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IRRIGATION EFFECTS ON THE PERFORMANCE OF GRAPEVINE (*VITIS VINIFERA* L.) CV. 'ALBARINO' UNDER THE HUMID CLIMATE OF GALICIA

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Abstract

Aims: Vine-growers worldwide are concerned about climate change effects on grape yield and quality. Drip irrigation systems are increasingly being installed even in humid regions such as Galicia (NW Spain). In this context, a field experiment was carried out over three seasons (2012-2014) on white *Vitis vinifera* L. cv. 'Albariño' to assess the effects of deficit irrigation on vine physiology, yield and must and wine composition.

Methods and results: Rain-fed vines were compared with a treatment irrigated to 50% of the estimated crop evapotranspiration (ET_c) from bloom to two weeks before harvest. Irrigated vines showed more positive stem water potentials than those rain-fed. Yield was unaffected by irrigation except in 2014 (19% increase). Pruning weight was increased by irrigation. Must soluble solids tended to decrease and total acidity to increase with irrigation; however, wines were similar between treatments. Water productivity was slightly higher under rain-fed conditions.

Conclusion: Under the conditions of this experiment, irrigation was of no interest either in terms of grape and wine quality or in terms of net income.

Significance and impact of the study: These results may be useful for managing water resources in vineyards under similar climatic conditions.

Key words: Drip irrigation, crop yield and quality, vine water status, water productivity, white wine

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INTRODUCTION

Irrigated vineyard (*Vitis vinifera* L.) area has increased in Spain from 6% to 22% in the last 20 years (MAGRAMA, 2015) due to vine-growers' concern about the negative impacts of water deficits on vine growth and yield (Gouveia *et al.*, 2012), even in Galicia (NW Spain), which receives high amounts of rainfall (700-1900 mm, depending on the site). However, irrigation studies in Galician vineyards are scarce (Fandiño *et al.*, 2012), and vine-growers need technical information in order to use water more efficiently.

Adequate soil water availability, according to the phenological stage of the vines, must be maintained over the growing season in order to obtain good-quality grapes (Jackson and Lombard, 1993; Deloire *et al.*, 2004). Water stress must be avoided at the beginning of the growing season, between bud-break and flowering, since it may reduce vegetative growth causing small canopies that would diminish the vine's capacity to set the fruits. From fruit set to veraison, mild water stress is advisable but severe water stress would reduce berry weight and decrease yield. Between veraison and harvest, water stress might cause a reduction in photosynthesis, although if this stress is very mild then it would be beneficial for accelerating berry maturation. In summary, excessive rainfall or irrigation slows ripening, increases yield partially by berry enlargement, elevates juice pH and acid content, and reduces anthocyanins due to shading from continuous and excessive shoot growth. In contrast, water stress causes early ripening but reduces yield, berry weight, and malic acid (Jackson and Lombard, 1993).

Global warming predictions estimate reductions in rainfall and increases in evapotranspiration for the near future (IPCC, 2007). In Galicia, an increase in temperature of up to 1.1 ºC (0.37 ºC for each decade from 1972 to 2006) has already been reported (Cruz *et al.*, 2009) as well as modifications in the spatial and temporal distribution of rainfall, with less rainfall in summer months (June-September) (Mirás-Avalos *et al.*, 2009), which could affect berry set and fruit maturation. These changes might cause Galician grapevine cultivars, adapted to temperate and cool climates, to reach more rapidly their optimum temperature and, consequently, lose their specific organoleptic qualities. In this context, the need for conducting field trials about timing and amount of water applied through irrigation in accordance with the characteristics of the different regions has been highlighted (van Leeuwen *et al.*, 2009; Intrigliolo and Castel, 2010; Basile *et al.*, 2012), even under cool-humid climates (Reynolds *et al.*, 2007).

Deficit irrigation strategies have been successfully adopted as management tools to ensure an adequate balance between vine vegetative and reproductive development while preserving yield and water resources and improving fruit composition (Dry *et al.*, 2001; Intrigliolo and Castel, 2008). However, irrigation must be applied (amount and time) in accordance with the climate and soil characteristics of the region and the type of wine to be produced to avoid potential negative impacts on vine vigour, berry composition and wine quality. Some authors remarked that irrigation must be customized for each cultivar (Basile *et al.*, 2012) and research reports are scant for white grapevine cultivars.

'Albariño' is one of the Spanish white grapevine cultivars recognized worldwide for giving high-quality wines and it is the main cultivar from Galicia. It is characterized by its great aromatic potential, giving fruity and floral odours (Versini *et al.*, 1994).

Several studies have investigated the irrigation and plant water stress effects on grape composition and wine quality of grapevine cultivars; however, the results differed due to the variety of climatic conditions and vineyard managements (Jackson and Lombard, 1993; Deloire *et al.*, 2004). With no history of vineyard irrigation in the area and minimal information in the literature on the behaviour of Albariño (Fandiño *et al.*, 2012; Martínez *et al.*, 2016), the aim of the current study was to assess the effects of deficit irrigation as a strategy for reducing water stress from flowering to two weeks prior to harvest (the most sensitive period of grape development to water deprivation) on soil-water relations, agronomic performance, and grape and wine composition of this renowned white cultivar.

