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ASSESSMENT OF MIDDAY STEM WATER POTENTIAL IN GRAPEVINES (cv. CABERNET SAUVIGNON) USING SPECTRAL REFLECTANCE INDICES

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Resumen

La medición del potencial hídrico de xilema al mediodía ha sido sugerida como una excelente herramienta para el monitoreo del estado hídrico en viñedos regados por goteo. Sin embargo, las aplicaciones prácticas de esta metodología están limitadas por su impracticabilidad y consumo de tiempo. Como una alternativa, se propone el uso de los índices espectrales, los cuales han sido reportados como un buen predictor del estado hídrico de las plantas en una forma no invasiva. El objetivo de este estudio fue identificar las relaciones entre el potencial hídrico de xilema al mediodía y cientos de índices espectrales en un viñedo regado por goteo creciendo en condiciones semiáridas. Tanto el potencial hídrico como la firma espectral fueron obtenidos al mediodía usando una cámara de presión (modelo 1000, PMS Instrument Co., Corvallis, Oregon, USA) y un espectroradiómetro portátil (modelo SVC HR-1024i, Spectra Vista Co., Poughkeepsie, New York, USA), respectivamente. Usando esta información, cientos de índices fueron calculados, basados en los espectros visible (VIS), infrarrojo cercano (NIR) e infrarrojo de onda corta (SWIR). Adicionalmente, un analisis de regreción lineal fue desarrollado para determinar la relación entre los índices espectrales y el potencial hídrico de xilema al mediodía. Los resultados indicaron que hubieron correlaciones lineales significativas entre el potencial y los índices, con valores de R^2 entre 0.02 y 0.48. El valor más alto de R^2 fue observado para la regresión lineal entre el potencial hídrico de xilema al medio día y el índice PRI2, usando valores de potencial desde -0.6 a -1.9 Mpa.

Abstract

The measurement of midday stem water potential (MSWP) have been suggested as an excellent tool for monitoring water status in drip-irrigated vineyards. However, practical application of this measurement is limited by its impracticality and time consuming. As an alternative, the use of spectral indices (SI) is proposed, which has been reported as a good predictor of plant water status in a non-invasive way. The aim of this study was to identify the relations between the MSWP and several SI in a drip-irrigated vineyard growing under semiarid conditions. Both MSWP and leaf reflectance were measured at midday using a pressure chamber (model 1000, PMS Instrument Co., Corvallis, Oregon, USA) and a portable spectroradiometer (model SVC HR-1024i, Spectra Vista Co., Poughkeepsie, New York, USA), respectively. Using this information, hundreds of indices were calculated based on visible (VIS), near-infrared (NIR) and shortwave infrared (SWIR) spectra. In addition, linear regression analysis were performed to determine the relationship between SI and MSWP. The results indicated that there were significant linear correlations between MSWP and SI with values of R^2 ranging between 0.02 and 0.48. The highest value of R^2 was observed for the linear regression between MSWP and PRI2 index, using values of MSWP from -0,6 to -1,9 MPa.

Keywords: Spectroradiometer, Midday stem water potential, Vineyard, Pressure chamber, Water stress, Spectral reflectance indices

INTRODUCTION

In the arid and semi-arid regions where grapevines are grown, rainfall is scarce during the growing season. Under this condition, irrigation mangement strategies are needed to improve water productivity and optimize grape yield and quality (Zúñiga et al., 2018). One of these strategies is the regulated deficit irrigation (RDI), which consists in reducing the water application during certain phenological stages that are less sensitive to water stress (Acevedo-Opazo et al., 2010; Chaves et al., 2010; Santesteban et al., 2011). To apply the RDI, it is indispensable to have irrigation tools for monitoring the irrigation scheduling and vine water status to avoid severe water stress in stages that could reduced significantly the yield and quality, due to a reduced carbon assimilation or pericarp cell volume expansion (Acevedo-Opazo et al., 2010; Cifre et al., 2005; Flexas et al., 2002; Keller, 2015; Medrano et al., 2002; Ojeda et al., 2001). For irrigation management, several methodologies have been used to monitor of the soil water content (tensiometers, watermark probes, neutron probes, or TDR equipment (Time Domain Reflectometry), actual evapotranspiration (ETa) and physological responses to water stress (stomatal conductance, water potential, among other). In viticulture, one of the most used tools is the water potential that measure the pressure of the sap inside the xylem through a pressure chamber (Rodríguez-Pérez et al., 2018; Williams et al., 2012). The water potential can be obtained through the midday leaf (ψ_{leaf}), midday stem (ψ_{stem}), and pre-dawn water potentials ($\psi_{pre\text{-}dawn}$) (Acevedo-Opazo et al., 2010; Choné et al., 2000, 2001; Girona et al., 2006).

