AGRICULTURAL AND FOREST METEOROLOGY

Row orientation effects on potted-vines performance and water-use efficiency

Ignacio Buesa[a,b]*, José M. Mirás-Avalos[b,c] and Diego S. Intrigliolo[b]

[a] *Centro para el Desarrollo de la Agricultura Sostenible del Instituto Valenciano de Investigaciones Agrarias (CEDAS-IVIA), 46113, Moncada, Valencia, Spain*

[b] *Departamento de Riego, Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC), 30100, Murcia, Spain*

[c] *Current address: Unidad de Suelos y Riegos (asociada a EEAD-CSIC). Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), 50059 Montañana, Zaragoza, Spain.*

**Ignacio Buesa*

e-mail: igbuepue@gmail.com

Address: Instituto Valenciano de Investigaciones Agrarias (IVIA)

CV-315, Km 10, 46113 Moncada, Valencia, Spain.

Phone: +34 650578152

Abstract

The relation between water-use and intercepted solar radiation depends on many factors involved in vine canopy architecture and physiology. In addition, vine productivity is related to the efficiency with which the intercepted photosynthetically active radiation (IPAR) is used, which in turn depends mainly on water availability and transport. In hedgerow-managed vines it exists the possibility to modulate IPAR by orienting their rows, influencing water-use efficiency (WUE), defined as dry matter produced by water used. Aiming to unravel the effects of row orientation on WUE, a three-year experiment was carried out in Valencia (Spain) on potted *Vitis vinifera* (L.) cv. Bobal and Verdejo with vine rows oriented either north-south (NS) or east-west (EW), under no-water restrictions. Simulated radiation interception over the growing seasons at the experimental plot showed an average 39% reduction in daily IPAR when EW was compared to NS. Vine transpiration was quantified by water balance, decreasing by 16% in Bobal and 8% in Verdejo when comparing EW against NS. In both cultivars, this reduction was 18% when considered relative to the total leaf area. Carbon assimilation was not markedly affected by row orientation. Therefore, since in both cultivars minor differences in vine performance occurred between orientations, WUE tended to increase by orienting the rows to the EW compared to NS. This resulted in most of the seasons an increase in water productivity calculated as grape yield/water-use ratio. Leaf gas exchange measurements partially agreed with the radiation interception simulations, suggesting a more complex regulatory mechanism and highlighting the importance of canopy microclimatic conditions in the physiological processes of hedgerow-managed crops. These findings encourage further research under field conditions and different soil water availabilities, aiming to optimize grapevine water productivity.

Keywords: Canopy sunlight interception; Hedgerow; *Vitis vinifera* (L.); Water productivity; Yield.

1. Introduction

Vineyards are complex agro-ecosystems where in general grapevine water-use (WU) is a function of the sunlight intercepted by the canopy (Trambouze et al. 1998, Williams and Ayars 2005), which influences the amount of dry matter produced (Grappadelli et al. 1994, Steduto et al. 2007). Grapevine canopies, regardless of the training system employed, are comprised of both sun-exposed and interior leaves. Shaded leaves contribute less to vine carbon assimilation than those sun-exposed because they receive less energy, which mostly comes from diffuse radiation (Spitters et al. 1986, Escalona et al. 2003). Canopy sunlight interception relates to the external leaf area, but also to leaf position and canopy structure (Petrie et al. 2009). As a consequence, the relationship between grapevine canopy radiation interception and leaf gas exchange is extremely complex (Baeza et al. 2010, Buckley et al. 2014). Plant shape, size, spacing, leaf inclination and position within the canopy, row orientation, cloudiness and latitude determine sunlight interception by vineyards and, consequently, grapevine microclimate and physiology (Smart and Barrs 1973, Carbonneau 1979). For a given training system, Poni et al. (2003) observed that the sunlight intercepted by vineyard canopy increases with leaf area until a threshold in which leaf mutual shading impedes the increase of carbon assimilation potential.

Regions with suitable climate for viticulture are located from 30° to 50°N and 30° to 40°S, where solar radiation does not usually restrict grapevine photosynthetic capacity. Hence, in the absence of water stress and limitations in source–sink relationships, photosynthetically active radiation (PAR) increases vine photosynthesis until a given saturation point (Iacono and Sommer 1996, Flexas et al. 2002). Since the response of canopy photosynthesis to radiation follows a convex asymptotic relationship (Spitters 1986), under high light intensity (> 1000 μmol m^{-2} s^{-1}), the limiting factor for carbon assimilation is the leaf internal concentration of CO_2 along with photoinhibition processes (Escalona et al. 2000, Long and Bernacchi 2003. In view of the predicted climate change, with an expected lower water availability (Vicente-Serrano et al. 2014, Fraga et al. 2016), a reduction in solar radiation interception by the vineyard can be used to mitigate the effects of reduced soil water availability (Moratiel et al. 2010).

Viticultural practices, such as training systems and canopy management, are tools for modulating the efficiency of grapevine radiation interception (Mabrouk and Sinoquet 1998). However, vineyard canopy orientation plays a determinant role in PAR and ultraviolet (UV) radiation interception and, consequently, in vine physiological processes (Palmer 1989, Intrieri et al. 2015). Many training systems have evolved towards maximizing the amount of sunlight intercepted and its distribution within the canopy. Among them, vertical shoot-positioning and Lyre systems, which allows exposing most leaves to high light levels leading to an increase in vine transpiration (Kliewer and Dokoozlian 2005, Reynolds and Vanden-Heuvel 2009, Albasha et al. 2019), aiming to maximize yield in the absence of water stress (Baeza et al. 2005).

Many experiments have focused on the influence of solar radiant energy intercepted by fruit trees on their photosynthesis and transpiration (Smart 1973, Mariscal et al. 2000, López-Lozano et al. 2011), but less research effort has been devoted to the specific effect of row orientation on the grapevine water-use efficiency (WUE) (Annandale et al. 2004, Campos et al. 2017). Some studies reported that the east-west (EW) row orientation tended to reduce growth, yield and total dry matter per vine as compared to NS, NE-SW and NW-SE orientations (Intrieri et al. 1996). Moreover, in potted vines, Intrieri et al. (2015) observed that the intrinsic water-use efficiency (WUE_i) at midday was higher in NS than in EW rows; however, on a daily basis, little variations between both orientations were detected. Indeed, PAR absorption regulates the rate of carbon assimilation but also the canopy microclimate conditions within the vine, both affecting grape ripening (Jackson and Lombard 1993, Bergqvist et al. 2001). In this sense, Hunter et al. (2016) observed that EW oriented rows intercepted lower radiation inside the canopy than those oriented NS, but EW captured a largest portion of total radiation in the cluster zone due to the higher soil reflected radiation. These authors measured higher overall gas exchange rates at the leaf level in vines EW-oriented compared to those NS-oriented, with less negative leaf water potential, pointing out to differences in energy balance and physiology induced by row orientation (Hunter et al. 2016). Nonetheless, in order to achieve a balanced ripeness in all clusters, the NS orientation of the vine rows is preferred to the EW, seeking for a uniform light distribution in the fruiting zone (Naylor et al. 2000, Tarara et al. 2005).

In this context, the objective of the current work was to unravel the effects of orienting row trellises EW, instead of the more usual NS, on vine WU and WUE. Taking into account that orienting rows EW reduces sunlight interception of hedgerow fruit trees, such as apple and olive, when compared to the NS orientation (Palmer et al., 1989; Connor et al., 2014; Trentacoste et al., 2015), our hypothesis was that this would also occur in grapevines, reducing canopy transpiration. At Mediterranean latitudes, solar radiation is not a limiting factor; therefore, this reduction in the intercepted photosynthetically active radiation (IPAR) might not compromise obtaining high yields, leading to the improvement of WUE. In order to confirm the hypothesis that row orientation can cause a reduction in transpiration without impairing vine performance, an experiment was carried out during three consecutive seasons in fully-irrigated potted-vines (both red and white cultivars) oriented NS and EW.