MATERIALS AND METHODS

1. Description of the study site and experimental design

The experiment was conducted over three consecutive growing seasons (2012-2014) in a 0.2-ha vineyard (*Vitis vinifera* L.) located in the experimental farm of the Estación de Viticultura e Enoloxía de Galicia (EVEGA), in Leiro (42º 21.6' N, 8º 7.02' W, elevation 115 m), Ourense, Spain. The vines were 'Albariño' grafted on 196-17C rootstock and planted in 1998. They were trained to a vertical trellis on a single cordon system (10-12 buds per vine). Rows were east-west oriented; spacings

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between vines and between rows were 1.25 and 2.4 m, respectively (3333 vines ha^{-1}).

The soil at the site was sandy-textured (64% sand, 16.4% silt, 19.6% clay), slightly acidic (pH 6.3), and of medium fertility (2.7% organic matter). It has a rather shallow profile (≈1.2 m) and available water capacity is 100 mm m^{-1}, approximately.

The climate of the studied site is considered temperate, humid with cool nights (Fraga *et al.*, 2014). Average annual rainfall amounts to 900 mm, about 70% of which falls during the dormant period. In spite of high annual rainfall (1283 mm), the second experimental growing season (April to mid-September 2013) was the driest one with 163 mm, similar to the last year of study (185 mm) and half the rainfall recorded in the 2012 growing season (313 mm). In contrast, annual rainfall increased from year to year: 841, 1283 and 1301 mm for 2012, 2013 and 2014, respectively. Average temperatures over the growing season also increased from year to year (17.2 ºC in 2012 and 18.0 ºC in 2014), causing higher potential evapotranspiration values: 698, 745 and 739 mm for 2012, 2013 and 2014, respectively (Figure 1). As a summary, in 2012, environmental water deficit (ET_0 – rainfall) began later than in the other seasons (around day 157, 115 and 98 for 2012, 2013 and 2014, respectively). This was caused by the high rainfall amounts registered in spring 2012. Moreover, cumulated environmental water deficit reached 582 mm in 2013, whereas it was 367 and 460 mm in 2012 and 2014, respectively.

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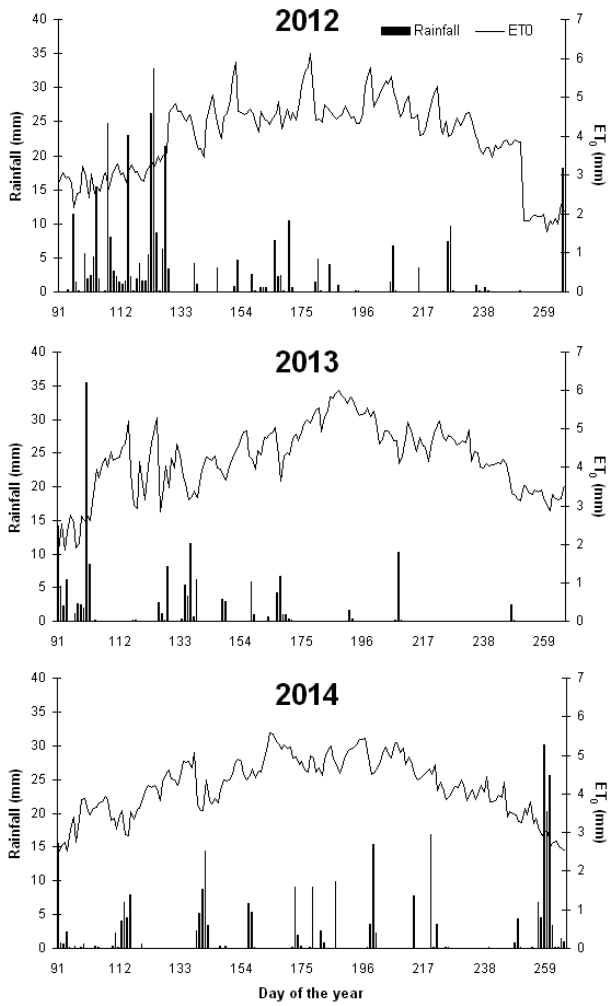


Figure 1 - Daily rainfall and potential evapotranspiration (ET_0) for the three studied growing seasons.

The reference evapotranspiration (ET_0) per week for the site was calculated from weather variables recorded at a station located 150 m away from the experimental vineyard using the Penman-Monteith equation (Allen *et al.*, 1998). The ET_0 was used, along with a constant crop coefficient (K_c = 0.8) to compute the amount of water required by the vines (ET_c), using the equation $ET_c = K_c \times ET_0$. The value of K_c was taken from previous reports that considered similar values (between 0.7 and 0.8) for vineyards with developed canopies (Reynolds *et al.*, 2007; Williams, 2012; Romero *et al.*, 2013), as our vineyard when irrigation was triggered. Moreover, similar K_c values for Albariño were found using the basal crop coefficient approach (Table 6 in Fandiño *et al.*, 2012). Precipitation was subtracted from ET_c each week. The calculated amount of water required was applied the following week.