Several reports have suggested the ψ_{stem} for irrigation scheduling because it presents a smaller variation between individual vine canopies compared to (ψ_{leaf}) (Rodríguez-Pérez et al., 2007). De Bei *et al.* (2011) mentioned that the ψ_{stem} is considered a more stable and integrative measure of the vine water status compared with the ψ_{leaf}. However, the measurement of ψ_{stem} is tedious, time-consuming, destructive and requires trained personnel (Acevedo-Opazo et al., 2008b, 2008a; Fang et al., 2017; González-Fernández et al., 2015; Gutiérrez et al., 2018; Rodríguez-Pérez et al., 2018; Romero et al., 2018) so it is not practical.

The alterations in the leaf water status, the photosynthetic pigment concentration, and the photosynthetic activity lead to changes in spectral reflectance properties. Thus, the spectral reflectance (SR) indices, consisting of non-contact measurement of the radiation reflected or emitted from the leaves have been suggested to estimate vine water status (Cozzolino, 2017; Mulla, 2013; Pôças et al., 2015, 2017; Pu, 2017; Rapaport et al., 2017). The spectroscopy emerges as an efficient, non-destructive and fast technique that can be applied to assess indirectly the plant water status (González-Fernández et al., 2015; Mariotto et al., 2013). Spectroradiometers measuring the reflectance between the wavelengths of the visible (VIS) up to the shortwave infrared (SWIR) are able of detecting small changes in the biochemistry of the leaves and have the potential to be applied in the estimation of the plant water status (Marino et al., 2014; Rapaport et al., 2015; Sun et al., 2014). Spectral reflectance has been measured for both canopy and leaves (Serrano et al., 2010), each having different advantages and disadvantages. Although the reflectance at canopy level has similar values to the leaf level, the first one is more complex. Usually, it is contaminated for variations in the lighting caused by the ground floor, the atmosphere, leaf orientation, leaf area, canopy architecture, and visualization geometry (Ma et al., 2019; Pu, 2017). Moreover, several gases present in the atmosphere contribute to generating absorption peaks in the solar radiation spectrum (VIS + NIR). Water vapor (H_2O) mainly affects wavelengths greater than 700 nm; ozone (O_3) significantly absorbs radiation between 550-650 nm, and oxygen (O_2) has a narrow but strong influence around 700 nm. While the concentration of O_2 remains constant over time, that of H_2O and O_3 vary according to time and place (Broge y Leblanc, 2000). About canopy architecture, it should be noted that a vine under water stress tends to have an erectophilic canopy (Palliotti et al., 2001). Pinter *et al.* (1985) mention that erectophilic canopies have lower reflectance in the VIS-NIR range than those planophiles and that reflectance of planophilic canopies is less sensitive to variations in the angle of the solar zenith than erectophilic canopies.

The leaf spectral is less variable, but it’s reflectance is altered by structural characteristics, as blade thickness, cuticle thickness, and pubescence. The light reflected directly from the surface of the leaf never enters the cells, so it is not influenced by pigments or water content. However, the one that does manage to enter follows a complicated path, due to dispersion and internal reflection (Sims y Gamon, 2002). Trichomes increase the reflectance in the VIS region (Rallo et al., 2014), while its effect in the NIR is less. Also, waxes increase the reflectance in the NIR, and thicker cuticles increase the reflectance of solar radiation (Slaton et al., 2001).

Water absorbs light energy throughout the entire spectrum, but in the NIR and SWIR regions , the maximum absorption peaks are found, specifically at 760, 970, 1200, 1450, 1930, 1940, 2500 and 2950 nm (Curran, 1989; Pasqualotto et al., 2018; Pôças et al., 2015). For these bands, the reflectance of the canopy, and the leaves decreases when the water content of the tissues increases (Rodríguez-Pérez et al., 2007). Carter (1991) and Eitel *et al.* (2006) point out that spectral absorption bands with high sensitivity to the leaf water content are from the SWIR region (from 1300 to 2500 nm). While Peñuelas et al. (1993, 1997) and Peñuelas y Filella (1998) found that the weakest water absorption band between 950-970 nm is also useful and defined an index as the ratio of the reflectance at 970 nm to 900 nm (R970 / R900). Other combinations of wavelengths sensitive to water (760, 970, 1450, and 1940 nm) have been used to generate other indices related to the water status of the plant and the availability of water in the soil. For example, De Bei et al. (2011) measured the spectral reflectance at leaf level on vines cv. Cabernet Sauvignon, Chardonnay, and Syrah. In that research, findings indicating that the most relevant water absorption peaks were found in the 970 and 1400–1450 nm regions, which allowed them to estimate the MSWP in vines.

