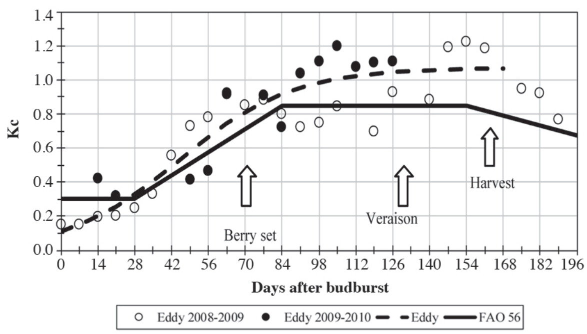


Figure 5. Comparison of crop coefficient (Kc) values calculated in two seasons (Eddy 2008-2009, Eddy 2009-2010) with the values proposed in FAO Paper nr 56 (Allen et al., 1998). Also shown are Kc values adjusted to the data (Eddy) for both study seasons using days after bud break (DAB). Arrows indicate the times of berry set, veraison, and fruit harvest.

be obtained at 155 DAB, close to the date of harvest, and would be approximately 1.05. We suggest that values proposed in the FAO paper (Allen et al., 1998) do not represent the local crop conditions for table grapes grown in an overhead trellis system. This has also been observed by other authors on other species; Castel (1997) reported that values obtained for clementines were about 20% lower than the FAO Kc values, while Paço et al. (2004) found that ETc was overestimated by 35% by the FAO Kc values for peach compared to those measured using the Eddy covariance technique in a peach orchard in Portugal. Also in Portugal, Conceição et al. (2008) confirmed the need to adjust published values for a pear orchard.

The Kc values obtained for different phenological stages and for DAB were different between the two seasons. For this reason, we analyzed the calculated Kc with the percentage of IRS on the same dates (Figure 6). The linear relation obtained is similar to that obtained in 'Thompson Seedless' with the trellis system by Williams and Ayars (2005a); their equation had a slope of 0.017 and an intercept of -0.008. The same linear relation between Kc and IRS has been reported in bananas (Santana et al., 1993), clementines (Castel, 1997), peaches (Johnson et al., 2000; Goodwin et al., 2006), and olives (Testi et al., 2004). Intercepted solar radiation explained 85% of the variation in water consumption by the orchard (Figure 6), and its relation with Kc appears to be very general (Johnson et al., 2000). This would explain why local conditions are not well represented by the FAO Kc values, which were derived from studies of table grapes using the trellis system, were the IRS is lower than overhead trellis system. Since the percentage of solar radiation intercepted by grapevines may vary according to the training system, plantation spacing and pruning, it is unlikely that the same Kc values will be found in table grapes cultivated with different agricultural management systems. Since IRS is a parameter easy to measure, Kc may be estimated at different ages in any locality and in plantations with different management systems, simplifying the prediction of ETc. This suggests that, instead of relying on tables with Kc for each phenological state or for DAB, it is more useful to have an equation which converts the percentage of IRS into a Kc value. The equation we obtained using measurements of two seasons, which is valid above 20% interception, is:

$$Kc = 0.012 \cdot IRS - 0.1029, R^2 = 0.85$$

where Kc is the crop coefficient and ISR is the percentage of intercepted solar radiation.

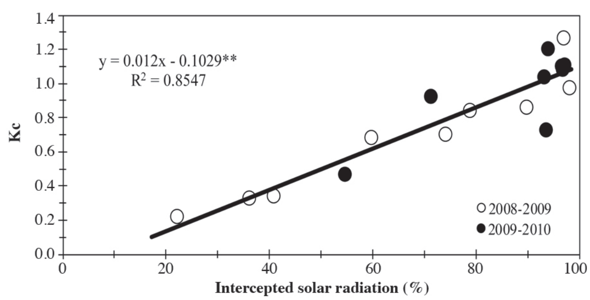


Figure 6. Relation between calculated crop coefficient (Kc) and percentage of solar radiation intercepted by the grape orchard during the 2008-2009 and 2009-2010 seasons. Kc is the weekly average around the date of measurement of solar radiation interception which was measured every 15 d.

CONCLUSIONS

Water requirements of ‘Thompson Seedless’ table grapes grown in overhead trellis may be estimated using the Eddy covariance method with reasonable precision. The value of Kc increased linearly with the percentage of solar radiation intercepted by the table grape orchard. The results suggest that knowledge of the percentage interception of solar radiation is more important than the phenological stage to determine the value of Kc, since the former takes into account the local conditions of crop management.

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