Treatments consisted of a rain-fed control and an irrigation treatment corresponding to 50% ET_c. The choice of this deficit irrigation was dictated by obeyed to reasons of vineyard management, since greater amounts would lead to an excessive vegetative growth and, thus, unbalanced vines. Weed growth in the vineyard was controlled mechanically. Thus, the treatments were as follows:

- Non-irrigated control (rain-fed).

- Deficit irrigation treatment (irrigated), following this expression: Irrigation amount (mm) = ((K_c x ET_0)/2) – rainfall.

- Irrigation was applied from full bloom (late June) till mid-August, approximately two weeks prior to harvest.

Each treatment had three replicates in a randomized complete block design. Each replicate consisted of

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three rows with 12 vines per row. The eight vines in the centre of the middle row were used for measurements and the rest acted as buffers.

Water was applied with two pressure-compensated emitters of 4 L h^{-1} located 25 cm on either side of the vine. Frequency of water applications varied from 3 to 5 days per week, depending on the amount of water required, in order not to apply more than 3 mm per day (the equivalent of 50% daily ET_c). Irrigation water was of good quality, with pH of 6.35, electrical conductivity of 163.4 □S cm^{-1} and 0.4 mg L^{-1} of suspended solids. The water amount applied each season was 50, 79 and 50 mm for 2012, 2013 and 2014, respectively.

2. Field measurements

Soil water content (SWC) was measured at 10, 20, 30 and 40 cm depth using a PR2 probe (Delta-T Devices, UK). One access tube was installed in each replicate at the beginning of 2013, with a total of three tubes per treatment. Access tubes were located between the vine trunk and the emitter.

Midday stem water potential was measured using a pressure chamber (Pump-Up, PMS Instruments, Albany, OR, USA) on mature leaves (one per vine) of three representative vines per replicate (9 readings per treatment). Leaves were enclosed in plastic bags covered with aluminium foil at least one hour prior to the measurements (Choné *et al.*, 2001), which were carried out fortnightly between 12:00 and 13:00 h solar time. This modality of leaf water potential has been proven the most appropriate for assessing vine water stress under Galician conditions (Mirás-Avalos *et al.*, 2014).

Stomatal conductance was measured on the same dates as stem water potential, around solar midday using a leaf porometer (model SC-1, Decagon Devices, WA, USA). Measurements were performed on mature and healthy leaves (one per vine) of three representative vines per replicate (9 readings per treatment).

Chlorophyll *a* (Chl *a*) fluorescence parameters were measured in situ with a pulse-amplitude-modulated fluorometer (FMS 2, Hansatech Instruments, Norfolk, UK) as described by Moutinho-Pereira *et al.* (2012). Leaves were dark-adapted for at least 10 minutes using dark-adapting leaf-clips. Several photosystem II (PSII) parameters were obtained (Maxwell and Johnson, 2000): the maximum quantum efficiency of PSII (F_v/F_m), the photochemical efficiency of PSII (□$_{PSII}$) and the electron transport rate (ETR). Chl *a* fluorescence measurements were always performed between 11:30 and 13:30 h. In 2013, these determinations were not taken due to equipment malfunctioning.

Chlorophyll concentration index (CCI) was estimated non-destructively using a CCM-200 portable chlorophyll meter (Opti-Sciences, Tyngsboro, MA, USA) that calculates a unit-less CCI value from the ratio of optical absorbance at 655 nm to that at 940 nm, which is correlated with total foliar extractable chlorophyll (Richardson *et al.*, 2002; van den Berg and Perkins, 2004). These measurements were performed from ripeness to harvest on three leaves per plant and three plants per replicate (total of 9 vines per treatment). Major veins and areas of obvious visual damage or disease were avoided. In 2012, measurements were not collected, due to equipment unavailability.

Yield was determined at harvest on each of the internal rows (8 vines per row) of each replicate. The number of clusters per vine was also recorded. Average cluster weight was obtained by dividing yield per plant by the number of clusters. Berry weight was determined on random samples of about 200 berries per replicate. Pruning weight was assessed in winter on six vines per replicate. Exposed leaf area was estimated after veraison on six vines per replicate, when shoot growth had ceased, following the method proposed by Sánchez-de-Miguel *et al.* (2010), in which the width and height of the canopy are collected at five different spots along the vine using a measurement tape.

3. Must and wine quality determinations, winemaking procedures

Basic parameters of musts (total soluble solids content, pH, titratable acidity, tartaric and malic acid contents) and wines (alcohol content, pH, titratable acidity, tartaric and malic acids contents) were determined by Fourier transform infrared spectrometry (FTIR) using a WineScan FT120 analyser (FOSS Electric, Barcelona, Spain) calibrated according to the official methods (OIV, 2009).

Grapes from the different treatments were manually harvested on the same day and transported to the experimental winery in field boxes. Vinifications were performed at EVEGA separately on samples of about 40 kg from each replicate (total of three vinifications per treatment).

