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RESEARCH ARTICLE

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Impact of water stress and nutrition on *Vitis vinifera* cv. 'Albariño': Soil-plant water relationships, cumulative effects and productivity

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Abstract

The objective of the present study is to apply different systems of fertigation (rainfed, R; surface drip irrigation, DI, and subsurface drip irrigation, SDI) in *Vitis vinifera* (L.) cv. 'Albariño' to evaluate the cumulative effect of water stress (water stress integral) on yield parameters and to establish the relationship between indices and production. The study was conducted over four years (2010-2013) in a commercial vineyard (Galicia, NW Spain). The volumetric soil water content (θ) (with TDR) and predawn (ψ_p), midday (ψ_m) and stem (ψ_{stem}) leaf-water potential were determined with a water activity meter during the growing stages (flowering-harvest) from 2010-2013. The number of clusters, their weight and yield/vine were determined at harvest. Must composition was studied to evaluate nutrition treatments. Ψ_p is presented as the best indicator of the water status of the plant, and the sole use of θ is not recommended as a reference. The soil-plant water status variables were strongly correlated, especially between foliar variables ($0.91<R^2<0.98$), with θ presenting the lowest reliability ($0.28<R^2<0.81$). SDI was the treatment with the highest hydric comfort and greater yield/vine (6.1 kg) and weight per cluster (95.0 g), but lower elements concentration in must. The water stress integral showed that the veraison and harvest stages were very sensitive to water stress in vines. Linear relationships were established between $S\psi_p$ and W ($R^2=0.65$) and Y ($R^2=0.56$) at veraison. The water stress integral is presented as a useful working tool for vine growers because it allows the prediction of future yield at early phenological states.

Additional key words: fertigation; leaf-water potential; phenological stage; soil water content; water activity meter; water stress integral.

Abbreviations used: DI (surface drip irrigation), ET_o (reference evapotranspiration); I (irrigation); R^2 (coefficient of determination); R (rainfed); Ra (rainfall); SDI (subsurface drip irrigation); S_Ψ (water stress integral), WD (water deficit); Ψ_m (midday leaf-water potential); Ψ_p (predawn leaf-water potential); Ψ_{stem} (midday stem water potential); θ (soil moisture at 0.6 m).

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Introduction

The Spanish northwest is currently experiencing a climate change that has not only been manifested in changes to normal temperature and rainfall patterns but has also caused variations in extreme event patterns (Cruz *et al.*, 2009). Horacio & Díaz (2009) have shown that these changes may have positive effects at the viticultural level (advanced harvest), and some cultivars as 'Albariño' may be affected by increased temperatures, which is a limiting factor for the production or quality of wines that are in demand by the current market.

Irrigation water supplied to a vineyard is '*an essential tool for controlling yield and quality of the grape*' (Martínez *et al.,* 2007) within the framework of sustainable irrigation. Salón *et al.* (2005), Santesteban & Royo (2006), Baeza *et al.* (2007), Ferreyra *et al.* (2007) and Lissarrague *et al*. (2007), among others, have shown that grape production and quality vary according to the applied irrigation treatment. An efficient irrigation strategy should supplement the deficit and irregularity of rainfall to guarantee must production and quality.

The application of fertilisers through irrigation systems (fertigation) (Conradie & Myburgh, 2000), allows not only the optimization of scarce resources (water), but also rationalize the use of nutrients to reduce cultivation costs, pollution environment and avoid fertilizer losses. Salazar & Melgarejo (2005) have observed that the optimal use of nutrition in vineyard can stabilize yields and improve production and quality of grapes. Sharma *et al*. (2008) and Thomaj *et al*. (2012) underscored the adequacy of fertigation using drip irrigation, improving the uniformity of irrigation, production and quality of musts.

In this context, stress signals must be monitored continuously in real time to provide information on the crop's water status and physiological response to water-stress situations (García-Tejero *et al*., 2010). Studies performed in the last five years have evaluated the water status of Galician grapevine cultivars, with early publications contributed by Berrios (2010), Cancela *et al*. (2012), Islam & Berrios (2012) and Martínez *et al*. (2012a,b) and more recent studies reported by Fandiño *et al*. (2013), Martínez *et al.* (2013b), Mirás-Avalos *et al*. (2014), Cancela *et al.* (2015) and Trigo-Córdoba *et al*. (2015). These studies lack an evaluation of the cumulative effect of water stress on the plant, on productivity parameters, and on the different phenological stages of the cultivar.

Methods for assessing the water status of the vineyard include: i) soil water assessments, ii) water balance modelling and iii) physiological indicators (van Leeuwen *et al*., 2009). In the field, water status is evaluated through punctuated or continuous measurements of the volumetric content or water potential of the soil (Asenjo & Yuste, 2003). At the plant level, leaf-water stress indices have been quantified according to the plant's water potential at different times of the day, such as predawn or midday, or in different plant parts, such as the leaf or stem. Leaf-water potential is easily determined using a Scholander pressure chamber (Scholander *et al.*, 1965) or, more recently, with a water activity meter (Martínez *et al*., 2011a, 2012a and 2013b). The integration of long-term leaf-water potential values into a single value was introduced by Myers (1988). He established a methodology for assessing the cumulative effect of water deficit (WD) on the stress-intensity of crops through the 'water stress integral' (S_Ψ). The application of this method to *Vitis vinifera* (L.) evaluates the effects of water stress on production and the relationship of water stress to vine-water status indicators (Ginestar *et al*., 1998a,b; De Souza *et al*., 2005; Salón *et al*., 2005; De la Hera *et al*., 2007; Martínez *et al*., 2007, Dayer *et al*., 2012). Baeza *et al.* (2007) consider that S_Ψ provides a faster method and may be a good parameter for explaining the long-term response of vines to water deficit with relation to yield or must composition.

The objective of this research was to apply different systems of fertigation in *Vitis vinifera* (L.) cv. 'Albariño' over four seasons with the following goals: i) to determine and establish the relationship between indices of plant-soil water status, and ii) to evaluate the cumulative effect of water stress (water stress integral) on yield and must parameters. In this research, the critical phenological stages in which the crop is most sensitive to water stress are established to determine the effects of fertigation systems in Galicia (NW Spain).

Material and methods

Experimental conditions

This research was conducted over four years (2010-2013) in a commercial *Vitis vinifera* (L.) cv. 'Albariño' vineyard in the wine-growing sub-region of '*Condado do Tea*' of the *Rías Baixas* Designation of Origin (Pontevedra, NW Spain) (42°3.5´N, 8°32.2´W). The study plot consisted of ten terraces with different surfaces, including two intermediate terraces with four and five rows of vines. The vines were approximately 25 years old and grafted on rootstock '19617C'. The planting framework was 1.5 m between vines and 3 m between rows, and the orientation was N-S. The vines were trained on a semi-trellised system with four wires and spur-prunes on a guyot system. The average crop height was 2 m, and the roots grew predominantly in the layer that was 0.6 m below the surface.