When water is lost from the leaf tissue, absorption decreases, and the reflectance tends to increase in the range of 1300 to 2500 nm. However, it also increases in the range of 400 to 1300 nm (Carter, 1991). These wavelengths correspond to the first harmonic band of the excitation of the water O-H bond (Rodríguez-Pérez et al., 2018). There are also absorption bands at 970 and 760 nm, in addition to those at 2950, 1940 and 1450 nm, which also relate to the OH bonds of water (Peñuelas et al., 1993). In this regard, Kim *et al.* (2011) indicates that water stress in plants changes the reflectance pattern due to a drop in photosynthetic efficiency, which causes the reflectance to increase in the visible region of the spectrum and lower in the NIR bands (contrary to what was proposed by the previous authors).

This is how the most common spectral reflectance indices related to the water state make use of the near-infrared to mid-infrared bands, due to the strong absorption that water causes in these regions of the electromagnetic spectrum (Pôças et al., 2015).

One way to analyze the spectral signature is through the so-called spectral indices (SI) or vegetation indices (VI), which are based on the combination of reflectance values at different wavelengths (Table 1). The advantage of this approach is that they are easy to use and also normalize background effects on the target spectrum, reducing the noise generated by the atmosphere and ground (Pu, 2017; Rallo et al., 2014). Among the indices that have been contrasted with the water potential, Pôças *et al.* (2015) have observed that VARI, GI, NDGI, RGRI, and PRI, which integrate information in the visible spectrum only, correlate well with pre-dawn water potential, with r^2 values from 0.77 to 0.82. These indices are associated with the pigment content of the leaves, so they would be able to reflect processes indirectly associated with the water status of the plant (Cifre et al., 2005; Eitel et al., 2006; Pôças et al., 2015). Other authors, such as Sun *et al.* (2008), Suárez *et al.* (2009), Rallo *et al.* (2014), also suggest that the water potential of plants could be estimated indirectly through indices that include bands from the VIS region related to photosynthetic pigments, such as the Photochemical Reflectance Index (PRI) or the Chlorophyll Index (CI), since drought is a condition that severely affects the biophysical and biochemical properties of the leaves, subsequently influencing the spectral reflectance.

Table 1. Main indices found in the literature that have been related to water potential

Grapevine Cultivar	***Water Potential***	***Index***	***Equation***	***R^2***	***Reference***
Cabernet Sauvignon	ψ_{leaf}	MDWI	$(R_{860} - R_{1240})/(R_{860} + R_{2140})$	0.34	(Rapaport et al., 2015)
		WABI-1	$(R_{1490} - R_{531})/(R_{1490} + R_{531})$	0.72	
		WABI-2	$(R_{1500} - R_{538})/(R_{1500} + R_{538})$	0.89	
		WABI-3	$(R_{1485} - R_{550})/(R_{1485} + R_{550})$	0.61	
Chardonnay	$\psi_{predawn}$	SR	R_{900}/R_{680}	0.56	(Serrano et al., 2012)
		NPQI	$(R_{415} - R_{435})/(R_{415} + R_{435})$	0.28	
		TCARI/OSAVI	$(3*((R_{700}-R_{670})-0.2*(R_{700}-R_{550})*(R_{700}/R_{670})))/(1+0.16)*(R_{800}-R_{670})/(R_{800}+R_{670}+0.16)$	0.41	
Thompson Seedless	ψ_{leaf}	PRI_{norm}	$[(R_{570} - R_{531})/(R_{570} + R_{531})]/\{[(R_{800} - R_{670})/(R_{800} + R_{670})^{0.5}] \cdot (R_{700}/R_{670})\}$	0.82	(Zarco-tejada et al., 2013)
Cabernet Sauvignon	ψ_{stem}	WABI	$(R_{1500} - R_{531})/(R_{1500} + R_{531})$	0.92	(Rapaport et al., 2017)
Tempranillo	$\psi_{predawn}$	GI	R_{Green}/R_{Red}	0.81	(Pôças et al., 2015)
		PRI	$(R_{531} - R_{570})/(R_{531} + R_{570})$	0.82	
		TCARI	$3[(R_{700} - R_{670}) - 0.2(R_{700} - R_{550})(R_{700}/R_{670})]$	0.55	
		MCARI	$[(R_{700} - R_{670})-0.2(R_{700} - R_{550})](R_{700}/R_{670})$	0.61	
		WI	R_{700}/R_{970}	0.71	
		SIPI	$(R_{800} - R_{445})/(R_{800} - R_{680})$	0.64	
		OSAVI	$(R_{NIR} - R_{Red})/(R_{NIR} + R_{Red} + 0.16)$	0.56	
Pinot noir	ψ_{stem}	NDWI	$(R_{860} - R_{1240})/(R_{860} + R_{1240})$	0.32	(Rodríguez-Pérez et al., 2007)
		fWBI	$R_{900}/\min(R_{930-980})$	0.30	
		SRWI	R_{858}/R_{1240}	0.32	
Cabernet Sauvignon and Chardonnay	ψ_{stem}	GI	R_{554}/R_{677}	0.14	(Romero et al., 2018)
Chardonnay	$\psi_{predawn}$	NDVI	$(R_{900} - R_{680})/(R_{900} + R_{680})$	0.64	(Serrano et al., 2010)