Grapes from each replicate were separately destemmed, crushed and pressed in a pneumatic press; SO_2 (50 mg L^{-1}) was added to avoid oxidation and for microbiological control. After one day, musts

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were racked and then fermented in 35-L stainless steel tanks; commercial yeast (Excellence FW, Lamothe-Abiet, Bordeaux, France) was added at a rate of 20 g hL^{-1}. Density and fermentation temperature were monitored daily. Wines were racked and sulphited to 35 ppm free sulphur dioxide once alcoholic fermentation finished. A tartaric stabilization was carried out at 4 ºC for one month. Finally, wines were filtered, bottled and stored. Analytical determinations in the wines were performed just after alcoholic fermentation.

4. Water productivity and gross incomes

Water productivity (WP) was determined as the annual crop yield (in kg per ha) divided by the amount of water received during the same period (rainfall over the growing season + irrigation applied).

For the assessment of the gross incomes, prices of grape yield for each treatment were calculated according to the regulated contracts issued in 2008 by the Consellería of Medio Rural of the Xunta de Galicia (Diario Oficial de Galicia 16th July 2008), regional government of Galicia, for the Ribeiro DO. Grape is paid according to its probable alcoholic grade. Hence, the price of one kg of Albariño grapes with 13% vol. probable alcoholic grade would be 1.39 €, whereas that of one kg with 11% vol. would be 1.06 €. Further cost-benefit and financial feasibility analyses were not considered since, in our case, both treatments received the same management practices except for the additional costs of irrigation. Therefore, gross incomes might indicate the sustainability of this practice in the medium term.

5. Sensory analysis

Sensory evaluation of wines was performed by ten judges, consisting of 7 males and 3 females, with experience in tasting Galician white wines. Panellists were between 30 and 62 years old. These individuals were oenologists and technicians either from EVEGA or from Galician commercial wineries. A scorecard including attributes for colour, aroma and

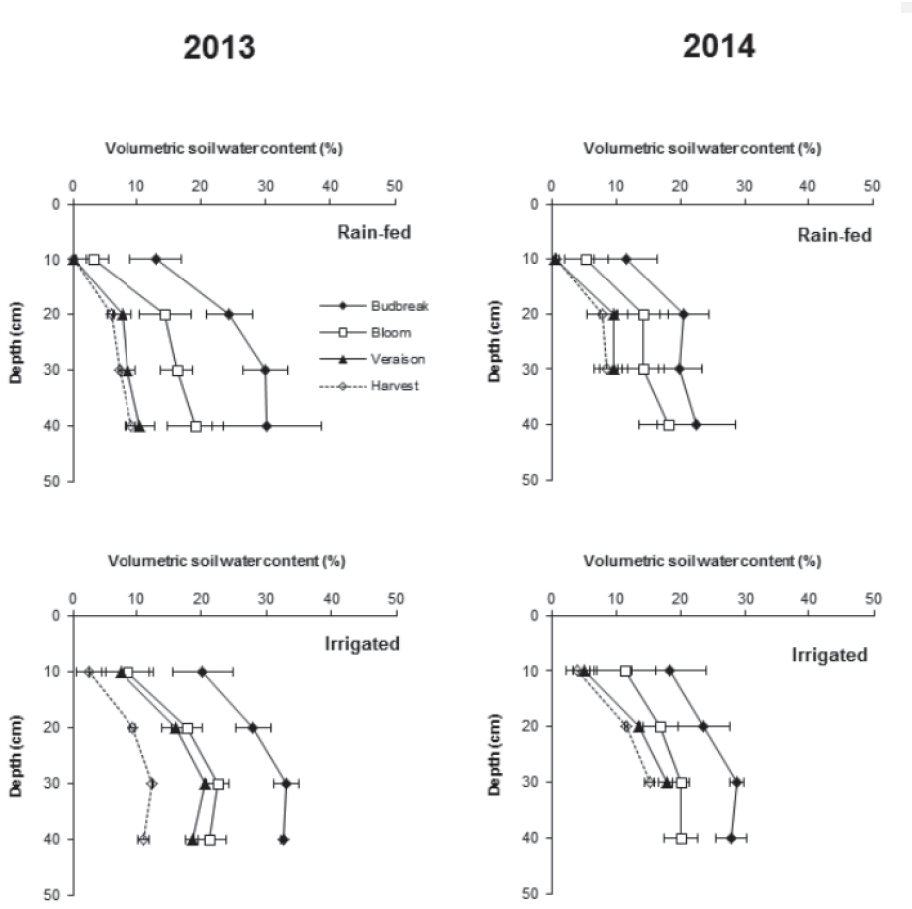


Figure 2 - Soil water content (% vol.) at four different stages of vine development over the 2013 and 2014 growing seasons of an Albariño vineyard under rain-fed and irrigation conditions. Values are treatment means ± standard errors.