Agrometeorological data were obtained from a nearby station maintained by the Consellería de Medio Rural, Xunta de Galicia (Entenza-Salceda de Caselas, 42º 7.1'N, 8º 56.1'W and 50 m a.s.l.). Rainfall (Ra) and cumulative reference evapotranspiration (ET_o) for the period from March to September in 2010-2013 are shown in Figure 1. The ET_o was calculated with the Penman-Monteith equation, using the methodology proposed by Allen *et al.* (1998) for limited weather data wherein the actual vapour pressure is derived from the daily minimum temperature and solar radiation, which is calculated from the daily maximum and minimum temperatures. The study area is characterised by mild temperatures and abundant rainfall that is concentrated in autumn and spring, which corresponds to the Köppen-Geiger classification Cfb (Peel *et al.*, 2007).

Soils from the experimental site were sandy-loam Cambisols (FAO, 1998) with 25.1% sand, 65.4% silt and 9.5% clay. The percentage of organic material was 3.9%. The soil moisture at field capacity was 0.294 m^3/m^3, and the permanent wilting point was 0.106 m^3/m^3, with the total available water to a depth of 0.6 m equal to 112.8 mm.

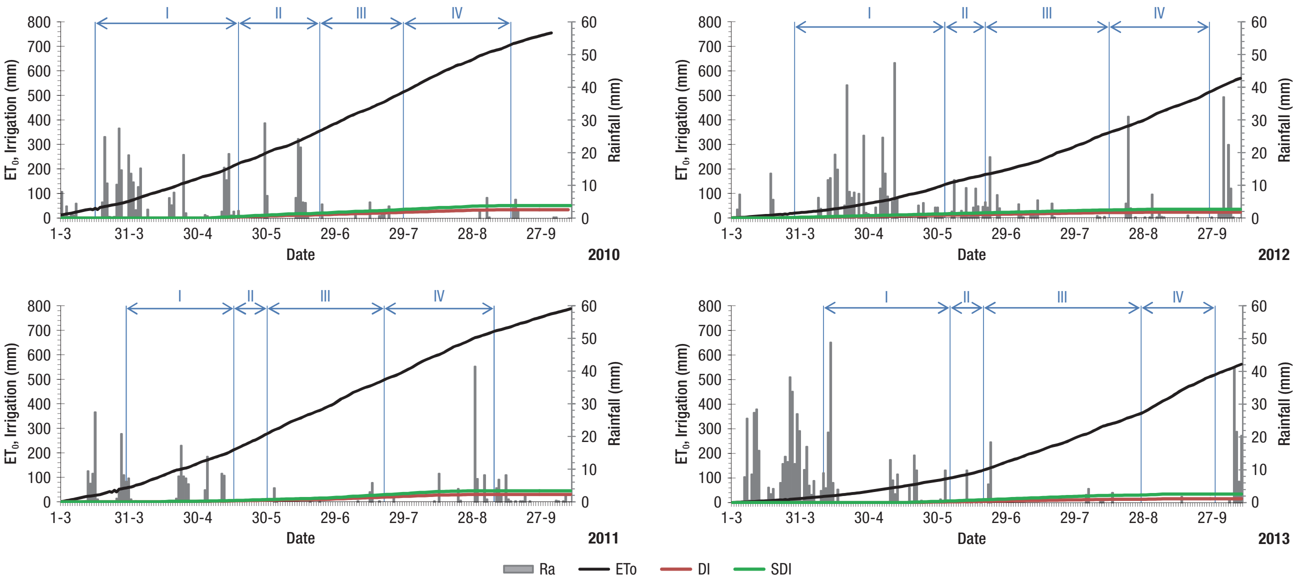

Figure 1. Irrigations (DI, SDI) and ET_o accumulated and rainfall from 2010 to 2013. Phenological stages: I: budburst-flowering, II: flowering-setting, III: setting-veraison, IV: veraison-harvest. Ra, rainfall; DI, surface drip irrigation; SDI, subsurface drip irrigation.

Experimental design and fertigation treatments

The experimental study included three fertigation treatments: rainfed (R); surface drip irrigation (DI), which dripped 2 L/h per plant from driplines located 30 cm above the ground; and subsurface drip irrigation (SDI), which used pressure compensating drippers (2 L/h) buried to 30 cm. Both the DI and SDI systems were also used to apply nutrients N, P, K, Mg and Ca (Table 1) at a rate of 0.44-0.66 mm/d, and these applications were scheduled for 1.5 h daily, five days per week from May 4 to August 31 of 2010, April 12 to August 18 of 2011, March 20 to August 22 of 2012, and May 13 to August 28 of 2013. The irrigation dose applied is that established and typically used by vine growers at the surrounding commercial vineyards in the study region. During the four years, a reduction of nutrients was defined by the winery, to reduce costs production; elements applied were lower than those applied by Howell & Conradie (2013), for cv. 'Bukettraube'. The starting irrigation is applied based on previous experience and weather conditions for that year. Irrigation is performed to support nutrient absorption by vines without attempting to meet the total water demand. In that context, this study evaluates the joint effect of water and nutrients (fertigation) on a commercial vineyard.

Table 1. Nutrient elements (kg/ha) applied to cv. 'Albariño' by fertigation. Years 2010 to 2013.

Year	N	P	K	Mg	Ca
2010	88.4	34.7	71.0	18.8	2.3
2011	55.3	7.3	38.7	17.6	15.8
2012	24.2	3.2	29.5	13.2	15.2
2013	14.0	2.2	15.5	6.9	11.4

For the plant measurements, six vines were randomly selected for the three treatments, with two vines per treatment, and with three repetitions/vine (n=6 per treatment). The R treatment vines were considered as control. All the selected vines exhibited a similar and adequate developmental and sanitary state.

Soil-plant measurements

The soil-plant measurements were performed every year from May to September, with the soil measurements beginning in March (data not shown). The number of days of simultaneous measurements for all variables (soil and plant) was 6 in 2010, 8 in 2011, 7 in 2012 and 5 in 2013.

The volumetric water content in the soil (θ) was measured discontinuously at a depth of 60 cm with six repetitions per treatment with a time-domain reflectometer (TDR) model TDR100 (Campbell Scientific, Logan, UT, USA), which operates in the field using the PCTDR software. Measurements were performed using a flexible reading head designed by Souto *et al.* (2008), with θ calculated using the equation by Topp *et al.* (1980). For this purpose, stainless steel rods were buried at the considered depth.

The leaf-water potential was measured with a water activity meter (Martínez *et al.*, 2011b), model WP4 (Decagon Device, Inc., Pullman, WA, USA), based on the chilled mirror dewpoint technique (Gee *et al.,* 1992; Martínez *et al*., 2011a) according to the methodology proposed by Martínez *et al*. (2013b). The technique for measuring leaf-water potential with a water activity meter implies the measurement of leaf disks with three repetitions (n=3) per plant, performed in sequential measurements by the measuring equipment, having previously sanded the leaves to eliminate the cuticle. This measure is applied to facilitate balancing the sample inside the measuring chamber and to shorten measuring time. Calibration is required between samples, following the methodology by Martínez & Cancela (2009), with 0.3 and 0.5 M KCl. Measurements were performed under three conditions: i) maximum water recharge, *i.e.*, predawn leaf-water potential (Ψ_p); ii) maximum daily stress, *i.e.*, midday leaf-water potential (Ψ_m); and iii) midday stem water potential (Ψ_{stem}). The leaf-water potential was determined using mature healthy leaves from the middle third of the branch representing similar developmental stages, with the leaves exposed directly to sunlight. Leaves were bagged before cutting at the petiole with a knife and were introduced to a low-temperature, ice-containing cooler with relative humidity close to 100%. They were transported to a lab under controlled conditions as quickly as possible (Ferreyra *et al*., 2007). To determine the Ψ_{stem}, leaves were covered with foil Zip Seal bags (PMS Instrument Company, Albany, OR, USA) 2 h prior to the measurement (Williams & Araujo, 2002). Ψ_m and Ψ_{stem} were determined during the four years of study, whereas Ψ_p was only determined for 3 years (2010-2012). The measurement times (local time) for each variable are as follows: 5:00-7:00 h for Ψ_p, 11:00-13.00 h for Ψ_m, and 13:00-15.00 h for Ψ_{stem}.