2. Materials and Methods

2.1 Description of the site and plant material

A pot experiment was carried out from 2014 to 2016 in *Vitis vinifera* (L.) cv. Bobal and Verdejo grafted onto rootstock 110 Richter at the Valencian Agriculture Research Institute (IVIA) experimental farm (Valencia, Spain, 39º35´13.952´´N, 0º23´54.005´´W). At the beginning of the experiment, vines were three years old. The climate at the site was Mediterranean, with annual rainfall and reference evapotranspiration (ET_o) of 370 and 1125 mm (1999-2016), respectively. The prevailing wind direction at the experimental site was south, with an average speed of 4.65 m s^{-1}. Weather data were recorded at an automated meteorological station located at 100 m from the experimental plot and ET_o was calculated with the Penman-Monteith approach (Allen et al. 1998). According to the climatic classification system for grape-growing regions (Tonietto and Carbonneau, 2004), the experimental area showed a warm climate, with temperate nights, while being moderately dry.

Seventy liter pots, of 0.45 m height and 0.55 m width, filled with a mix of coco fiber substrate and compost, were used. Pots were covered with silver plastic in order to minimize heating and water evaporation from the substrate. Vines were placed outdoors in rows with spacing of 2 m between vines and 2.5 m between rows, simulating a common spacing in the study region. The vines were winter pruned to approximately 10 spurs per vine and 2 nodes per spur on a bilateral Royat cordon and trained to a vertical trellis system consisting of a forming wire and three double catch wires spaced 0.4 m apart. These vine arrangements reflects the general viticulture practices carried in the region when vertically shoot positioning is employed as training system (Buesa et al., 2019). Cluster thinning was applied during flowering in order to standardize the number of clusters per vine and to balance leaf area to yield (7 and 12 clusters per linear meter of trellis in Bobal and Verdejo, respectively), since initial shoot fruitfulness (number of clusters per shoot) was too high. Shoot thinning was performed before flowering and shoot trimming when shoots reached nearly 2 m height. When secondary shoots reached the double catch wires, they were manually distributed to form a homogeneous canopy. The final hedgerow was continuous of 0.2-0.3 m wide (Supplemental Figure). The pots were drip irrigated to avoid water restrictions during the whole season and not to add an additional experimental factor to the responses to be determined. Irrigation scheduling was the same for both cultivars and aimed to ensure some drainage after each water application. Irrigation was applied 3 to 5 times per day (10 to 15 minutes per event) through 3 pressure-compensated emitters of 3.8 L h^{-1} per plant. Vines were seasonally fertigated at a rate of 30-20-60-7.5 kg·ha^{-1} of N, P_2O_5, K_2O, and MgO, respectively, as well as with iron chelates and other microelements at specific times.

2.2. Row orientation treatments

Two orientations were tested in each cultivar 1) north-south (NS) and 2) east-west (EW). Each orientation consisted of 4 rows, and each row consisted of 12 vines. The 10 vines in the middle of the rows were used for measurements and samplings while the remaining 2 vines at each end acted as buffers. Each experimental unit (EU) consisted of 5 vines and each cultivar was in every row. During the first season (2014), each treatment consisted of 10 vines per treatment (2 EU), and 20 vines per treatment (4 EU) during the subsequent seasons (2015 and 2016).

2.3. Modelling grapevine radiation interception

In order to estimate the differences in the radiation interception by a grapevine hedgerow-oriented NS and EW, the simple approach proposed by Oyarzun et al. (2007) was used. This model calculates radiation interception based on the portion of the floor shaded by the vines at any given time using geometric relationships of the length of the shadow cast by the vines and the configuration of the plantation. Inputs required by this model include hedgerow parameters, location data and meteorological variables.

In the current study, the values employed for the hedgerow parameters referred to the experimental vines and were the following: vine height (1.9 m), height of the insertion of the lower branches (0.8 m), canopy width perpendicular (0.3 m) and along the row direction (2.5 m), spacing between vines along the row (2 m), noon light porosity (0.44) and the row azimuth (0º for NS and 90º for EW). Location data include altitude (68 m), latitude (39.5 º), longitude (0.4 º), standard meridian (1 º), slope (0 º) and aspect of the terrain (0 º). The only meteorological input required is the daily global solar radiation (MJ m^{-2} s^{-1}), taken from the weather station located at the study site.

Outputs from the model include the fraction of intercepted PAR (fIPAR), the PAR intercepted by the canopy (IPAR), and the PAR intercepted daily (DIPAR). Simulations were carried out from June 1st until August 31st for each experimental season.

2.4. Field determinations

2.4.1. Vine phenology and vegetative development

Phenological stages were monitored by visual inspection in two shoots per vine on a weekly basis during the whole season. At veraison, the percentage of coloured berries was determined in two clusters per vine. Vegetative growth was determined monthly in a sample of 4 shoots per vine by measuring, non-destructively, the length of primary and secondary shoots. Removed vegetative fresh mass was weighted for each vine after thinning (clusters), trimming (shoot tips) and pruning (wood) operations at the usual times of vineyard management, previously indicated in this section. Dry matter was calculated as the sum of the fresh mass of each plant organ after oven-drying it at 60 ºC for one week. Leaf area was estimated from allometric relations between shoot length and leaf area per shoot, using a LI-3100C Area Meter (LI-COR Bioscience, Lincoln, NE, USA) and separating main shoots and laterals. These relations were obtained from samples of 10 shoots of different vigor coming from the buffer vines for each cultivar and season. After harvest, total leaf area (LA) was estimated in each experimental vine by measuring the length of all main and secondary shoots. The ratio LA-to-yield was calculated for all experimental vines.

2.4.2. Vine water-use (WU)

In 2014, daily vine WU was obtained by water balance in all pots on 5 occasions during the early spring and summer time of the season (coinciding with the end of the rapid leaf area growth). This was calculated by subtracting the weight at 7:00 solar time during two consecutive days. Additionally, pots were weighted at solar noon in order to obtain morning and afternoon transpiration separately. During these determinations, the irrigation applied (1 L in the morning and 1 L in the afternoon) was taken into account. This amount of water was accurately supplied by hand to each pot in order to prevent vine water stress, while controlling the absence of drainage. For total vine WU estimation, the daily transpiration values obtained by weighting were extrapolated to the subsequent days until the next measurement, assuming a constant transpiration rate between consecutive actual determinations. It should be noted that evaporation from the substrate was minimized by covering the pots with silver plastic. In 2015, a drainage collector system was built with a tank and a water meter per EU. Therefore, during the 2015/16 seasons, WU was estimated weekly by water balance (discarding the periods with rainfall), calculated as the subtraction between the irrigation volume registered by the water meters and the water volume drained to the tanks. However, in 2015 because of some episodes of heavy rainfall, WU measurements started later in the season than in 2016. The possible variation in substrate water content between determinations was disregarded since the measure was carried out immediately after the end of the occurrence of drainage after an irrigation event.

2.4.3. Vine water relations and physiology

Vine water status was determined monthly before dawn in un-bagged leaves (Ψ_{pd}) and at midday in bag-covered leaves (Ψ_{md}) during the three experimental years (Santesteban et al. 2019). For the Ψ_{md} determination, leaves were enclosed in hermetic plastic bags covered with aluminum foil for at least 1 h prior to the measurement. Water potential was measured with a Scholander pressure chamber (Model 600, PMS Instrument Company, Albany, OR, USA) on 1 basal leaf per plant from 2 vines per EU. Leaves were taken from the west side of the NS rows and from the north side of the EW ones. Additionally, stomatal conductance (g_s), net photosynthesis (A) and transpiration rate (E) were determined at the leaf level by means of a portable photosynthesis analyzer (LCpro+, ADC BioScientific Ltd., Hoddesdon, England) (Long and Bernacchi 2003). Gas exchange was assessed in 2 vines per EU and cultivar, on the same vines and dates in which water potential determinations were conducted. In 2014, these measurements were carried out coinciding with the date of pot-weighting. Gas exchange measurements were taken under ambient conditions in two basal and mature leaves per vine of the sun-exposed side of the canopy, avoiding the modification of the natural leaf arrangement (without fixing CO_2, light intensity, relative humidity or leaf disposition). Gas flow was set not to exceed 2-3 ºC the ambient temperature. Determinations were carried out in the following time intervals 7:00-9:00, 11:00-13:00 and 16:00-18:00 during the morning, midday and afternoon, respectively. In addition, intrinsic water-use efficiency (WUE_i) at the leaf level was calculated as the ratio of A to g_s.