Dobrowski *et al.* (2005) indicated that PRI is sensitive to rapid changes in the photosynthetic state of the plant, because when the plant is in water stress and the metabolic processes are diminished, the excess light that chlorophyll is unable to handle dissipates as heat thanks to the xanthophyll cycle, wich involves the conversion of the pigment violaxanthin into zeaxanthin and varies according to photosynthetic efficiency (Suárez et al., 2010). Medrano et al. (2002) mentions that because of heat dissipationd the values of chlorophyll flourescence (F_s) are lowered, which is highly correlated with the drop in stomatal conductance (gs) and it is this relationship that provides a method for remote sensing. PRI is able to sense this changes in xanthophyll cycle pigments, because it is suggested that wavelength of 531 nm is associated with the protection of the photosynthetic apparatus by the reaction of the xanthophyll cycle that dissipates excess light, while 570 nm are used as a reference, because in the short term it is not affected by stress events(Inoue et al., 2008).

The usefulness of the PRI index lies in his ability to detect the loss of the photosynthetic capacity of the plant due to water stress induced by water restriction (Sarlikioti et al., 2010; Stagakis et al., 2012).

Rapaport et al. (2015, 2017) has recently developed a SWIR-based index for water stress monitoring with good succes. It is call water balance index (WABI) and it responds simultaneously to changes in chlorophyll fluorescence (530-550 nm) and water content (1500 nm).

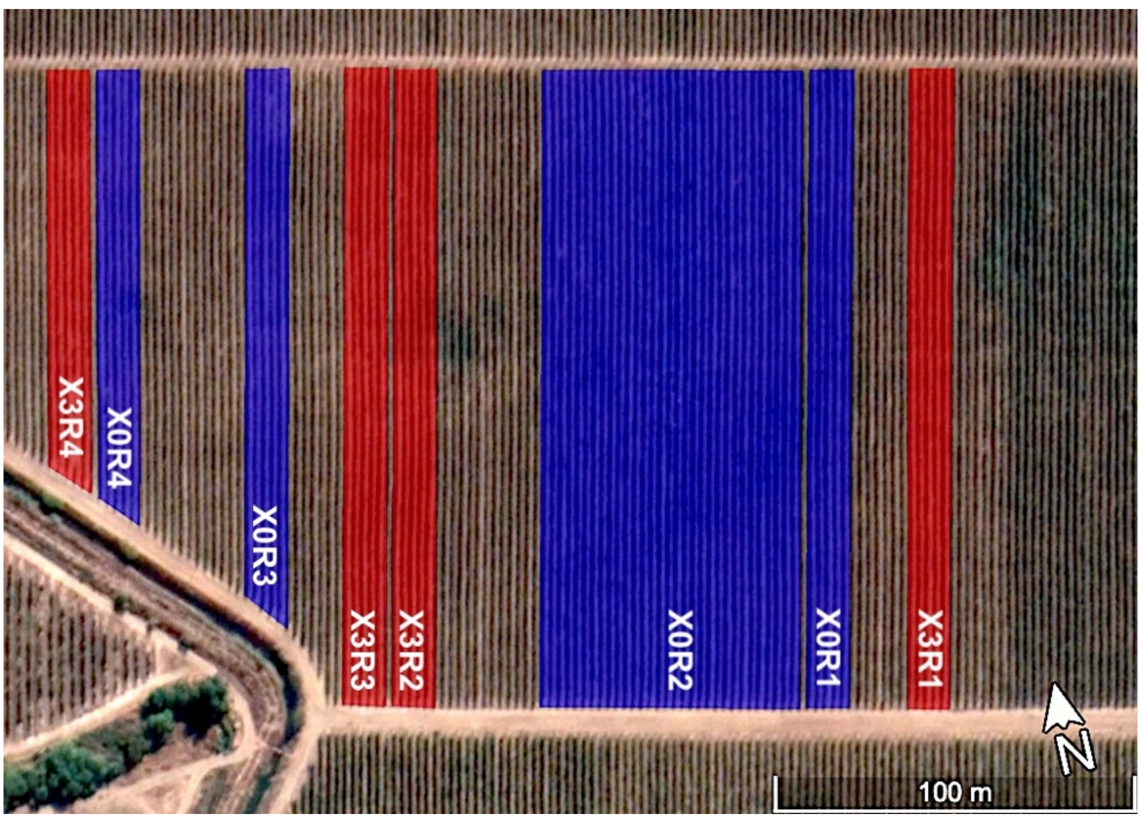
In this regard, the main goal of this study was to identify the best spectral reflectance indices to estimate the MSWP in a drip-irrigated vineyard growing under mediterranean semi-arid conditions with the aim of develop a new methodology to monitor the water status of a vineyard.