Phenological stages were determined over four years according to Baggiolini (1952). The measurement periods for the four variables corresponded to the phenological stages of setting to harvest in 2010 and from flowering to harvest in the remaining years.

Productivity and must parameters

The principal productivity parameters were quantified at harvest by determining the number of clusters/vine and the yield/vine by weighing the vine fruits (kg/vine) for the three treatments. The weight of the clusters was determined by dividing the yield/vine by the number of clusters/vine. The number of plants included in the trial was 17 healthy vines per treatment, and the number always represented 25% of the total plants under each treatment in the study plot.

The influence of fertigation on must composition was also evaluated. The berries of three vines per treatment were crushed, and the concentrations of Ca, Cu, Mg, Mn, Zn and K were determined from a must sample using ICP-OES, after a dry digestion-incineration process.

Soil-plant water stress integral

The duration and intensity of the water stress was determined by calculating the water stress integral (S_Ψ), which is defined by Myers (1988) as the sum of the water potential during the period of interest (Eq. [1]):

$$S_\Psi = \left| \sum_{i=0}^{i=t} \left(\Psi(i, i+1-c) \right) n \right| \qquad [1]$$

where Ψi,i+1 is the average water potential (Ψ) for the interval (i,i+1); c is the maximum value of Ψ during the entire stage; and n is the number of days of the treatment period. The values of both Ψ and c are negative and thermodynamically correct; however, the value of the water stress integral is expressed in absolute values for convenience. When calculating S_Ψ, Myers (1988) assumed that the stress reflected in the value of Ψ causes a reduction in the growth rate, with lower potential values causing a maximum reduction in growth.

With respect to soil, the integral was determined according to the values obtained with TDR relative to θ, not to the water potential. For the plant measurements, different leaf-water potentials were used. The interpretation of the soil water stress integral ($S_{\Psi\theta}$) differs with respect to the leaf-water measurements because it is not a suction force, which is assumed when calculating the potential, but rather volumetric water content. Therefore, increased integral values for each period indicate that greater water content is available for the plant during this period, which translates to less cumulative stress.

In both cases, the values are calculated according to the different phenological stages (Baggiolini, 1952) for each stage, from budbreak to harvest, and four different periods (Fig. 1), and they are named by the final phenological phase.

Statistical analysis

The different treatments and variables were statistically analysed with an analysis of variance (ANOVA and MANOVA, SPSS statistical package, SPSS, Chicago, IL, USA), and the mean separation was performed with Tukey's test ($p<0.01$, $p<0.05$, $p<0.001$). A linear regression was also performed among the leaf-water potential, soil moisture, water stress integrals and production parameters ($p<0.01$).

Results

Phenological stages of vineyard and environmental conditions

During the growing stage, which extends from budbreak to harvest, there was an irregular distribution of rainfall in phenological stages III and IV (Fig. 1), corresponding to the periods from setting to veraison and from veraison to harvest, respectively. During 2011, the lowest cumulative precipitation was recorded (295 mm); it was mainly concentrated between March and May and accompanied the highest ET_o demand (788 mm accumulated). These values translate to the driest year of the period studied, with a water deficit ($WD=ET_o$-Ra-I) of 413-458 mm (Table 2). In contrast, in 2013, the highest precipitation was recorded (654 mm accumulated), although it was concentrated during the phenological states before flowering. That year coincided with the lowest irrigation by vine growers: 35 mm in SDI and 15 in DI (Fig. 1). For the phenological states studied (flowering to harvest), the most humid year was 2011, with cumulative precipitation of 558 mm and ET_o of 569 mm (Fig. 1). For that year, the water deficit was 43-76 mm, depending on treatment (Table 2).

The months with the greatest ET_o demand were June to August 2010 (125-143 mm/month) and May to August 2011, 2012 and 2013 (133-139 mm/month, 104-129 mm/month and 108-143 mm/month, respectively).

During all growing seasons (2010-2013), the cumulative ET_o was greater than the rainfall; thus, cv. 'Albariño' had a higher climatic water deficit. Although irrigation doses are small compared to ET_o (Fig. 1) –its only goal is to aid nutrient absorption– a difference is observed between the water deficit values sustained by R vines relative to fertigated plants: the R treatment showed a WD of 77 mm in 2012 (wet year) and 457 m in 2011 (dry year). In the fertigation treatments, the WD was lower: between 54 and 428 mm in the DI and 43 and 413 mm in the SDI.

The amount of support irrigation per treatment can be seen in Fig. 1, showing similar values in the four years studied: between 15.4 (in 2013) and 52.4 mm (in 2010) in DI and between 34.6 and 50.8 mm in the same years in SDI. However, despite the water added to the soil by the joint effect of rainfall and fertigation, the evolution of the soil water content determined with TDR (Fig. 2) shows progressive water loss, thus indicating that water addition cannot compensate for water loss due to evapotranspiration.

The distribution of water deficit over the different phenological stages is shown in Table 2. The period between budburst and flowering from 2010 to 2012 is the only period in which all treatments show hydric comfort. During the remaining years and periods, water deficit occurred, particularly from setting to veraison (except in 2010, when water deficit was higher from veraison to harvest), which coincided with increased ET_o demand but not Ra. For our climatic conditions, minor changes were observed in relation to harvest date, with an early harvest on August 29 in 2011 and a late harvest on September 19 in 2013 (Fig. 1).

Changes in soil-plant measurements during the growing season

During all phenological stages, significant differences were detected among treatments in all soil-plant parameters (Fig. 2). According to ET_o and rainfall scarcity from setting to veraison and veraison to harvest (Fig. 1), the values of θ showed a progressive loss of water at 60 cm, which is the depth that corresponds to

Table 2. Water deficit in cv. 'Albariño'. Years 2010 to 2013.