2.4.4. Water-use efficiency (WUE) and water productivity (WP)

The whole-vine WUE was estimated at harvest as the ratio between total dry mass (cluster thinning, shoot trimming, pruning wood and grape clusters) and the amount of water used (transpired). Additionally, water productivity (WP) was calculated as yield (fresh grape mass) and the amount of WU. Since the measuring periods of water balance do not comprise the whole growing season and the data collected were not exactly the same in all seasons, the absolute values of WU, WUE and WP will not be comparable among seasons. In any case, our goal was to quantify the differences in between the two treatments explored and, within each season, the same procedure was followed in all experimental treatments. In 2014, the water balance was calculated for each experimental vine from June 1st to the end of July. In 2015-2016 it was calculated for each EU (5 vines), from July 7th to September 7th in 2015, and from April 1st to the end of August in Bobal, and until September 23rd in Verdejo in 2016.

2.4.5. Vine performance

Vine yield was determined at harvest. Harvest was performed when grapes attained 16 and 21.5 ºBrix respectively for cv. Bobal and Verdejo. The low value of total soluble solids in Bobal was caused by the early harvests performed in order to avoid yield losses caused by *Botrytis cinerea* attacks. Cluster weight was obtained by dividing the yield of each vine by its number of clusters. Clusters per vine were counted both before applying cluster thinning (initial) and at harvest (final). Additionally, the number of berries per cluster was determined from samples of one average-size cluster per vine. At harvest, fresh berry mass was determined from samples of 200 berries collected randomly per EU.

2.5. Statistical analysis

Data analysis was performed using “Statgraphics Centurion XVI” package version 16.0.07 (StatPoint Technologies, Inc., Warrenton, VA, USA). The significance of the treatment, season and their interaction on vine traits were assessed by two-way analysis of variance (ANOVA). Additionally, transpiration data were analyzed in two steps (Sadras et al. 2009). First, we plotted actual transpiration rate for each orientation against the environmental mean. This procedure has been widely used to capture the aggregated effects of multiple driving factors on a trait (Lacaze et al. 2009, Peltonen-Sainio et al. 2011, Trentacoste et al. 2011, Sadras et al. 2012), such as transpiration which is driven by multiple soil, weather, management and crop factors. Second, we calculated the deviations relative to the 1:1 line and used Fisher's LSD multiple range test ($p < 0.05$) to separate means when ANOVA indicated significant differences among treatments.

3. Results

3.1. Weather conditions

The annual ET_o at the study site was 1320, 1268 and 1268 mm in 2014, 2015 and 2016, respectively. The daily evolution of ET_o, mean temperature and solar radiation during each growing season (1st of March to 30th September) is depicted in Figure 1. The maximum daily ET_o values were 8.4, 10.2 and 8.7 mm in 2014, 2015 and 2016, respectively. These days of high evaporative demand, corresponded with maximum temperatures over 33-40 ºC, westerly winds of 2.8-3.3 m s^{-1} and relative humidity of 30-40%. Radiation during the three growing seasons was fairly homogeneous, with most days with a clear sky and 25 MJ m^{-2} on average each season, corresponding to 51.5 mol PAR m^{-2}.

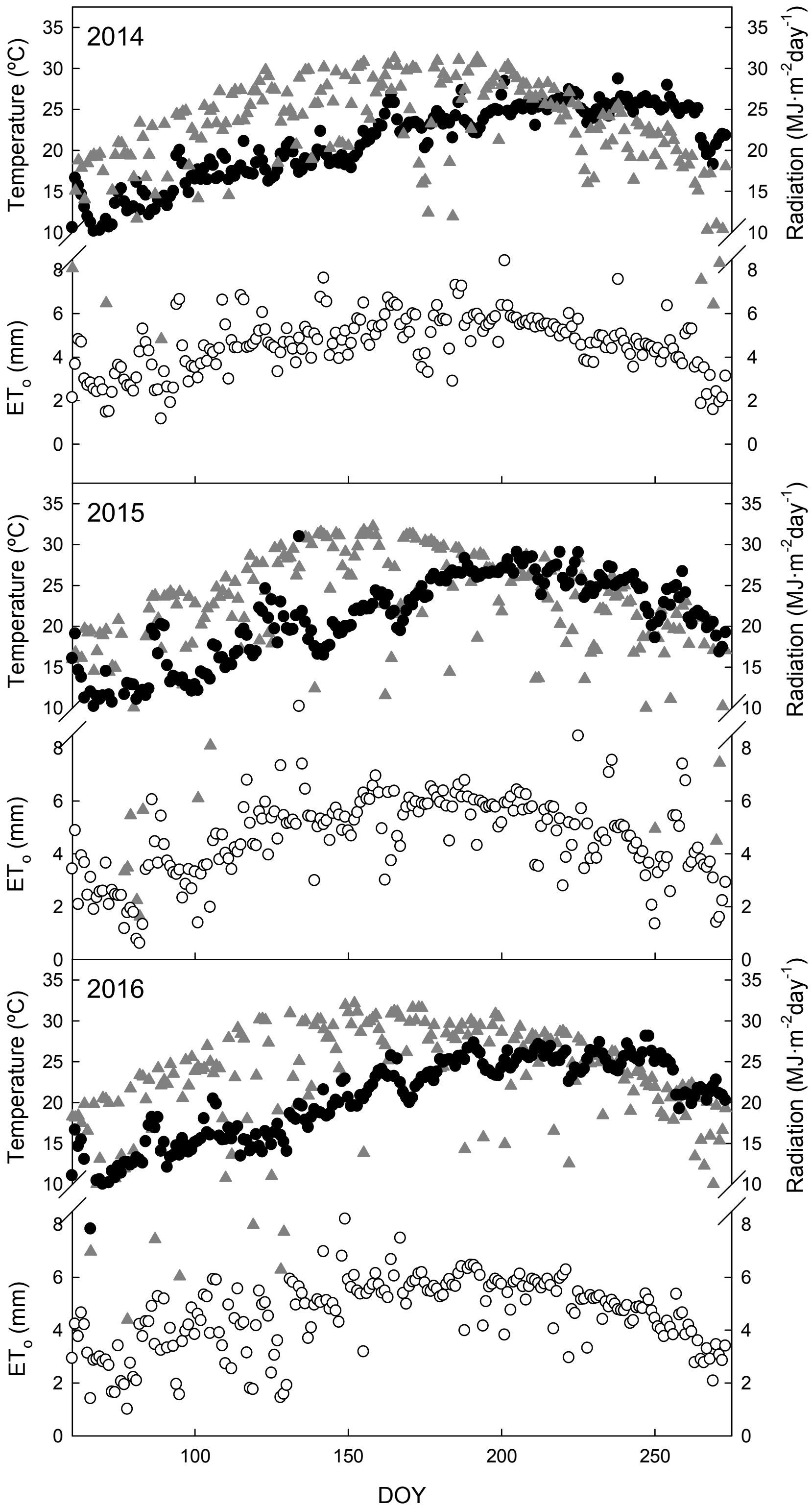

Figure 1. Seasonal patterns of daily reference evapotranspiration, ET_o (○); mean air temperature (●); and incoming solar radiation (▲) in Moncada, Valencia, Spain. The day of year (DOY) follows a continuous annual-time scale from March 1st to September 30th.

3.2. Modelling canopy radiation interception

In all seasons the EW orientation decreased with respect to NS by an average of 39% the amount of PAR intercepted daily by the vines (Figure 2).