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taste was used. The descriptors were scored from 0 (absence) to 9 (very intense). Each wine sample (30 mL) was served at 12 ºC in a standard wine glass and was coded in order to prevent tasters from knowing its origin. The tasting sessions were held on different days (April and May of each vintage) at the tasting room of EVEGA. A more comprehensive description of the tasting sessions and scorecard used can be found elsewhere (Trigo-Córdoba *et al.*, 2014).

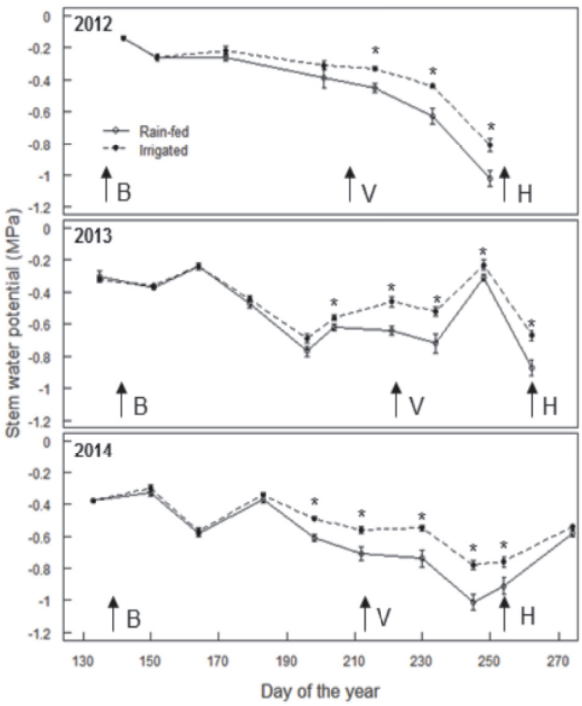


Figure 3 - Seasonal variation of midday stem water potential for Albariño cultivar under rain-fed and irrigation conditions.
Values are treatment means ± standard errors. Asterisks indicate significant differences between treatments at $p < 0.05$. Arrows indicate the beginning of vine developmental stages (B: bloom; V: veraison; H: harvest).

6. Statistical analysis

Two-way ANOVA was carried out for analysing the data (R software version 2.11.1; R Development Core Team, 2010). Factors considered were irrigation treatment, year and their interaction. Differences were considered significant when $p < 0.05$.

RESULTS

Soil water content on the topsoil was greatly affected by the rainfall regime of the corresponding year, causing an erratic behaviour of this variable. Deeper in the soil profile, soil water content was similar between treatments at bud-break and bloom (Figure 2). However, irrigation caused significant increases in soil water content down to a depth of 40 cm at veraison. At harvest, both treatments presented similar soil water contents at 10 and 20 cm depth, whereas at 30 and 40 cm, soil water content was slightly higher under the irrigation treatment (Figure 2).

Although 2012 was the wettest growing season, the lowest values of stem water potentials (–1 MPa) were recorded that year at harvest (Figure 3). The other years, stem water potentials reached –0.9 MPa. Significantly more negative stem water potential values were found for rain-fed vines from mid-July (day 200) till harvest (Figure 3), which occurred between 11th and 18th September depending on the year.

In 2013 and 2014, stomatal conductance values were high. Rain-fed vines presented a significantly lower stomatal conductance than those irrigated in mid-July (day 196), late August (day 234) and early

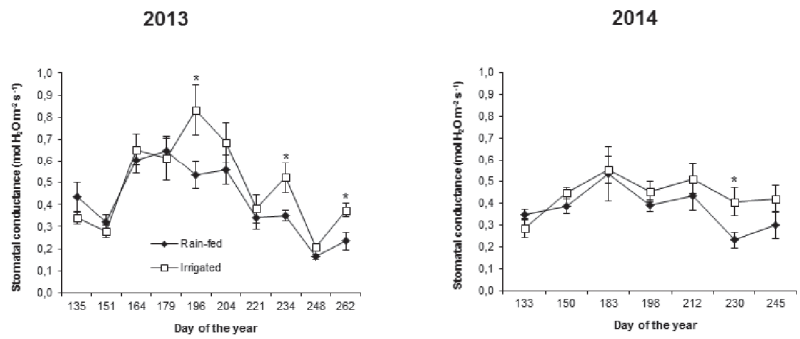


Figure 4 - Effect of irrigation on stomatal conductance during the 2013 and 2014 growing seasons for Albariño cultivar.
Bars indicate the standard error of the mean. Asterisks indicate significant differences ($p < 0.05$) for each date.

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September (day 262) in 2013 and mid-August in 2014 (day 230) (Figure 4).

Chlorophyll *a* fluorescence parameters at veraison (Table 1) showed significant differences between treatments. Effective quantum efficiency of PSII was higher for irrigated vines in both years. In addition, ETR was greater in irrigated vines in 2014. In contrast, the maximum quantum efficiency did not show significant differences between treatments. CCI values were significantly higher under the irrigation treatment for all the measurement dates (Figure 5).