Year		Budburst-Flowering	Flowering-Setting	Setting-Veraison	Veraison-Harvest	Total (March-Sept.)
2010	R	-95.5	33.1	137.4	197.7	272.7
	DI	-99.9	24.3	127.3	187.1	238.8
	SDI	-102.1	19.9	122.2	181.9	221.9
2011	R	61.9	66.1	204.7	125.1	457.8
	DI	58.0	63.5	191.7	114.7	427.9
	SDI	56.5	62.2	185.2	109.5	413.4
2012	R	-115.1	13.2	161.4	16.9	76.4
	DI	-125.2	10.3	153.5	15.1	53.7
	SDI	-130.3	8.9	149.9	14.3	42.8
2013	R	11.8	39.8	262.5	114.5	428.6
	DI	8.7	37.6	254.0	112.9	413.2
	SDI	4.8	34.8	243.4	111.0	394.0

All parameters in mm. Water deficit: $WD=ET_o - Ra - I$. R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation.

the bulk of the vine roots and location of the TDR measuring rods (Fig. 2). These results show the effect of climatic water deficit in the soil and the minimal effect of the fertigation doses applied by local vine growers. Significant differences were observed in the four years −especially in 2010 (p<0.001)− among the three treatments, with greater average annual values for SDI at 0.15-0.20 m^3/m^3 and similar values in the R treatment. Lower θ values on all measurement days were achieved in the DI treatment, with values of 0.10-0.15 m^3/m^3. In all treatments, the lower values of θ were obtained at veraison, with values close to the permanent wilting point in certain cases. The lack of significant differences in flowering during 2011 is noteworthy (Fig. 2).

The evolution of ψ_p, ψ_m and ψ_{stem} showed the same trend as θ (Fig. 2), but in this case, rainfed vines (R) showed lower hydric comfort compared to fertigated vines, even when the volumetric water content in the soil was similar to SDI. All leaf indices showed significant differences among the treatments for all years, although with different probability values (p<0.01 to p<0.001). ψ_p can be identified as the best indicator of plant water status (p<0.001), compared to ψ_m and ψ_{stem}, whose significance levels decrease at veraison (Fig. 2).

Based on the plant measurements, 2012 was the most hydrated year, followed by 2013, 2011 and 2010. Changes in the plant stages in relation to the water deficit according to year are notable (highest in 2011 and lowest in 2012); these changes were caused by the vines' varying water use (Table 2). During the year with the highest water deficit at the soil-plant level (2010), the ψ_p measurements showed a range of averages values for all stages, from -1.38 MPa to -2.17 MPa in the R treatment, with similar values in the DI treatment (Fig. 2). The average SDI values ranged from -1.24 to -1.88 MPa, showing that the vines in this treatment had the most effective nocturnal water recovery. For ψ_m, extreme values of -2.53 MPa, -2.37 MPa, and -2.17 were obtained in the R, DI and SDI treatments, respectively, with intermediate values obtained for ψ_{stem} for all treatments. During the wet year (2012), the extreme values were lower with respect to 2010, with ψ_p reductions of 29.4%, 28.3% and 30.5% in the SDI, R, and DI treatments, respectively. These percentages decreased relative to ψ_m in 2012, with the SDI treatment showing a reduction of 24.4% and the R and DI treatments showing reductions of 25.3% compared with the values in 2010 (Fig. 2). The R-treatment vines were less hydrated; with increasing moisture, their hydration levels appeared less affected under both predawn and midday conditions compared with the irrigated vines. However, over the four studied years, the SDI treatment

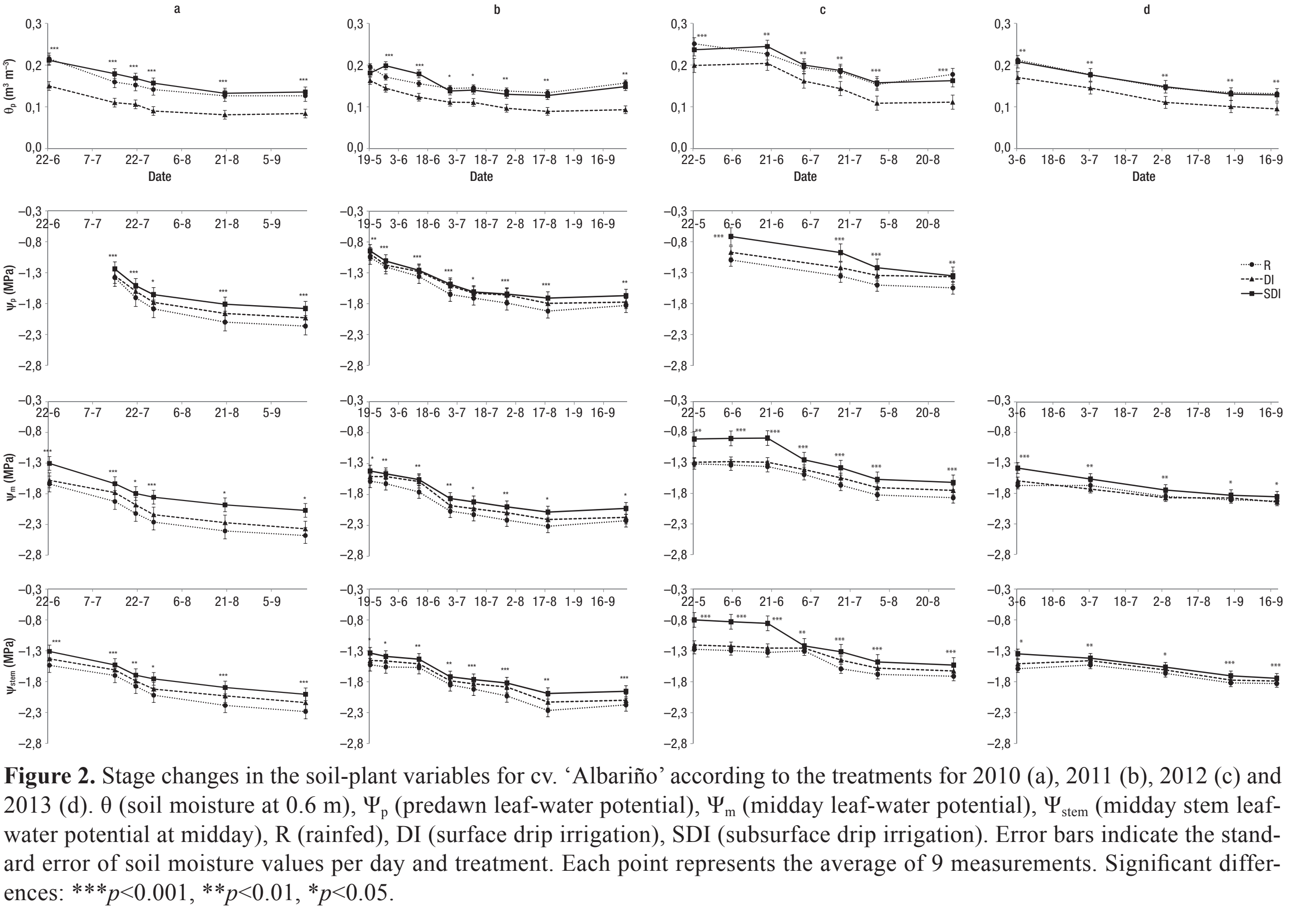

Figure 2. Stage changes in the soil-plant variables for cv. 'Albariño' according to the treatments for 2010 (a), 2011 (b), 2012 (c) and 2013 (d). θ (soil moisture at 0.6 m), Ψ_p (predawn leaf-water potential), Ψ_m (midday leaf-water potential), Ψ_{stem} (midday stem leaf-water potential at midday), R (rainfed), DI (surface drip irrigation), SDI (subsurface drip irrigation). Error bars indicate the standard error of soil moisture values per day and treatment. Each point represents the average of 9 measurements. Significant differences: ***p<0.001, **p<0.01, *p<0.05.

presented the lowest average differences between ψ_p and ψ_m at 0.15 MPa in 2010, 0.36 MPa in 2011 and 0.16 MPa in 2013; thus, these vines showed the lowest degree of fluctuation in leaf-water potential throughout the day between the maximum water demand (midday) and maximum water recharge (predawn).