MATERIALS AND METHODS

Experimental site

The experiment was conducted during the 2019-2020 growing season from anthesis to harvest in a vineyard located in the Pencahue Valley, Maule Region of Chile (35°25´58” S; 71°47´56” W; 105 m.a.s.l.) in a surface of 4.5 hectares (Figure 1). The vineyard was established in 2014 with *Vitis vinifera* L. *cv.* Cabernet Sauvignon grafted onto SO4 planted in a north-south orientation, 1.2 m apart within a row, 2.3 m distance between rows (3.623 plants ha^{-1}) and trained onto a vertical shoot positioning system (VSP). Irrigation was applied once a week using 2.5 l h^{-1} self-compensated drippers spaced every 60 cm.

Figure 1. Location of the experiment, showing the irrigation treatments distribution.



The study site belongs to the agroclimatic district of Talca (CIREN-CORFO, 1990) with a Warm-summer Mediterranean climate (Csb) according to the Köppen classification, with a dry season of 7 to 8 months and with moderate rainfall that concentrates on winter (DGA, 2015) and reach an average of 709 mm year^{-1}. The effect of the sea breeze is attenuated due to the presence of the coastal mountain, so there is a strong diurnal temperature variation and the summer temperature is high. The mean temperature between October to March and from June to August are 18.5ºC and 8.8ºC respectively. Between September and February they accumulated 1550 growing degree-days (GDD) base 10 and 1140 annual chill hours (CIREN-CORFO, 1990).

The soil belong to Rauquén series and its texture is loam, with a percentage of sand, silt and clay or 48, 31 and 21 respectively. Field Capacity is 12.7% and Wilting Point is 5.4 %. The organic matter reaches a 1.1%, wich is considered low. The soil pH is 5.6. The effective depth of the soil goes between 40 cm to 1m, due to the presence of a compacted sandstone that limits root development (CIREN, 1997).

Experimental design

A randomized block design was established in order to block the effect of a compacted layer present in the soil. The experiment consisted of 2 irrigation treatments with 4 repetitions (6 rows each, except for X0R2, wich is 32 rows), as shown in Figure 1. The experimental unit correspond to a group of 6 plants located approximately in the middle of each central row. Treatments correspond to 2 irrigation regimes applied from fruit set to veraison with the aim of generating 2 levels of stress in plants (Table 2).

Table 2. Water replacement regimes of each irrigation treatment.

Treatment	***Water replacement***	***Water deficit***	***Midday Stem Water Potential (MPa) thresholds***
X0	100% ET	No to moderate water deficit	>-1.1
X3	30% ET Fruit set – Veraison 100% ET Veraison - Harvest	Moderate to severe water deficit	< -1.1

Measurements

In the experimental units mentioned above, measurements of Water Potential and Spectral Reflectance were made. These were taken between January and March , covering the period from fruit set to harvest.