The vintage effects on vine growth and yield components were highly significant (Table 2). In addition, no significant interactions between treatment and year were detected, except for the exposed leaf area. Exposed leaf area was significantly increased by irrigation as well as pruning weight, which increased by 11% on average for the three studied years (Table 2). For the entire study period, irrigation exerted significant effects on yield and cluster weight (Table 2). On average for the three studied seasons, irrigation increased yield by 11.6% and cluster weight by 11%. Other yield components such as cluster number per vine and berry weight did not significantly increase due to irrigation. Although no significant differences between treatments were detected, rain-fed vines tended to show greater water productivities (6-30%, depending on the year) in comparison with irrigated vines (Table 2). In contrast, the irrigation treatment provided greater gross incomes than the rain-fed treatment, mainly in the last two years of the experiment, when 10-15% increases were observed (11% on average for the three years). However, these increases were not significant (Table 2).

Vintage effects on must attributes were significant for tartaric and malic acid concentrations but not for total

Table 1 - Maximum (Fv/Fm) and effective (ΦPSII) quantum efficiency of photosystem II and apparent electron transport rate (ETR) in 'Albariño' grapevine attached leaves, subjected to rain-fed and irrigated conditions, determined at veraison.

Treatment	F_v/F_m	F_{PSII}	ETR
3 August 2012			
Rain-fed	0.77	0.34 a	109.77
Irrigated	0.77	0.45 b	103.32
	ns	*	ns
31 July 2014			
Rain-fed	0.87	0.34 a	95.00 a
Irrigated	0.89	0.45 b	131.81 b
	ns	*	*

Different letters in the column, for each date, indicate significant differences between treatments at $p < 0.05$. ns = not significant, * $p < 0.05$.

Table 2 - Exposed leaf area, pruning weight, yield components, water productivity and expected gross incomes of rain-fed and irrigated vines averaged for the three studied years (2012-2014).

Values are means ± standard error.

Parameter	Treatment		Year	Treatment	Year x Treatment
	Rain-fed	Irrigated			
External leaf area (m^2 m^{-2})	1.25 ± 0.04	1.35 ± 0.02	***	***	***
Pruning weight (kg $vine^{-1}$)	1.45 ± 0.06	1.61 ± 0.08	***	*	ns
Yield (kg $vine^{-1}$)	3.11 ± 0.20	3.63 ± 0.24	***	*	ns
Clusters per vine	41.40 ± 1.92	43.42 ± 1.99	***	ns	ns
Cluster weight (g)	73.63 ± 2.81	80.57 ± 2.98	***	*	ns
Berry weight (g)	1.16 ± 0.02	1.15 ± 0.02	*	ns	ns
Water productivity (kg m^{-3})	5.85 ± 0.88	5.01 ± 0.80	**	ns	ns
Gross incomes (€ ha^{-1})	15613.5 ± 1384.4	17322.9 ± 2105.4	**	ns	ns

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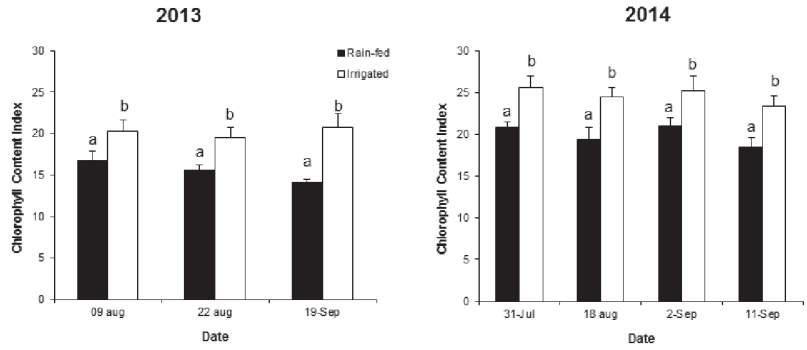


Figure 5 - Effect of irrigation on the chlorophyll content index during the 2013 and 2014 growing seasons for Albariño cultivar.
Bars indicate the standard error of the mean.
Different letters above bars indicate significant differences ($p < 0.05$) for each date.

soluble solids content, titratable acidity and pH (Table 3). Overall, musts from the irrigated treatment were more acidic and presented a greater concentration of malic acid. However, no significant differences between treatments were detected for total soluble solids content, pH and tartaric acid concentration (Table 3). In addition, no significant interactions between year and treatment were found for any of the must attributes.

Wine pH and titratable acidity were significantly affected by season (Table 4). Irrigation significantly increased wine acidity and tartaric acid concentrations; however, this treatment did not affect alcohol content, pH and malic acid concentrations on average for the three seasons studied (Table 4). No significant interactions between factors were detected for any of the considered wine attributes. At the sensory level, colour descriptors did not produce significant differences between treatments (data not shown). In contrast, aroma descriptors such as white fruit, terpenic, persistence and intensity were given higher marks in wines from the rain-fed treatment than those from the irrigated one (Figure 6a). Similarly, rain-fed wines obtained higher scores for mouth descriptors such as softness, balance, alcohol and body (Figure 6b).