Relationship between soil and plant measurements

The linear regressions and relationships between variables used to estimate the water status in cv. 'Albariño' were generally well correlated when all measurements were analysed as a whole with no distinctions between treatments (Table 3). The indicator variables of leaf-water status –ψ_p, ψ_m and ψ_{stem}– showed strong correlations and presented determination coefficients (R^2) between 0.92 and 0.96. When the three water potentials were related to θ, the relationship was weak (*e.g.*, ψ_m presented an R^2 of 0.54) or negligible or unreliable (*e.g.*, ψ_p and ψ_{stem} presented R^2 values of 0.28 and 0.48, respectively).

An independent analysis of all the variables in the R vines against the three treatments (R, DI and SDI) was performed, and the coefficients of determination ranged from 0.63 for ψ_{stem} *vs* θ and 0.95 for ψ_m *vs*. ψ_{stem}, which indicated a high degree of reliability for the estimates with the equations shown in Table 2. In the vines under DI fertigation, strong correlations were obtained ($0.76<R^2<0.94$). In the SDI treatment, none of the equations provided a reliable estimate of ψ_p based on the values of θ (R^2=0.41).

Soil-plant water stress integrals

The water stress integrals calculated for each of the leaf-water status variables ($S_{\Psi p}$, $S_{\Psi m}$ and $S_{\Psi stem}$) showed that for the four studied years, an increase in stress accumulation occurred, especially at the veraison and harvest stages (Table 4), coinciding with the periods of least rain and lowest soil water content (Figs. 1 & 2). For $S_{\Psi p}$, only the period until harvest (veraison-harvest) exhibited significant differences ($p<0.05$) among the

Table 3. Regression equations between the methods of measuring water status in the cv. 'Albariño' grapevines. Years 2010 to 2013.

Treatment[1]	Parameter[2]		Regression equation	R^2[*]
	Dependent	Independent		
R+DI+SDI	Ψ_p	θ	$\Psi_p=4.84\ \theta - 2.21$	0.28
	Ψ_m	θ	$\Psi_m=5.84\ \theta - 2.67$	0.54
	Ψ_{stem}	θ	$\Psi_{stem}=5.05\ \theta - 2.42$	0.48
	Ψ_p	Ψ_m	$\Psi_p=0.95\ \Psi_m + 0.27$	0.93
	Ψ_p	Ψ_{stem}	$\Psi_p=1.05\ \Psi_{stem} + 0.32$	0.92
	Ψ_m	Ψ_{stem}	$\Psi_m=1.08\ \Psi_m + 0.01$	0.96
R	Ψ_p	θ	$\Psi_p=11.77\ \theta - 3.43$	0.68
	Ψ_m	θ	$\Psi_m=7.66\ \theta - 3.16$	0.70
	Ψ_{stem}	θ	$\Psi_{stem}=6.56\ \theta - 2.84$	0.63
	Ψ_p	Ψ_m	$\Psi_p=1.00\Psi_m + 0.40$	0.93
	Ψ_p	Ψ_{stem}	$\Psi_p=0.42\Psi_{stem} + 1.10$	0.91
	Ψ_m	Ψ_{stem}	$\Psi_m=1.09\Psi_m + 0.02$	0.95
DI	Ψ_p	θ	$\Psi_p=10.34\theta - 2.66$	0.81
	Ψ_m	θ	$\Psi_m=7.27\ \theta - 2.70$	0.81
	Ψ_{stem}	θ	$\Psi_{stem}=6.56\theta - 2.47$	0.76
	Ψ_p	Ψ_m	$\Psi_p=0.98\ \Psi_m + 0.34$	0.93
	Ψ_p	Ψ_{stem}	$\Psi_p=1.07\ \Psi_{stem} + 0.38$	0.93
	Ψ_m	Ψ_{stem}	$\Psi_m=1.05\ \Psi_m - 0.05$	0.94
SDI	Ψ_p	θ	$\Psi_p=5.53\ \theta - 2.31$	0.41
	Ψ_m	θ	$\Psi_m=6.70\ \theta - 2.77$	0.71
	Ψ_{stem}	θ	$\Psi_{stem}=5.99\ \theta - 2.55$	0.64
	Ψ_p	Ψ_m	$\Psi_p=1.00\ \Psi_m + 0.32$	0.92
	Ψ_p	Ψ_{stem}	$\Psi_p=1.05\ \Psi_{stem} + 0.30$	0.93
	Ψ_m	Ψ_{stem}	$\Psi_m=1.05\ \Psi_m + 0.02$	0.98

[1] R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation. [2] Ψ_p, predawn leaf-water potential [MPa]; Ψ_m, midday leaf-water potential [MPa]; Ψ_{stem}, midday stem leaf-water potential at midday [MPa]; θ, soil moisture at 0.6 m [m^3/m^3]; [*]R^2, coefficient of determination; highly significant $p\leq0.01$.

Table 4. Annual mean values of the water stress integral for cv. 'Albariño' according to the variable, period studied and treatment. Years 2010 to 2013.

Variable[1]	Treatment[2]	Phenological stage			
		Flowering	Setting	Veraison	Harvest
$S_{\Psi\theta}$ (m^3/m^3/period)	R	1.1 ± 0.1^a	1.0 ± 0.3^a	5.0 ± 3.7^a	3.2 ± 0.4^a
	DI	3.3 ± 0.7^b	1.9 ± 0.5^b	7.5 ± 5.0^a	5.3 ± 0.9^b
	SDI	1.7 ± 0.4^a	0.8 ± 0.4^a	5.2 ± 4.0^a	3.2 ± 0.1^a
$S_{\Psi p}$ (MPa/period) [3]	R	13.4 ± 10.5^a	8.3 ± 2.1^a	33.2 ± 20.1^a	44.0 ± 1.8^b
	DI	8.7 ± 7.5^a	6.9 ± 1.5^a	27.0 ± 14.9^a	39.6 ± 0.8^{ab}
	SDI	0.7 ± 0.6^a	4.5 ± 2.0^a	24.9 ± 15.6^a	33.7 ± 2.2^a
$S_{\Psi m}$ (MPa/period)	R	17.8 ± 6.7^b	8.2 ± 1.5^a	67.6 ± 17.2^a	34.1 ± 12.8^a
	DI	14.6 ± 7.3^{ab}	6.7 ± 2.4^a	53.1 ± 11.0^a	31.7 ± 10.3^a
	SDI	2.7 ± 1.8^a	4.7 ± 1.4^a	69.8 ± 18.0^a	24.0 ± 7.0^a
$S_{\Psi stem}$ (MPa/period)	R	18.3 ± 7.9^a	6.1 ± 3.0^a	37.2 ± 23.7^a	31.4 ± 12.7^a
	DI	14.6 ± 7.6^a	4.6 ± 3.5^a	33.0 ± 22.6^a	27.6 ± 11.2^a
	SDI	2.7 ± 1.4^a	4.7 ± 1.3^a	28.1 ± 20.8^a	22.8 ± 8.5^a

[1] $S_{\Psi\theta}$, soil water stress integral; $S_{\Psi p}$, predawn water stress integral; $S_{\Psi m}$, midday water stress integral; $S_{\Psi stem}$, stem water stress integral; [2] R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation. Standard deviations are shown for all water stress integrals (n=6). [3] Years 2010 to 2012. For each variable and phenological stage, values followed by the same letter in a column do not differ statistically according to Tukey's test ($p<0.05$).

treatments, with values ranging from 33.72 to 44.04 MPa depending on treatment, whereas the $S_{\Psi m}$ values ranged from 2.69 to 17.81 MPa, and the $S_{\Psi stem}$ values ranged from 2.71 to 18.32 MPa at the flowering stage.