1. **Water status**

Grapevine Water Status was evaluated through the Midday Stem Water Potential (MSWP). Measurements were made on two healthy leaves per repetition, selected from the middle third of the canopy. The procedure involves covering the leaf with plastic paper to avoid gas exchange and then is covered with aluminum foil in order to block the light interception. The leaf remains in this condition for at least one hour. Subsequently, the leaf is extracted from the branch and through a Scholander-type pressure chamber (PMS Instrument Company, model 600, Oregon, USA) the water potential measurement is carried out (Fulton et al., 2014; Scholander et al., 1965). Also, the Midday Leaf Water Potential (MLWP) was measured.

Figure 2. Metodology for Midday Stem Water Potential measurement.

2. Spectral Reflectance

A model SVC HR-1024i (Spectra Vista Corporation, Inc., USA.) spectroradiometer attached with a Leaf-Clip Reflectance-Probe, able to measure between 350 and 2500 nm, was used to obtain the spectral reflectance of the leaves (Figure 3). The leaf clip has a halogen light source, which allows controlling the incident radiation on the leaf and its exposure to atmospheric gases, reducing noise sources over the measurement.

The reflectance capture was made at the same time as the water potential measurement, that is, at solar noon. Before each treatment measurement, a calibration with a white Spectralon surface was done.

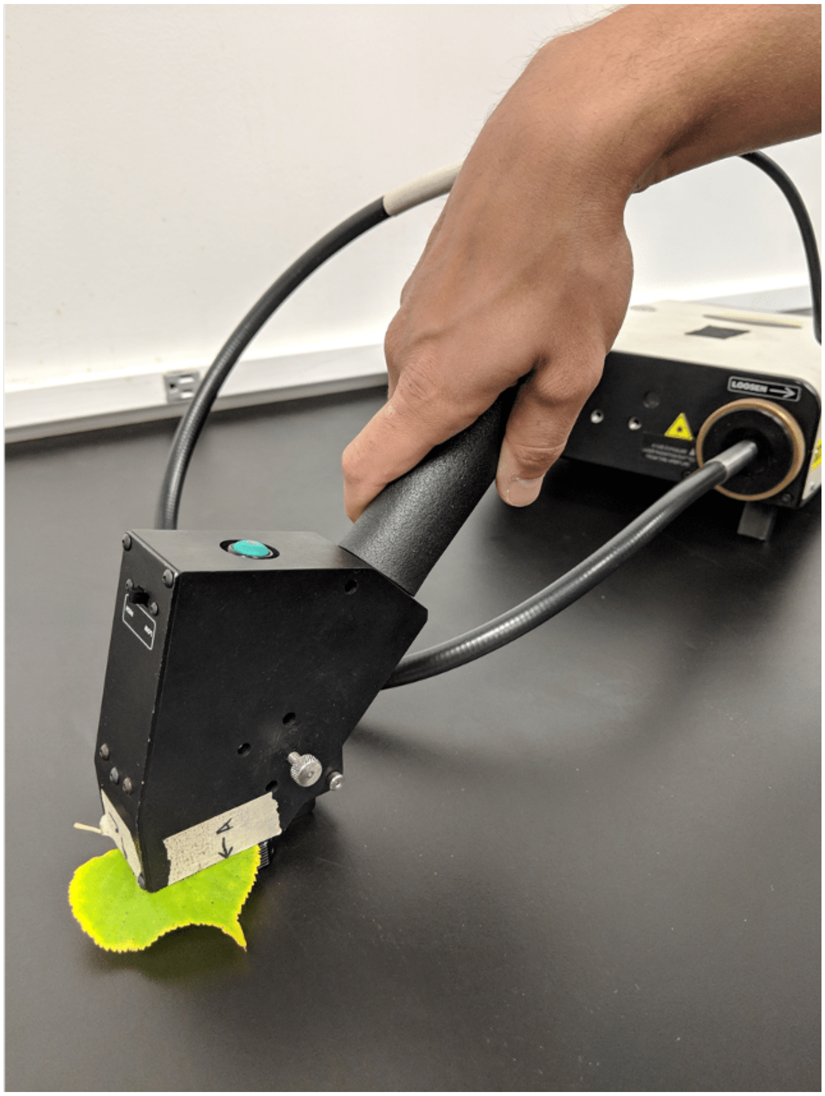


Figure 3. Example of leaf spectral reflectance measurement with a leaf clip attached to the spectroradiometer. The probe has is own light source.

Statistical Analysis

The obtained data were evaluated by means of a linear regression analysis in order to establish a correlation between the different spectral indices versus water potential. The degree of association between the aforementioned variables was evaluated using the determination coefficient (R^2) and the significance of the correlation using a t-test for the slope. For the analysis of the differences between the irrigation treatments by dates, an ANOVA was performed, first verifying that the assumptions of normality and homogeneity of variances were met.