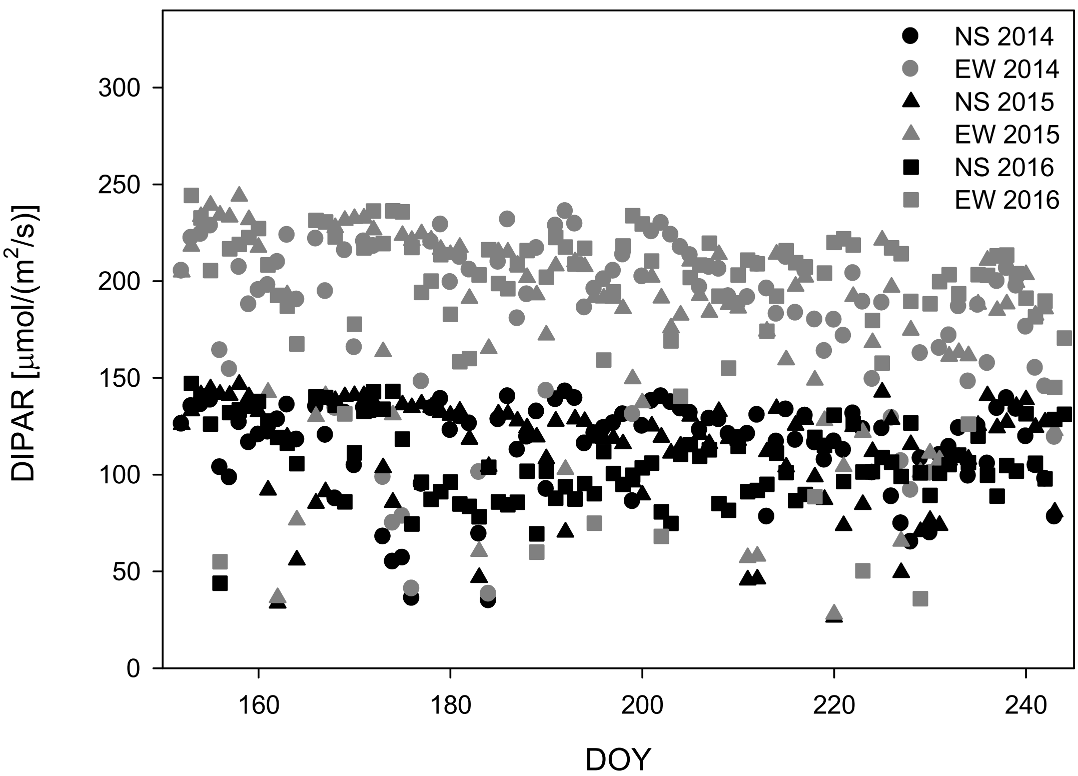

Figure 2. Daily averages of photosynthetically active radiation intercepted by grapevine canopies (DIPAR) as simulated during summer for the north-south (NS; ●■▲) and east-west (EW; ●■▲) row orientations in Valencia (Spain). Data are averages of the estimations from the model proposed by Oyarzun et al. (2007) for the 2014 (○), 2015

(□) and 2016 (Δ) seasons. The day of year (DOY) follows a continuous annual-time scale from June 1st to August 31st.

The differences observed on the hourly fraction of PAR intercepted (fIPAR) for each orientation explain this reduction in DIPAR for EW. Figure 3 shows the daily pattern of fIPAR for both orientations on three different dates. During most hours of the morning and afternoon, fIPAR is greater in NS than in EW (Figure 3). In contrast, EW orientation intercepts more PAR at noon. As shown in Figure 3d, 3e and 3f, IPAR is also higher for the NS orientation during the morning and afternoon, but the contrary occurs at noon. Reductions in DIPAR caused by EW orientation were 35-40% for the dates shown in Figure 3.

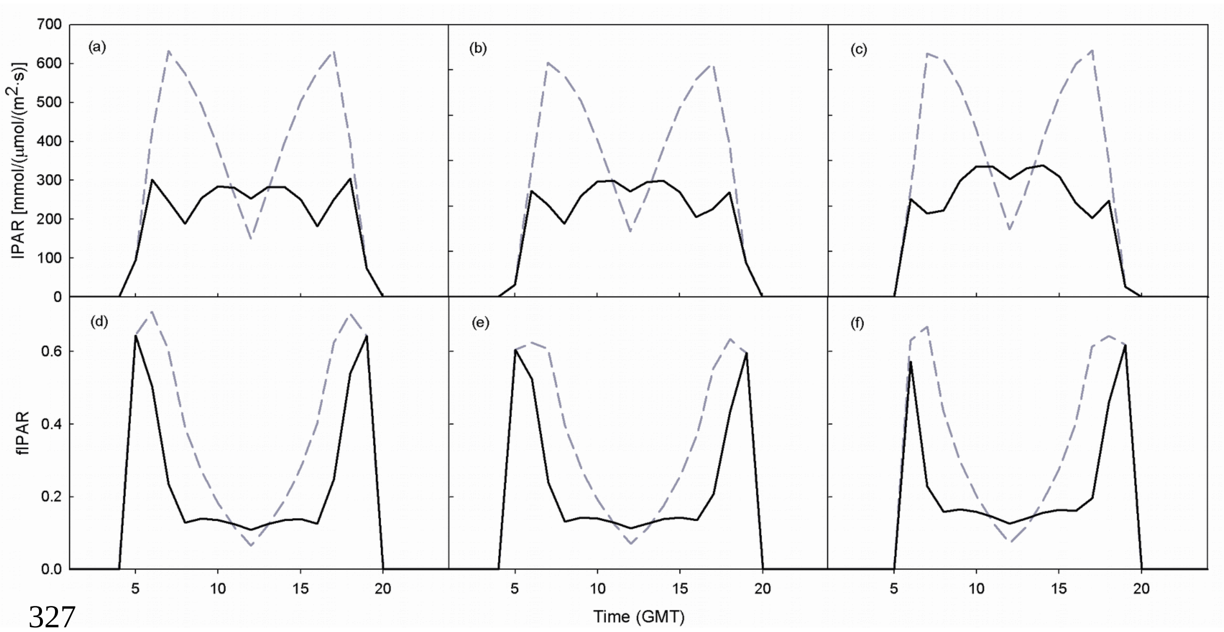

Figure 3. Hourly evolution of the fraction of intercepted photosynthetically active radiation (fIPAR) [a-c], and the intercepted PAR (IPAR) [d-f], simulated for the hedgerow orientation EW (——) and NS (— —) in Valencia, Spain. Simulated data corresponded to a day in June (Day of the year, DOY, 153) in 2016 [a, d], a day in July (DOY 201) in 2015 [b, e] and a day in August (DOY 217) in 2014 [c, f].

3.3. Vine phenology and vegetative development

Budburst took place, approximately, in the second week of March in the case of Verdejo (DOY 67-73) and during the fourth week in Bobal (DOY 88-94). Anthesis occurred in the second week of May (DOY 130-137) and during the subsequent (DOY

137-145), in Verdejo and Bobal, respectively. Veraison took placed during the first fortnight of July in both cultivars. The phenological stages of Verdejo were not significantly affected by the treatments imposed, but those of Bobal were delayed in each season by the EW row orientation compared to NS (Figure 4). However, this delay between orientations was recovered as the season progressed.

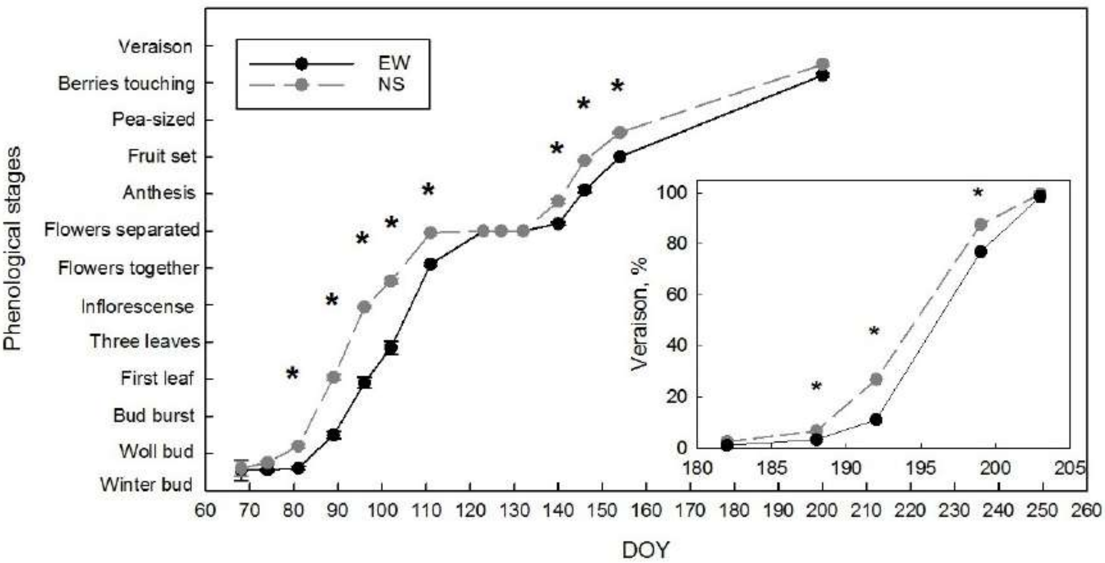

Figure 4. Evolution of the different phenological stages in Bobal in north-south (NS; ●) and east-west (EW; ●) hedgerow orientations during 2016. The percentage of colored berries (veraison) is depicted for the 2014 season. Data are averages and standard errors of two shoots per vine (n=40). Asterisks denote significant differences between orientations at $p<0.05$. DOY, day of the year.