DISCUSSION

Under our experimental conditions, the level of water stress experienced by non-irrigated vines was low, particularly in 2012 when rainfall over the growing season amounted to 313 mm. This fact explains the small differences between treatments in regards to yield. Nevertheless, midday stem water potential reached values of –1 MPa, which can be considered as mild or moderate water stress (van Leeuwen *et al.*, 2009), and were more negative for rain-fed than for irrigated vines. However, this moderate water stress occurred 2-3 weeks before harvest, which is rather positive for grape maturation. According to Ojeda (2008), midday stem water potential must be maintained around –0.9 MPa during berry maturation in order to obtain quality young wines, as those produced with Albariño.

The low level of water stress over the study period was caused by sufficient soil water availability and high relative humidity in the atmosphere (never lower than 45%); hence vines developed large canopies and presented an active transpiration. In fact, stomatal conductance values were higher than those reported for Mediterranean areas (e.g. Williams and Araujo, 2002; Intrigliolo and Castel, 2009), where vines are subjected to greater water restrictions. Nevertheless, Williams and Trout (2005) and Teszlák *et al.* (2013) found peak values of stomatal conductance greater than 0.8 mol H_2O m^{-2} s^{-1} in well-irrigated 'Thompson Seedless' and 'Riesling' vines, respectively, similar to those observed for Albariño in the current study.

Similarly, the low water stress conditions did not negatively affect vines at the photochemical level, and F_v/F_m was close to 0.8, the threshold for healthy terrestrial plants (Cavender-Bares and Bazzaz, 2004). However, a greater activity of the PSII and a higher electron transport rate were observed for irrigated vines. CCI confirmed the fluorescence readings and reflected a greater concentration of photosynthetic pigments in vines from the irrigation treatment, since CCI is directly correlated with chlorophyll concentration in leaves (Steele *et al.*, 2008).

Despite the low level of water stress in the rain-fed treatment, irrigation significantly increased vine

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Table 3 - Must attributes of rain-fed and irrigation treatments averaged for the three studied years (2012-2014).

Values are means ± standard error.

Attribute	Treatment		Year	Treatment	Year x Treatment
	Rain-fed	Irrigated			
Total soluble solids (ºBrix)	22.9 ± 0.1	22.4 ± 0.3	ns	ns	ns
Titratable acidity (g L^{-1} tartaric acid)	8.1 ± 0.1	8.7 ± 0.2	ns	*	ns
pH	3.08 ± 0.02	3.07 ± 0.03	ns	ns	ns
Tartaric acid (g L^{-1})	8.3 ± 0.3	8.7 ± 0.2	*	ns	ns
Malic acid (g L^{-1})	3.0 ± 0.2	3.7 ± 0.2	**	**	ns

** $p < 0.01$, * $p < 0.05$, ns = not significant.

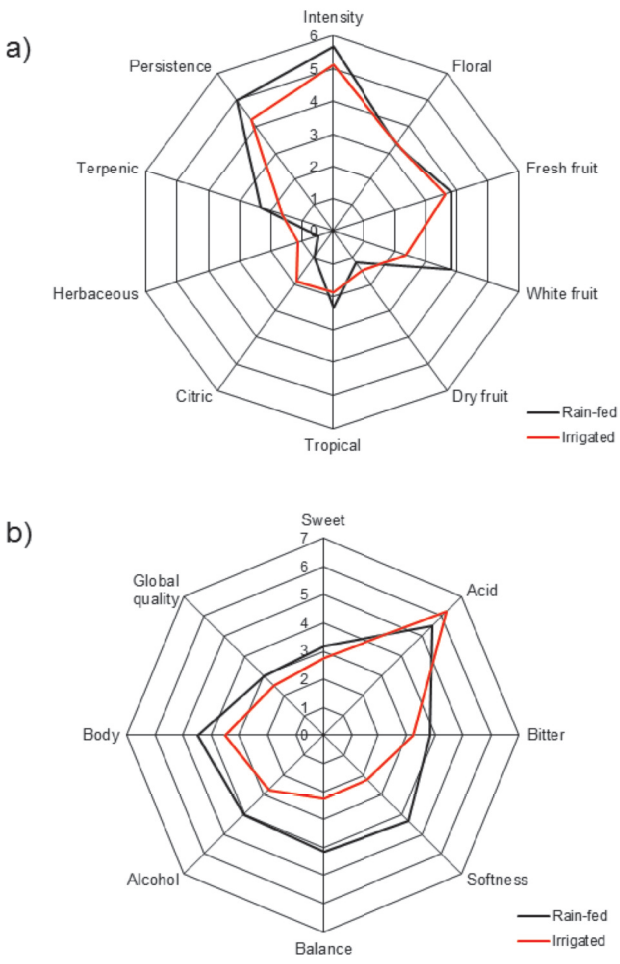


Figure 6 - Sensory profiles of 'Albariño' wines from the medians of the vintages 2012, 2013 and 2014, as a function of the irrigation treatment: a) aroma attributes; b) mouth attributes and global quality.

vigour (both exposed leaf area and pruning weight). In 2012, no differences were detected because there was no water stress before day 240 (27th August); however, in 2013 and 2014 a moderate stress was observed in the non-irrigated treatment, causing the reduction in pruning weight. In addition, yield increased with irrigation due to a significant increase in cluster weight. This finding agrees with previous reports on cool and humid climates (Reynolds *et al.*, 2007; Martínez *et al.*, 2016).