All statistical analyzes were performed using the Rcmdr library of the R software (R Core Team, 2020).

RESULTS AND DISCUSSION

Vine Water Status

According to Figure 4, wich compares the MSWP againts the MLWP, it is evident that during the experiment there was not a good relationship between these two fisiological variables. This is due to the fact that leaf water potential is a highly variable measurement, because it depends on the especific microclimatic environment condition of each particular leaf (Jones, 2004; Van Leeuwen et al., 2009): local leaf water demand, soil water availability, internal plant hydraulic conductivity and stomatal regulation (Choné et al., 2001). On the contrary, the stem water potential is more stable and is considered a strong and accurate indicator of water status of the whole plant (Acevedo-Opazo et al., 2010; Ahumada-Orellana et al., 2017; Choné et al., 2000).

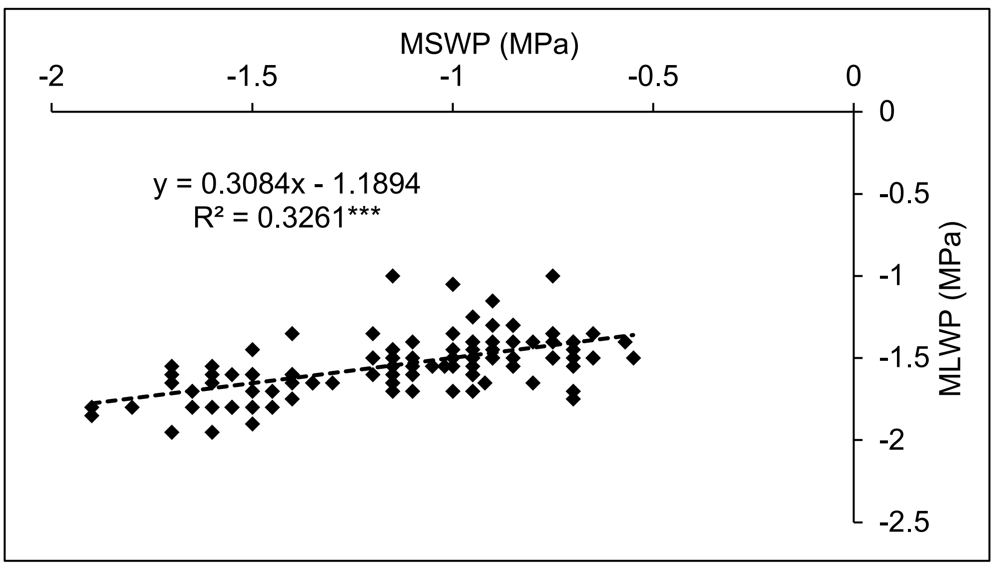


Figure 4. Comparison between MSWP and MLWP during season.
***Significant at $P < 0.001$

In addition to the above, it is very difficult to separate the behavior of the treatments X0 and X3 throughout the experiment by means of the leaf water potential, as can be seen in Figure 6. Therefore, for the spectral analysis, the MSWP was used.