In agreement with the evolution of phenology in Bobal vines, shoot growth and development was delayed in EW compared to NS (data not shown). In contrast, Verdejo vines did not show significant differences in shoot growth between the two orientations and the total dry matter produced by the vine was not affected by row orientation (Table 1). However, in Bobal vines, the NS orientation increased the total dry matter produced.

The number of shoots per treatment did not differ between treatments since the pruning and thinning criteria were the same (Table 1). Total leaf area (LA) was not consistently affected by row orientation in any cultivar during the three seasons studied. In 2015, LA was significantly increased by EW in comparison with NS for Verdejo. On the contrary, in 2016, LA of Bobal vines was significantly reduced by EW orientation compared to NS. In fact, in both cultivars, an interaction between season and treatment was detected for LA. Additionally, the LA-to-yield ratio was differently affected by the treatments imposed depending on the season.

Table 1. Vine shoot number, total dry matter, leaf area (LA) and LA-to-yield ratio in north-south (NS) and east-west (EW) oriented *Vitis vinifera* cv. Bobal and Verdejo potted-vines during three seasons.

Cultivar	Season	Orientation	Shoot number vine^{-1}	Dry matter, g vine^{-1}	LA, m^2 vine^{-1}	LA-to-yield, m^2 kg^{-1}
Bobal	2014	NS	17.0	482	6.3	2.6
		EW	17.6	453	6.7	2.4
	2015	NS	17.2	635a	5.0	0.5a
		EW	18.0	572b	4.9	0.4b
	2016	NS	18.2	893a	7.4b	1.8
		EW	18.4	671b	6.2a	1.4
	Average	NS	17.5	670a	6.2	1.6
		EW	18.0	565b	5.9	1.4
		Treatment	0.09	< 0.01	0.14	0.17
		Season	0.03	< 0.01	< 0.01	< 0.01
		T x S	0.69	< 0.01	< 0.01	0.59
Verdejo	2014	NS	17.7	503	6.1	3.5
		EW	17.5	579	6.7	4.1
	2015	NS	17.9	755	5.3b	1.2b
		EW	16.9	782	7.1a	1.7a
	2016	NS	18.2	1019	8.4	0.5a
		EW	18.0	1025	8.0	0.4b
	Average	NS	18.0	852	6.9b	1.2
		EW	17.6	873	7.5a	1.3
		Treatment	0.08	0.59	< 0.01	0.49
		Season	0.05	< 0.01	< 0.01	< 0.01
		T x S	0.33	0.52	< 0.01	0.07

For each parameter, data are average values of each treatment. Within each season and cultivar, different letters indicate significant differences at p<0.05. The statistical significances of the treatment (T), season (S) and their interaction are also indicated by means of p-values. Dry matter, total vegetative dry mass (cluster thinning, shoot trimming and pruning wood); LA, leaf area.

Table 2. Water-use (WU), water-use relative to leaf area, water-use efficiency (WUE) and water productivity (WP) in north-south (NS) and east-west (EW) oriented *Vitis vinifera* cv. Bobal and Verdejo potted-vines during three seasons.

Cultivar	Season	Orientation	WU, L vine^{-1} day^{-1}	Relative WU, L m^{-2} day^{-1}	WUE, g L^{-1}	WP, kg m^{-3}
Bobal	2014	NS	9.2a	1.46a	0.15b	4.3b
		EW	7.8b	1.16b	0.22a	6.4a
	2015	NS	9.4a	1.91a	0.51b	19.7b
		EW	7.6b	1.56b	0.60a	25.2a
	2016	NS	7.4a	1.01	0.13	4.9
		EW	6.5b	1.03	0.12	5.0
Verdejo	2014	NS	9.4a	1.54a	0.18b	4.1b
		EW	8.2b	1.22b	0.29a	5.3a
	2015	NS	8.8a	1.67a	0.07	2.0
		EW	8.2b	1.16b	0.07	1.9
	2016	NS	9.1	1.08	0.12	2.9
		EW	8.7	1.10	0.13	2.5

For each parameter, data are average values of each treatment. Within each season and cultivar, different letters indicate significant differences at $p<0.05$. WU, water-use; WUE, water-use efficiency (total vegetative and grape cluster dry mass/water-use); WP, water productivity (grape fresh weight/water-use).

3.4. Vine water-use (WU)

In all seasons, the peak transpiration rates were recorded in July (Figure 5), coinciding with the maximum ET_o (Figure 1). In both cultivars, vine WU was significantly higher in NS than in EW in most measurements (Figure 5). During the first season, when morning and evening transpiration were determined separately, differences between orientations occurred in both periods of the day (data not shown). In the Bobal cultivar in all the three seasons EW reduced transpiration in comparisons to NS by 12 to 23%. In the Verdejo cultivar reductions in water use brought by the EW rows orientation were less important and in 2016 there were not statistically significant differences between the two experimental treatments (Table 2). Nonetheless, the analysis of deviations relative to the 1:1 line from each treatment with the daily average of transpiration across seasons, cultivars and orientations (environmental mean), showed that EW significantly reduced grapevine transpiration compared to NS in both cultivars (Figure 6). The null hypothesis was that, for each cultivar, treatments are not different; hence, transpiration for individual treatments should align with the 1:1 line. Under our experimental conditions combining seasons, cultivars and row orientation, transpiration environmental mean ranged from almost zero in vines at the beginning of the growing season to 15 L day^{-1} in vines fully developed under high ET_o conditions. In 2014 and 2015 in both cultivars, vine WU relative to leaf area was significantly higher in NS than in EW (Table 2). Moreover, in both cultivars, EW increased WUE in comparison to NS, by 18% and 23% in Bobal and Verdejo, respectively. In terms of WP, in the Bobal variety, there was a clear increase in the EW compared to NW in the first two experimental seasons (Table 2). In the Verdejo cultivar, significant and clear differences in WP were obtained only during the first experimental seasons.