At the edaphic level, the veraison and harvest stages presented greater amounts of accumulated water, especially in SDI ($S_{\Psi\theta} \approx 3.25$ to 5.22 m^3/m^3), with significant differences among the treatments only absent during veraison (Table 4).

Production parameters and must composition

For the period from 2010-2013, the vines subjected to SDI had a greater average yield (6.1 kg) and weight of clusters (95.0 g/vine) compared with the other treatments (Table 5). In R, the number of clusters/vine and cluster weight was lower (57.5 and 82.8 g, respectively), which produced an average yield per plant (4.9 kg) that was 20% less than that of the SDI treatment. The vines in the DI treatment produced a number of clusters higher than R treatment, which showed an intermediate result to the weight of clusters between R and SDI vines. Of the parameters that were evaluated and analysed, only the weight of clusters has showed significant differences, in 2011 and 2013 (0.057 and 0.064, respectively, Table 5). The effect of the year showed significant differences for the evaluated production and must composition parameters (Tables 5, 6).

During the years 2011 to 2013 the concentration of K and Ca showed no significant differences; however in 2013, must concentration showed significant differences to Mg (Table 6), with the higher values to SDI treatment. Multivariate analysis showed significant differences for Mg (0.002), with higher values in DI and SDI treatments, than in R treatment. The rest of elements studied (Cu, Mn and Zn) are highly dependent on fungicides treatments; since the products concentration were identical in all treatments; no significance differences were obtained (data not shown).

Relationships between the soil-plant water stress integral and productivity

In Table 7, significant relationships were observed for $S_{\Psi p}$ and the weight of the clusters (R^2=0.65) and $S_{\Psi p}$ and yield (R^2=0.56) in the veraison stage, whereas $S_{\Psi m}$ and $S_{\Psi stem}$ presented weak relationships with the weight of the clusters (R^2=0.46) at the setting stage.

An evaluation of the relationship with $S_{\Psi\theta}$ showed a slight relationship with the number of clusters (R^2=0.41) during the flowering stage.

Discussion

Changes in soil-plant measurements during the growing season

This paper shows that the variables and equipment used to determine the water status of a vineyard can

Table 5. Plant production parameters (N, number of clusters; W, cluster weight; Y, yield) for cv. 'Albariño' according to treatment and year (2010-2013). Mean values and standard deviations (in brackets) are presented.

Year	**Treatment**[1]			**Variance analysis (*p*-value)**			
	R	**DI**	**SDI**	**Treat./yr**	**Treat.**	**Year**	**Treat. × Year**
			N (nº/plant)				
2010	54.4 (32.7)	60.1 (29.6)	53.3 (33.3)	0.802	0.386	< 0.001	0.997
2011	65.1 (28.7)	72.4 (29.2)	67.5 (29.5)	0.763			
2012	43.5 (17.3)	51.4 (15.2)	44.5 (14.8)	0.295			
2013	67.1 (22.5)	69.5 (21.3)	70.2 (24.7)	0.916			
Average	57.5 (27.1)	63.3 (25.4)	58.9 (27.9)	0.418			
			W (g)				
2010	87.2 (40.0)	95.4 (40.0)	78.9 (35.8)	0.464	0.091	< 0.001	0.088
2011	108.7 (34.9)	113.6 (34.6)	134.1 (25.1)	0.057			
2012	45.6 (17.4)	49.4 (30.0)	45.5 (13.6)	0.766			
2013	89.9 (22.0)	104.7 (25.7)	121.3 (56.3)	0.064			
Average	82.8 (37.4)	90.8 (39.4)	95.0 (50.1)	0.245			
			Y (kg/plant)				
2010	4.61 (3.42)	5.38 (3.13)	4.65 (3.66)	0.759	0.085	< 0.001	0.665
2011	7.09 (3.92)	8.22 (3.78)	9.17 (4.28)	0.324			
2012	1.87 (0.75)	2.59 (1.63)	2.05 (0.92)	0.185			
2013	6.11 (2.88)	7.29 (3.00)	8.46 (4.62)	0.173			
Average	4.92 (3.54)	5.87 (3.64)	6.08 (4.62)	0.193			

[1] R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation. Standard deviations are shown for all parameters (n=17).

Table 6. Must composition for cv. 'Albariño' according to treatment and year (2011-2013). Mean values and standard deviations (in brackets) are presented.

Year	**Treatment**[1]			**Variance analysis (*p*-value)**			
	R	**DI**	**SDI**	**Treat./yr**	**Treat.**	**Year**	**Treat. × Year**
			K (mg/L)				
2011	1031.6 (134.0)	807.8 (126.2)	936.2 (102.3)	0.137	0.431	0.000	0.601
2012	1435.2 (130.3)	1411.8 (292.3)	1468.6 (118.8)	0.952			
2013	552.1 (52.1)	465.9 (59.3)	504.5 (46.3)	0.245			
Average	1004.0 (407.1)	909.9 (414.8)	990.2 (403.2)	0.000			
			Mg (mg/L)				
2011	56.8 (4.0)	55.5 (13.2)	64.6 (7.7)	0.388	0.002	0.000	0.241
2012	57.5 (5.0)	66.2 (7.6)	73.5 (9.0)	0.078			
2013	70.9 (3.7)	69.0 (7.4)	84.4 (20.8)	0.033			
Average	62.2 (7.9)	68.9 (15.8)	66.1 (6.8)	0.000			
			Ca (mg/L)				
2011	32.2 (9.8)	25.9 (1.3)	30.8 (1.3)	0.369	0.707	0.025	0.604
2012	35.2 (2.8)	38.1 (0.6)	37.7 (1.8)	0.290			
2013	39.5 (8.4)	35.8 (11.4)	34.3 (5.9)	0.769			
Average	35.9 (7.2)	32.2 (7.6)	33.9 (4.0)	0.175			

[1] R, rainfed; DI, surface drip irrigation; SDI, subsurface drip irrigation. Standard deviations are shown for all parameters (n=3).

provide information that is not always easy to interpret. Various criteria have been established to determine the degree of stress imposed on a vineyard according to the leaf-water potential, such the criteria developed by Deloire *et al.* (2004), Linares *et al.* (2007) and van Leeuwen *et al.* (2009). Although these criteria do not present the same ranges of stress, they established their classifications using an Scholander pressure chamber; therefore, these classifications cannot be directly applied when other equipment is used,

Table 7. Regression equations between the water stress integrals for each variable and productivity parameter in cv. 'Albariño'. Years 2010 to 2013.