In accordance with the differences in yield and cluster weight, irrigation significantly modified must composition, and musts from the irrigated treatment were more acidic and had higher malic acid concentrations than those from the rain-fed treatment. Moreover, although not significant, musts from the irrigated vines tended to show lower total soluble solids concentrations. These results are consistent with previous reports on other cultivars (e.g. dos Santos *et al.*, 2003; Reynolds *et al.*, 2007; Intrigliolo and Castel, 2009).

Similarly to that observed in the musts, wine attributes such as titratable acidity and tartaric acid concentration were significantly increased by irrigation. In addition, there was a trend toward lower pH and alcohol content in wines from the irrigation treatment. These variations in wine attributes might be detected at the sensory level, as previously reported (Trigo-Córdoba *et al.*, 2014). In fact, aroma and mouth-feel descriptors were significantly altered by irrigation, and rain-fed wines received higher marks for relevant aspects such as softness, balance or aroma intensity, clearly indicating that agricultural practices may exert a significant effect on sensory perception of wines (García-Muñoz *et al.*, 2014).

In spite of the higher yield under irrigation, WP was greater in rain-fed vines, although these differences were not significant. As suggested by Cancela *et al.*

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Table 4 - Wine attributes of rain-fed and irrigation treatments averaged for the three studied years (2012-2014). Values are means ± standard deviations.

Attribute	Treatment		Year	Treatment	Year x Treatment
	Rain-fed	Irrigated			
Alcohol (% Vol.)	13.6 ± 0.2	13.3 ± 0.2	ns	ns	ns
Titratable acidity (g L^{-1} tartaric acid)	9.1 ± 0.2	9.6 ± 0.1	*	*	ns
PH	3.03 ± 0.03	2.98 ± 0.03	***	ns	ns
Tartaric acid (g L^{-1})	4.8 ± 0.2	5.3 ± 0.2	ns	*	ns
Malic acid (g L^{-1})	2.7 ± 0.1	2.7 ± 0.1	ns	ns	ns

*** $p < 0.001$, * $p < 0.05$, ns = not significant.

(2016), this may be explained by the fact that this index has been developed for Mediterranean climates, where summer rainfall is much lesser than that registered in an Atlantic climate such as the one of our study site. Moreover, the rainfall amount and distribution over the growing seasons studied caused rain-fed Albariño wines to be subjected to low levels of water stress, and as a consequence, rain-fed vines showed a reasonable yield when compared to irrigated vines, which caused the lack of differences in WP. From an economic point of view, irrigation seems not to be a viable practice for Albariño under the conditions of our trial, since gross incomes were not significantly increased and higher costs must be faced when using irrigation. From our data, and given the fact that management costs were the same for both treatments, except for irrigation, net revenues would be greater for the rain-fed approach due to lower production costs. In order to recover within 10 years the investment made on the drip irrigation systems (installation, power, maintenance and water), growers will need to get around 1300 €/ha more than under rain-fed conditions. In addition, the prices for grape yield used in the current study were those officially issued by the regional government in 2008 and nowadays the revenues are lower, although no official prices have been released. Therefore, it would be difficult for growers to obtain those extra 1300 €/ha under the current conditions. Besides, yield is regulated under the Galician DO, hence growers must not exceed a given threshold, usually 12500 kg/ha; therefore, irrigation will cause vineyard yield to surpass this upper threshold, leading to economic punishments.

In summary, yield was significantly increased and berry composition was affected (more acidic and lower soluble solids content) when using irrigation. Under the water scarcity scenario that the world is facing, our results indicated that irrigation in Albariño vineyards from a humid region is not necessary and, likely, not sustainable, confirming previous results obtained for other white cultivars (Trigo-Córdoba *et al.*, 2015). However, studies with other irrigation periods and amounts in other areas of Galicia may produce different results (Martínez *et al.*, 2016), as observed for other white varieties in cool-humid (Reynolds *et al.*, 2007) and Mediterranean climates (Basile *et al.*, 2012).

CONCLUSION

Albariño vines showed no water stress under the condition of this study, and even those under the rain-fed treatment remained in a comfortable situation, suggesting that water supplied by rainfall was sufficient for adequate plant functioning. Irrigation increased yield on average for the three seasons studied. However, must composition was affected by irrigation, causing higher concentrations of tartaric acid and titratable acidity. Wines from the irrigation treatment were more acidic than those of the rain-fed and obtained lower marks for relevant aroma and mouth-feel descriptors. Water productivity tended to be greater in rain-fed vines; although no significant differences between treatments were detected. As a consequence, gross incomes were not significantly increased by irrigation. The results obtained in this study provide useful information for saving water in agriculture, suggesting that irrigation is not a viable agricultural practice under the conditions of this trial.

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