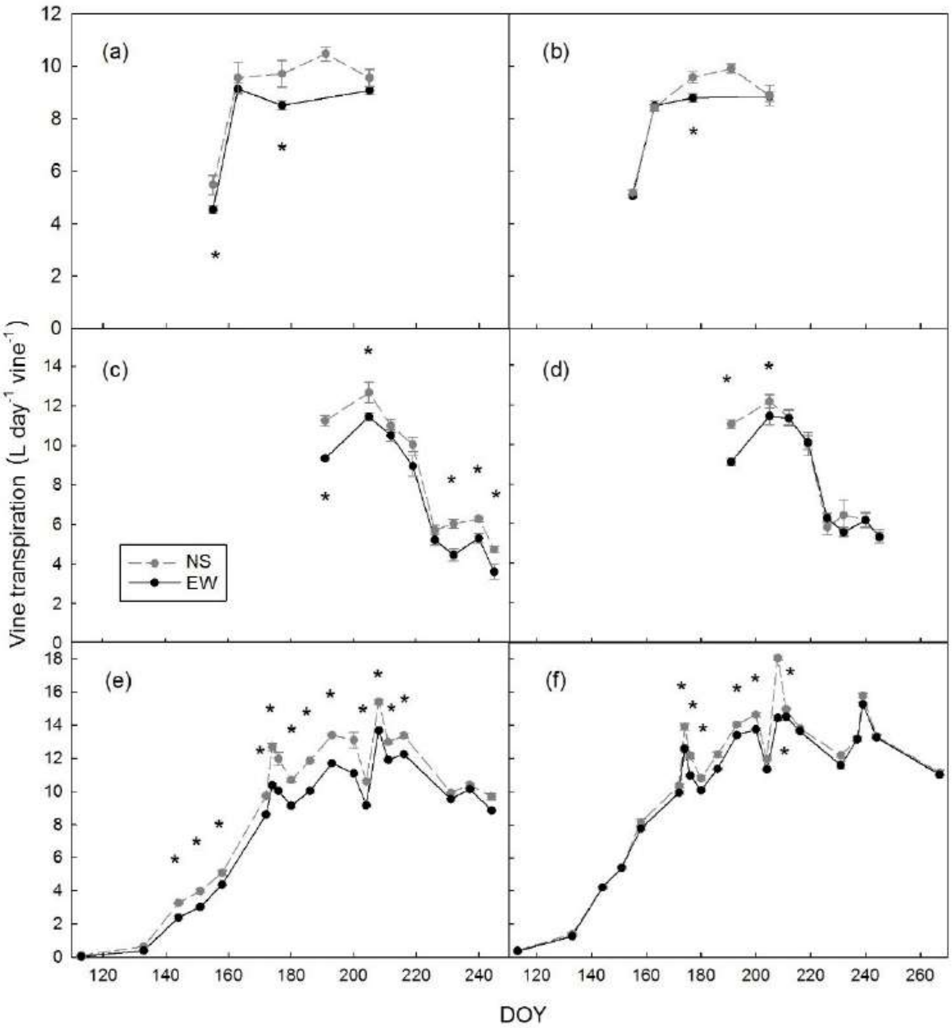

Figure 5. Seasonal transpiration measured by water balance in Bobal (left) and Verdejo (right) potted vines oriented north-south (NS; ●) and east-west (EW; ●) during 2014 [(a) and (b)], 2015 [(c) and (d)] and 2016 [(e) and (f)]. Data are averages and standard errors of each treatment, consisting of 5 vines per experimental unit and date. Asterisks denote significant differences between treatments at $p<0.05$. DOY, day of the year.

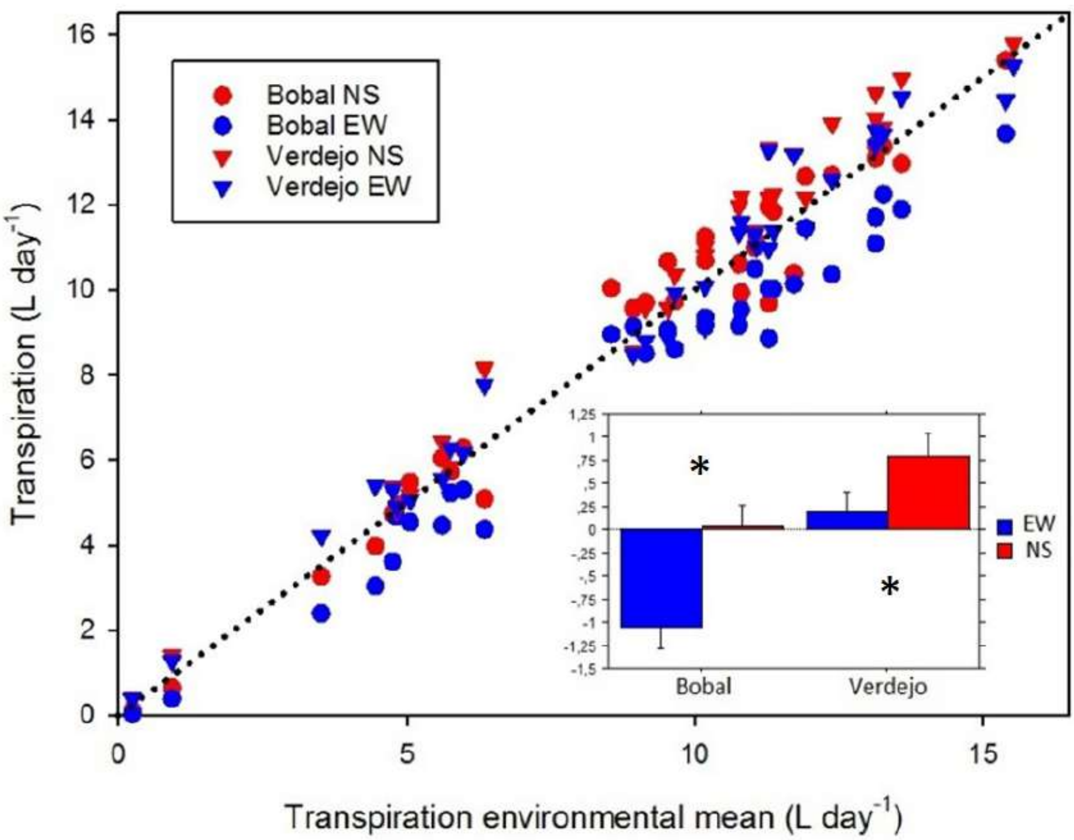

Figure 6. Scatter plot relating potted-vines transpiration environmental mean to daily transpiration of Bobal in north-south (NS; ●) and east-west (EW; ●) and of Verdejo in north-south (NS; ▼) and east-west (EW; ▼) hedgerow orientation in 2014/16. Data are averages of every experimental unit of each treatment. Bar chart shows significant deviation of each treatment and cultivar from the 1:1 line of the daily average of transpiration across seasons, cultivars and orientations. Asterisks indicate significant differences between orientations for each cultivar.

3.5. Vine water relations and physiology

Vines were over-irrigated during the whole season, ensuring water leaching after each irrigation event, and vines did not suffer from water deficit (Intrigliolo and Castel 2006, Williams and Baeza 2007). As an example, the Ψ_{pd} and Ψ_{md} evolution during 2016 is depicted for both cultivars in Figure 7. Values of Ψ_{pd} and Ψ_{md} never went below -0.25 MPa and -0.75 MPa, respectively. Moreover, the treatments imposed did not cause significant differences in vine water status. In 2014, the Ψ_{md} in Bobal had a seasonal average of -0.56 MPa in NS and -0.55 MPa in EW and, in Verdejo, -0.61 MPa and -0.59 MPa, respectively. In 2015, Ψ_{md} in Bobal was on average -0.50 MPa in NS and -0.43 MPa in EW and, in Verdejo, -0.47 MPa and -0.46 MPa, respectively.