Variable		**Phenological stage**	**Equation regression**	**R^2**[*]
Dependent[1]	**Independent**[2]			
W	$S_{\Psi p}$	Veraison	$W= -1.77\ S_{\Psi p} + 118.81$	0.65
Y	$S_{\Psi p}$	Veraison	$Y= -0.17\ S_{\Psi p} + 10.01$	0.56
W	$S_{\Psi m}$	Setting	$W= -9.55\ S_{\Psi m} + 133.11$	0.46
N	$S_{\Psi \theta}$	Flowering	$N= -12.79\ S_{\Psi \theta} + 97.37$	0.41

[1] W, cluster weight (g); Y, yield (kg); N, number of clusters. [2] $S_{\Psi p}$, predawn water stress integral (MPa/period); $S_{\Psi m}$, midday water stress integral (MPa/period); $S_{\Psi \theta}$, soil water stress integral (m^3/m^3/period). [*] R^2, coefficient of determination; highly significant, $p \leq 0.01$

e.g. the water activity meter that was used for this paper. Martínez *et al.* (2013b) performed the first and only existing calibration between both types of equipment and established an average difference of -0.43 MPa between water activity meter and Scholander pressure chamber measurements for each determination. Accordingly, van Leeuwen *et al.* (2009) used the most recent stress level classification as a reference and showed that in the dry year (2010), extreme values of Ψ_p, Ψ_m and Ψ_{stem} occurred in all treatments up to the harvest stage; moreover, these conditions were classified as a state of severe water deficit. For the wet year (2012), Ψ_p presented a severe water deficit in the three treatments, whereas Ψ_m presented a moderate-to-weakwater deficit in the extreme values observed in the SDI treatment, a moderate-to-severe water deficit in the extreme values observed in the DI treatment and a severe water deficit in the extreme values observed in the R treatment. An analysis of the climatic variables (Table 2) showed that the only periods without a water deficit were from budburst to flowering in 2010 and 2012, with θ values close to the field capactiy. Therefore, the application of van Leeuwen *et al.*'s (2009) classification adapted by Martínez *et al.* (2013b) is considered useful. However, although the degree of stress has been established, limited volume of total fertigation was applied in our trial, and the vineyards of Galicia traditionally have been dry; thus, native cultivars such as 'Albariño' have the ability to withstand dry conditions without compromising their production *a priori* (Table 5).

The use of different leaf-water status indices can verify the suitability of the different status indicators according to the conditions of the study, which is a factor that has been discussed by authors such as Choné *et al.* (2001) and Carbonneau *et al.* (2004). In this paper, the three leaf indicators show significant differences within each year; therefore, they are useful in the evaluation of the water status of a vineyard. These differences were more significant in 2012 for all indices measured. The occurrence of low water-deficit values during this year might have resulted in nocturnal rehydration that was sufficient to produce differences in the treatments; thus, the differences were not caused by water shortages resulting from insufficient rehydration, as shown by Ameglio *et al.* (1999).

In this paper, Ψ_p is the best indicator for the four years studied, with differences that primarily showed $p<0.001$. These results do not agree with studies by Mirás-Avalos *et al.* (2014), who argue that Ψ_p is not the best indicator for Galician grapevine cultivars such as 'Albariño', 'Godello' and 'Treixadura' because it does not detect differences between plants under rainfed and irrigation conditions. For cv. 'Albariño', Ψ_m also presented the most significant differences between treatments in 2012. Ψ_m can be used to determine the maximum water demand of a crop at a specific time and show the daily changes (Martínez *et al.*, 2013a). Studies by Girona *et al.* (2006) and Mirás-Avalos *et al.* (2014) note the utility of Ψ_m as both a parameter for irrigation scheduling and a good indicator of differences between treatments, a conclusion that agrees with the results of this study.

The studies of Choné *et al.*(2001), Yuste *et al.* (2004) and Mirás-Avalos *et al.* (2014) emphasise the usefulness of Ψ_{stem}, which is generally determined during midday conditions and does not present the same climatic dependency of Ψ_m (van Leeuwen *et al.*, 2009). In this paper, the usefulness of Ψ_{stem} is particularly supported by the period from 2010-12, with 2013 questioning its reliability from flowering to veraison ($p<0.05$).

The decreasing trend in the three leaf indices measured (Fig. 2) may be explained, according to Ferreyra *et al.* (2007), by the fact that, as time passes and vines grow, there is greater evaporation demand from the atmosphere, leaves become older, and soil water availability decreases overall. The latter can be seen in Fig. 2.

The volumetric water content of the soil shows significant differences among treatments, especially in 2010 and 2012, although the degree of soil moisture does not entirely conform to the degree of stress on the vines (Fig. 2) because spontaneous vegetation both competes for water resources in the vineyard (Fandiño *et al.*, 2012) and uses resources differently than do other vines. Similar values of volumetric water content between R and SDI could be explained by the proximity of the treatments to the slopes of the upper terraces, which may promote deep percolation to lower levels when high rainfall events occur. Conversely, the small effect of rainfall events on non-irrigated vines (R) may occur because as soil becomes drier, water conductivity decreases, which in turn may lead to the slow recovery of vine-water content when new events occur (Ferreyra *et al.*, 2007).

Caution must be taken when using θ as the only indicator of the water status of a vineyard, according to studies by Asenjo & Yuste (2003) and Mirás Avalos *et al.* (2013), who question the effect of the moisture profile of the first 60 cm of soil on plants' water status because plants may extract moisture from greater depths (Smart *et al.*, 2006). Authors such as Bravdo & Proebsting (1993) consider that neither the evaluation of the water status of a vineyard nor irrigation calendars should be based on the water content of the upper layers of soil with localised irrigation when the deeper layers are not depleted because percolation out of the profile and nutrient leaching may occur.

Relationships between soil and plant measurements

This is the first exhaustive four-year study on a Galician vine variety to compare the three standard methods for estimating vine-water status in the field (Ψ_p, Ψ_m and Ψ_{stem}), determined with a water activity meter and TDR measurements of soil water content. Although Ψ_p is considered to be in equilibrium with soil moisture, the linear relationship established between Ψ_p and θ only presented strong correlations in the DI and R treatments. Thus, Bravdo (2008) emphasises that the application of nutrients through localised irrigation can generate water gradients in the soil that hinder the relationship between both of these parameters, especially in the SDI treatment. Williams & Trout (2005) observe a small (polynomial) relationship between both variables (R^2=0.52) in cv. 'Thompson', which is consistent with the results of Centeno *et al.* (2010) in cv. 'Tempranillo' (R^2=0.43), which presented a linear relationship. In contrast Asenjo & Yuste (2003) did not observe a relationship with cv. 'Tempranillo'; however, Williams & Araujo (2002) did identify a good linear relationship with cv. 'Chardonnay' (R^2=0.69), and van Zyl (1987) showed a good linear relationship with cv. 'Colombar' (R^2=0.89).

Ψ_m presented a good fit with the established linear relationships, especially when each treatment was considered separately in relation to θ ($0.70<R^2<0.81$); these results are consistent with the reliable relationship established between both variables by Williams & Trout (2005) (R^2=0.94) and Cancela *et al.* (2015), who established potential relationships in Galician varieties –cv. 'Godello' ($0.74<R^2<0.90$) and cv. 'Mencía' ($0.78<R^2<0.94$)– with irrigation and/or location treatments. The relationships were less reliable in the case of Williams & Araujo (2002) (R^2=0.69) and Centeno *et al.* (2010) (R^2=0.50).

Our trial measurements showed a linear relation between Ψ_{stem} and θ, which presented a determination coefficient of $0.48<R^2<0.76$ according to the treatments, with the value improving when treatments were evaluated separately ($0.63<R^2<0.76$). Through individual treatment evaluations, Cancela *et al.* (2015) showed potential relationships and found coefficients of $0.65<R^2<0.90$ in cv. 'Godello'; these values were greater than those observed by Williams & Araujo (2002) (R^2=0.63; linear relationship) and less than those observed by Williams & Trout (2005) (R^2=0.90; polynomial relationship) in cv. 'Thompson Seedless'.

The relationships established among Ψ_p, Ψ_m and Ψ_{stem} are highly reliable and present R^2 values ranging from 0.91-0.98. Williams & Araujo (2002) also established good relationships among these parameters (Ψ_{stem} *vs* Ψ_p, R^2=0.85; Ψ_m *vs* Ψ_p, R^2=0.88; Ψ_m *vs* Ψ_{stem}, R^2=0.92).

Soil-plant water stress integral and relationships with productivity

S_Ψ is presented as a useful tool for differentiating among treatments for any of the variables studied (Table 4), which is consistent with the results of De Souza *et al.* (2005) in c*vs*. 'Moscatel' and 'Castelão' and Ginestar *et al.* (1998a,b) in cv. 'Shiraz'. Conversely, a study by De la Hera *et al.* (2007) did not identify significant differences between treatments in cv. 'Monastrell' with the use of the water stress integral. The cumulative effect of water stress in vines is especially important in cv. 'Albariño,' and under the conditions of this study, during the phenological stages of veraison and harvest, vine growers should retain particular control over the adequate water status of the vineyard because these are critical phenological stages.

The relationship established between the water stress integrals and productivity parameters (weight of clusters and yield) for the phenological period of veraison highlight the influence of plant water status during these period, during which berries achieve either greater or lesser weight depending on the irrigation treatment used; according to the studies of Girona *et al.* (2006), changes in weight entail an increase or decrease in the number of berries per cluster, weight of clusters and yield, especially for different irrigation doses (Lissarrague *et al.,* 2007). For cv. 'Merlot' subjected to different hydration levels, Shellie (2006) observed that berry size at veraison and berry weight and yield at harvest decreased under reduced irrigation doses. Baeza *et al.* (2007), in cv. 'Cabernet-Sauvignon' with three irrigation treatments, observed that berry weight was the main yield component affected by water availability, and $S_{\Psi p}$ was the most highly correlated to berry weight (R^2=0.81). For cv. 'Merlot' with four irrigation treatments, Chacón *et al.* (2009) highlights the importance of $S_{\Psi p}$ and its relationship with berry composition, the influence is manifested in sensory terms by significant variation of the colour and body of the wines. In 'Albariño', during veraison, 65% of cluster weight and 56% of yield may be explained by water stress accumulated during predawn, a phenomenon that this study considers to be the most significant indicator among all factors studied. In our study, the effect of the year showed significant differences for production parameters, that were evaluated (Table 5). Intrigliolo & Castel (2010) showed that vine yield and berry weight presented a significant effect of the year by treatment interaction, suggesting that the effect of the irrigation regime on these parameters was different among seasons.

For the SDI treatment, the weight of the clusters and yield showed higher values than other treatments (Table 5) and the lowest water deficit during both the veraison and harvest periods (Table 2). Therefore, regressions established between the water variables and productivity variables (weight of clusters and yield) assumed a greater importance during these periods. The relationship established at flowering for the variables number of clusters and $S_{\Psi\theta}$ highlights the importance of water availability on the initiation of floral buds, although varietal differences in relation to decreases of θ should be considered (Lissarrague *et al.*, 2007). This last relationship could be useful for predicting the harvest at the early stages of the crop. S_{Ψ} demonstrated an influence on the productivity parameters of the vine, which is consistent with the results of Salón *et al.* (2005) with cv. 'Bobal', Martínez *et al.* (2007) with cv.'Merlot' or Baeza *et al.* (2007) with cv.'Cabernet-Sauvignon'.

This study concludes that under working conditions, a combination of the leaf indicators studied (Ψ_p, Ψ_m, Ψ_{stem}) and volumetric water content (θ) enabled the identification of significant differences in the water status of a commercial cv.'Albariño' vineyard as a function of the irrigation system used. Vines with fertigation applied by subsurface drip irrigation (SDI) showed higher hydric comfort compared to the other treatments evaluated, but lower element concentration in must, despite fertigation (Tables 1 and 6). This last aspect agrees with Ciotta *et al.* (2015), who did not obtain significant differences between treatments in berry composition. The K content in cv. 'Bukettraube' must ranged between 1606 - 2593 mg/L (Howell & Conradie, 2013), which is somewhat higher than the observed for cv. 'Albariño' in the current study. Ca and Mg contents in cv. 'Albariño' must were similar to those observed for cv. 'Bukettraube' (Howell & Conradie, 2013).

Ψ_p appears to be the best indicator of the water status of vines, and the sole use of θ is not recommended as a reference of a vineyard's real water status. This is the first time that relationships among the three standard methods for determining water status in vineyard with water activity meter and soil water content with TDR have been established in Galician vines. The establishment of these relationships will facilitate and expedite the determination of these variables in future studies that aim to evaluate the water status of vineyards.

The cumulative effect of water stress (water stress integral), assessed for the first time in cv. 'Albariño', shows that phenological states of veraison and harvest are very sensitive to water stress in vines. The relationships established between the water stress integral and productive parameters enable confirmation of the importance of hydric level in vines at both predawn and veraison, as much on cluster weight as on vine yield. The water stress integral is presented as a useful working tool for vine growers to predict –from an early phenological stage (flowering)– the evolution of hydric conditions and characteristics of potential yield, which enables the determination of corrective measures to reduce negative effects at the most critical phenological stages. Irrigation treatments showed significance differences, exposed in water stress integral, however nutrition effects not showed differences in must composition, mainly due to the small quantities of elements applied to vines (Table 1). For this reason, fertilizer elements in vines are scarce and, consequently, the amount absorbed and accumulated in grapevine organs decreases, including in the must.

Future work should evaluate the cumulative effect of other variables, such as the osmotic potential and/or the joint effect of the parameters measured at leaf turgor pressure on the agronomic performance of the vineyards; such efforts could generate more efficient and sustainable management alternatives. These studies would also provide a better understanding of the crop's actual behaviour. Thus, commercial plantations would have the ability to implement irrigation and nutrient management to obtain improvements and produce improved health and water conditions for the crop, which would provide qualitative and quantitative improvements.

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