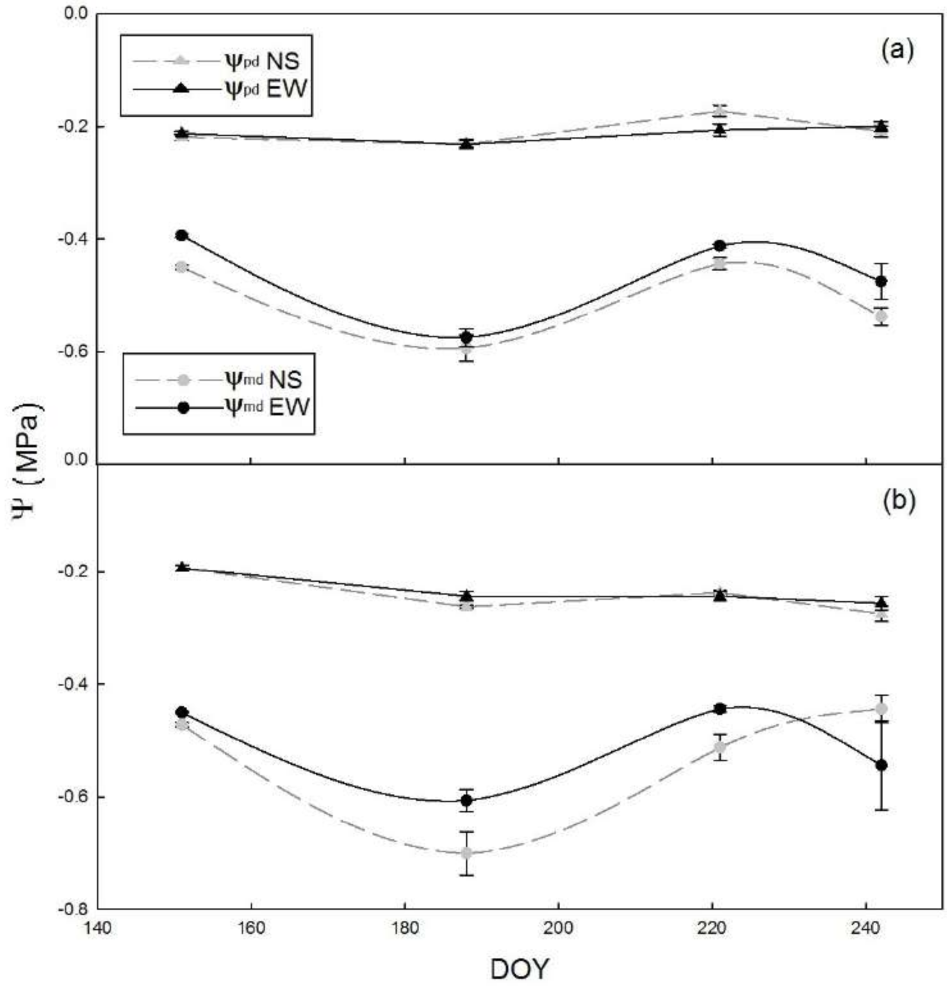

Figure 7. Evolution of vine water status at predawn (Ψ_{pd}) and at midday (Ψ_{md}) during the 2016 season in north-south (NS) and east-west (EW) oriented *Vitis vinifera* cvs. Bobal [(a)] and Verdejo [(b)] potted vines. Data are averages and standard errors of 2 leaves per experimental unit (n=8) for predawn leaf water potential (▾, ▾) and midday stem water potential (●, ●). DOY, day of the year.

Regarding gas exchange determinations in both cultivars (Table 3), pooling data across seasons, daily transpiration (E) was slightly higher in NS compared with EW. This trend was consistent with the water balance measurements (Figure 5). However, the differences in E found on a leaf basis resulted significant only in Bobal during the afternoon. The stomatal conductance (g_s) and net photosynthesis (A) were significantly higher in NS than EW during the morning in Verdejo, and during the afternoon in Bobal. At midday, leaf-gas exchange parameters did not show significant differences between treatments. On a daily scale, g_s and A were significantly higher in NS than in EW in both cultivars (Table 3). The WUE_i was not significantly affected by row orientation, although in both cultivars it tended to decrease in NS in the morning and to increase in the afternoon when compared to that of EW. On a daily basis, these effects were mostly offset. The effect of the season was significant in most gas-exchange parameters and times of the day, but not the interaction between year and treatment.

Table 3. Leaf gas exchange parameters of Bobal and Verdejo potted-vines oriented north-south (NS) or east-west (EW). Data were pooled across three seasons.

Cultivar	Time of the day	Orientation	E, mmol H_2O m^{-2} s^{-1}	g_s, mol m^{-2} s^{-1}	A, µmol CO_2 m^{-2} s^{-1}	WUE_i µmol CO_2 $mmol^{-1}$ H_2O
Bobal	Morning	NS	3.1	197	11.5	49.3
		EW	3.4	211	11.3	51.4
		Treatment	0.29	0.01	0.20	0.57
		Season	< 0.01	< 0.01	0.37	< 0.01
		T x S	< 0.01	0.14	0.03	0.15
	Midday	NS	3.4	205	10.1	52.3
		EW	3.3	211	10.2	53.5
		Treatment	0.76	0.74	0.92	0.79
		Season	< 0.01	< 0.01	< 0.01	< 0.01
		T x S	0.27	0.25	0.85	0.76
	Afternoon	NS	2.6a	208a	10.0a	50.5
		EW	2.0b	146b	6.7b	46.6
		Treatment	< 0.01	< 0.01	< 0.01	0.51
		Season	0.02	0.14	< 0.01	0.06
		T x S	0.46	0.33	0.97	0.54
	Daily	NS	3.2	257a	10.8a	50.0
		EW	3.0	207b	9.7b	51.2
		Treatment	0.11	< 0.01	0.03	0.65
		Season	< 0.01	< 0.01	0.04	< 0.01
		T x S	0.37	0.38	0.47	0.75
Verdejo	Morning	NS	3.1	290a	11.8a	48.0

	EW	3.3	227b	10.5b	53.4
	Treatment	0.39	< 0.01	0.02	0.09
	Season	< 0.01	< 0.01	< 0.01	< 0.01
	T x S	< 0.01	0.51	0.81	0.10
Midday	NS	3.3	200	10.3	56.7
	EW	3.0	160	9.4	60.1
	Treatment	0.13	0.22	0.83	0.47
	Season	< 0.01	0.83	< 0.01	< 0.01
	T x S	0.11	0.03	0.10	0.92
Afternoon	NS	2.5	185	9.2	50.7
	EW	2.2	163	7.9	48.5
	Treatment	0.08	0.17	0.10	0.51
	Season	< 0.01	< 0.01	< 0.01	< 0.01
	T x S	0.89	0.59	0.23	0.01
Daily	NS	3.1	234a	10.8a	52.5
	EW	3.0	199b	9.9b	54.8
	Treatment	0.30	< 0.01	0.04	0.32
	Season	< 0.01	< 0.01	0.08	< 0.01
	T x S	0.14	0.04	0.06	0.04

For each parameter, data are averages foreach treatment, consisting in 4 leaves per experimental unit and 3 dates of measurement during each season. Within each time of the day and cultivar, different letters mean significant differences at p<0.05. The effects of the treatment (T), season (S) and their interaction are also shown by means of p-values. E, transpiration; g_s, stomatal conductance; A, net photosynthesis; WUE_i, intrinsic water-use efficiency (A/g_s).

3.6. Yield components

Yield was rather variable across seasons in both cultivars, without significant effects, on average for the study period, in response to the treatments imposed (Table 4). Exceptionally, yield was increased by EW compared with NS in Bobal in 2015, whereas it was reduced in Verdejo in 2016. Number of clusters per vine, berries per cluster or cluster mass were similar between treatments in both cultivars. The initial number of clusters per vine, before thinning, did not differ between treatments (Table 4). Finally, berry mass significantly decreased under NS when compared with EW in Verdejo, whereas in Bobal this effect was only significant in the first experimental season.

Table 4. Yield components of potted-vines in rows oriented north-south (NS) and east-west (EW) in Bobal and Verdejo cultivars during three seasons.

Cultivar	Season	Orientation	Initial clusters vine^{-1}	Final clusters vine^{-1}	Cluster mass, g	Berries cluster^{-1}	Berry mass, g	Yield, kg vine^{-1}
Bobal	2014	NS	7.2	6.3	421	120	3.0b	2.9
		EW	6.7	6.6	422	135	3.2a	2.9
	2015	NS	17.2	13.3	785	287b	2.7	10.5b
		EW	17.3	14.4	813	319a	2.5	11.8a
	2016	NS	9.5	8.1	613	193	3.1	5.3
		EW	11.0	8.9	540	170	3.2	4.8
	Average	NS	11.3	9.2	608	200	3.0	6.3
		EW	11.7	10.0	592	208	3.0	6.5
		Treatment	0.57	0.10	0.58	0.41	0.85	0.49
		Season	<0.01	< 0.01	< 0.01	< 0.01	<0.01	< 0.01
		T x S	0.37	0.78	0.20	0.02	0.25	0.06
Verdejo	2014	NS	21.0	16.7	92	32	2.8b	1.8
		EW	22.3	16.2	113	34	3.3a	2.0
	2015	NS	30.3	24.9	178	70	2.6b	4.4
		EW	27.8	24.5	179	64	2.8a	4.4
	2016	NS	29.5	24.5	173	87	2.0b	4.5a
		EW	27.3	23.6	167	77	2.2a	3.6b
	Average	NS	26.9	23.6	164	73	2.4b	4.1
		EW	25.8	23.0	166	67	2.7a	3.7
		Treatment	0.13	0.63	0.49	0.15	<0.01	0.411
		Season	<0.01	< 0.01	< 0.01	< 0.01	<0.01	< 0.01
		T x S	0.05	0.95	0.41	0.31	0.05	0.06

For each parameter, data are average values of each treatment. Within each season and cultivar, different letters mean significant differences at $p<0.05$. The statistical significance effect of the treatment (T), season (S) and their interaction are also indicated by means of p-values.

4. Discussion

Assessing seasonal transpiration and WUE of grapevines in response to hedgerow orientation in Mediterranean latitudes is important to optimize vineyard water balance. As light interception is related to the potential crop evapotranspiration, techniques that reduce canopy radiation load and therefore vine water requirements are needed for adapting Mediterranean viticulture to the effects of the projected increase in water deficit (Schultz 2000, van Leeuwen et al. 2019). In the current study, orienting hedgerows EW decreased grapevine transpiration when compared with rows oriented NS (Figure 6). The average reduction in WU (-18%) found in EW compared to NS rows occurred in both cultivars independently of LA (Table 2). Moreover, WUE and

WP across seasons increased in both cultivars when orienting rows EW. When gas exchange was determined at the single leaf level, transpiration in the vines oriented EW compared to NS vines was reduced only by 7% in Bobal and by 4% in Verdejo (Table 3). This suggests that the row orientation effects on water-use were not only due to modifications in gas exchange on a leaf basis. Nevertheless, we cannot rule out the possibility that some modification of the conditions of temperature, humidity, radiation that the gas exchange measurement device causes on the leaf environment, might have inevitably influenced transpiration determinations carried at the leaf level. In this sense, Poni et al. (2009) pointed out that extrapolating single-leaf-based determinations to the whole-canopy level do not necessarily reflect the whole-canopy behavior, and even more when, as in our experiment, the treatments imposed also affected the whole vine micro-climate.

In the present research, in fact, the estimated seasonal IPAR reduction due to the EW row orientation was 39% (Figure 2) in accordance with the experimental data and model simulations for radiation interception in row vineyards tested by Campos et al. (2017). This estimated reduction in IPAR is therefore higher than the decrease in WU determined at the whole vine level. This might be because the regulation of canopy conductance depends not only on the radiation interception, but also on the interrelation between grapevine physiology and the microclimatic conditions within the canopy (Steduto et al. 2007). Under ambient conditions the higher transpiration induced by the NS orientation may have decreased the vapor pressure deficit in the air surrounding the canopy affecting therefore the evaporative demand at the vine level.

Phenological stages and shoot growth were significantly anticipated only in the Bobal cultivar when it was oriented towards NS compared to EW (Figure 4) suggesting that the thermal effect of hedgerow orientation on vine phenology is cultivar dependent. This effect could have been enhanced by the heating effect of radiation onto the pots and thus the warmer root system. Nevertheless, the advancement in phenological stages was attenuated during the course of the season. Notwithstanding, increments in Bobal dry matter were found in 2015 and 2016 in NS compared to EW. This seems to be related to the advancement in shoot growth due to the earlier phenology caused by NS. In Bobal, indeed, if shoot trimming had not been performed, differences in WU between NS and EW might have been higher. In Verdejo, where advancements in phenology caused by changing row orientation did not occur, few differences in total dry matter were found between treatments .

Vine productivity was primarily unaffected by the reductions in the estimated radiation load provoked by orienting grapevine trellis systems towards EW instead of NS (Table 4). This lack of effects disagrees with previous studies assessing row orientation effects of olive (*Olea europaea* L.) hedgerows (Trentacoste et al. 2015), which can be attributed to the obvious morphological and physiological differences between these crops. The positive linear relationship of growth and yield of olive trees with IPAR (Villalobos et al. 2006) was not observed in our experiment. Grapevine productivity under conditions of high radiation load has been reported to be more dependent on the vine water relations than on the vine source capacity (Mirás-Avalos et al. 2017). In our experiment, the only yield component that seems to have had a consistent effect in response to row orientation was berry mass, which tended to decrease in NS (Table 4), with lower sensitivity in Bobal grapes. This might be caused by turgor pressure effects (Intrigliolo and Castel 2010); however, there were no significant differences in vine water status between treatments to support this hypothesis (Figure 7). Indeed, a large number of factors affects the physiology of berry growth (Dai et al. 2009). For instance, Hunter et al. (2016, 2017) observed a reduction in berry size in field-grown Shyraz grapevines not explainable by the low vine water potential differences due to row orientation. The authors explained this reduction in berry size by a lower berry transpiration in the clusters of the EW oriented vines compared to those NS-oriented. In addition, these authors observed that vines NS-oriented consistently yielded 6% more than EW vines during a seven-year trial under mild water stress. On the contrary, under our non-limiting water conditions, only total dry matter in Bobal significantly decreased by EW compared to NS (Table 1).

Improving WP, estimated as yield to water-use ratio, is crucial for a sustainable viticulture, especially in semi-arid regions (Medrano et al. 2015b). Growing different cultivars can be an option to improve WP because, as observed in our trial, yield response depends greatly on the genotype. However, for winemaking purposes, local cultivars determine wine typicity. In both cultivars, WUE and WP significantly increased in EW when compared to NS (Table 2), with the exception of 2016, when a significant yield reduction occurred in EW Verdejo, and no differences in Bobal. Overall, the higher WU and the higher photosynthesis rates of NS oriented vines compared to those EW (Table 3), did not involve higher yields or the initial number of clusters per vine (Table 4), reducing both WP. A possible explanation to this lower efficiency in NS compared to EW might be their lower WUE_i (assimilation-to-transpiration ratio) during the morning hours, when grapevine is more physiologically active and NS rows were intercepting more radiation than those EW (Figure 3). However, this hypothesis could not be statistically confirmed with the single leaf gas exchange data reported in Table 3. This, together with the limitations of extrapolating the gas exchange results from single-leaf level to the whole-canopy (Poni et al. 2009, Tomàs et al. 2012), although to a lesser extent in well-watered vines (Medrano et al. 2015a), suggest that the explanation for this effect may be attributed to different reasons. First, the higher direct radiation interception in NS rows could have affected thermal distribution within the canopy (Albasha et al. 2019) and thus increased transpiration, but also photorespiration and mitochondrial respiration in NS rows, and consequently reduced carbon assimilation efficiency (Amthor 1989). It should not be overlooked that daily respiration accounts for more than 25% of daily total photosynthesis (Poni et al. 2006, Escalona et al. 2012). Hunter et al. (2016) reported a greater portion of diffuse light intercepted by vineyard EW rows than those NS, which may be related to higher radiation use efficiency (Petrie et al. 2009). Moreover, the nonlinearity of the photosynthetic response to direct-light could be pointing to some degree of photoinhibition in the canopies oriented NS. Secondly, the greater photosynthesis of NS would have been used to synthesize other organic compounds, besides carbohydrates and woody structures, to a greater extent than in EW because, under high light intensities, alternative biochemical pathways can be stimulated to protect leaves and fruits from photo-oxidative damages (Grappadelli and Lakso 2007, Losciale et al. 2010).

In summary, the findings from the current work, encourage further studies on sunlight interception and canopy architecture designs as potential techniques for adapting vineyards to climate change. Field research under different soil water availability conditions and particularly under deficit irrigation should be carried out. In any case our research demonstrates that under no soil water limitations, grapevine consumptive water-use can be reduced by row orientation. In an irrigated area, adopting the E-W row orientation might therefore reduce the pressure on the available water resources by reducing the consumptive water-use. An aspect of importance in semi-arid environments with chronic water scarcity conditions where tools for decreasing water-use in addition to increase the agro-ecosystem water productivity are needed.

5. Conclusions

This experiment quantified the effects of row orientation on grapevine water-use on potted vines of two grapevine cultivars. Vine transpiration was reduced in EW compared to the NS orientation, although to a lesser extent than simulated IPAR. Specifically, it was decreased seasonally by 16% in Bobal and by 8% in Verdejo, corresponding to an 18% per unit of leaf area in both cultivars. Carbon balance was not markedly affected by row orientation. Consequently, WP increased significantly across seasons by 25% in EW compared to NS. Therefore, at Mediterranean latitudes, where solar radiation falls more perpendicular to the Earth's surface during the grapevine growing season, modifying canopy sunlight interception by orienting hedgerows EW instead of NS, reduces grapevine radiation load, which under no water deficit conditions, decreases WU and can improve WUE. Further research, especially under field conditions, is needed to determine the effects of vineyard row orientation under different degrees of water stress, paying attention to the potential effects on grape composition for winemaking purposes.

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Supplementary Figure

Supplementary Figure. A photograph showing the pot experiment with vines NS-oriented and EW-oriented.