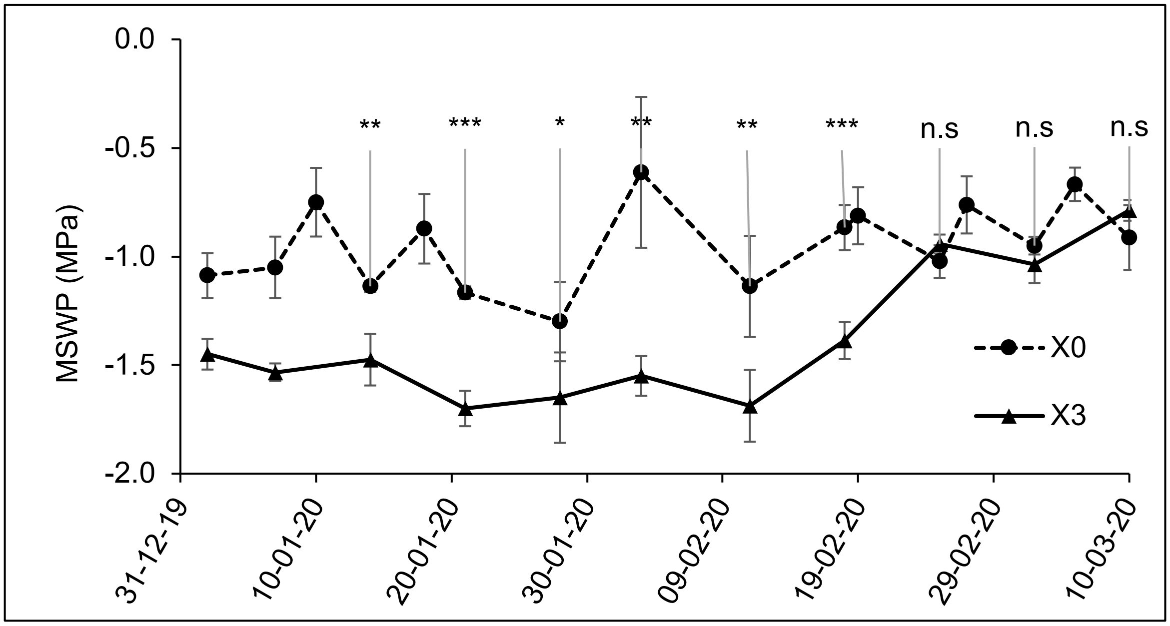


Figure 5. Evolution of the MSWP in two irrigation treatments during season. Each point is an average of four measurements. Significance level: * P < 0.05; ** P < 0.01; *** P < 0.001

The vines were exposed to a range of water potential between -0.6 to -1.7 MPa during the season (Figure 5). This indicates that the plants experienced levels of stress between weak to severe, according to the thresholds proposed by Van Leeuwen et al. (2009) for MSWP. The greatest differences between treatments occurred at the beginning of February, when the highest values of atmospheric demand were experienced. Following this, the values of water potential of X3 start to rise, associated with the restoration of irrigation.

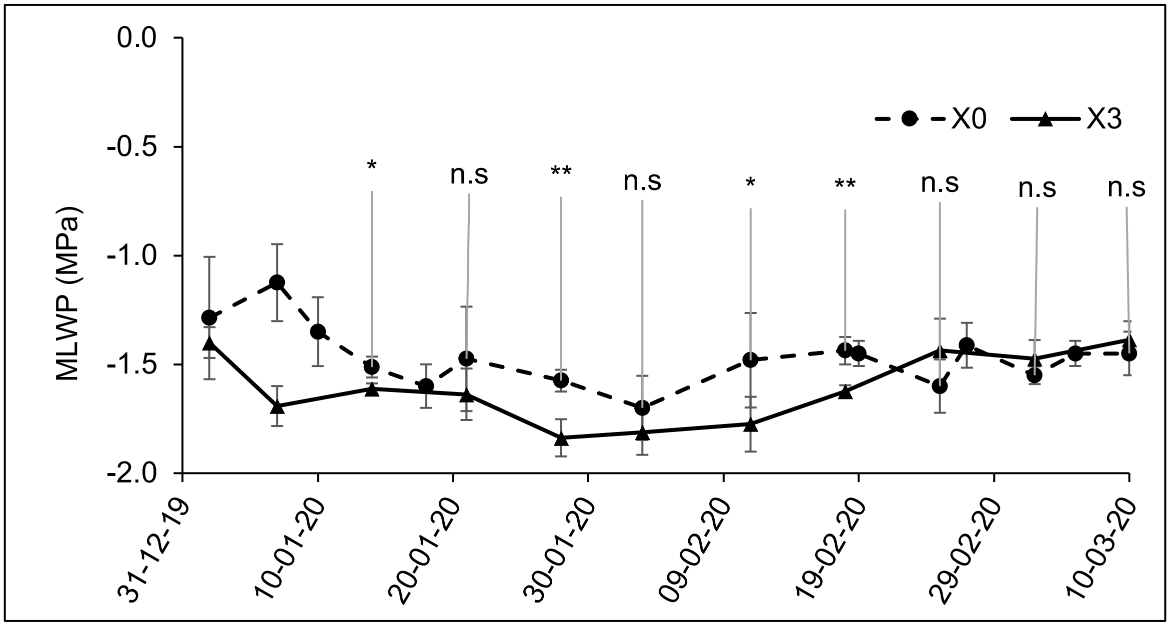


Figure 6. Evolution of the MLWP in two irrigation treatments during season. Each point is an average of four measurements. Significance level: * P < 0.05; ** P < 0.01; *** P < 0.001

Spectral analyses

Following the Van Leeuwen`s criterion, it was defined a threshold of -1.1 MPa for MSWP and all the spectra was separated into 2 categories (stressed and not stressed) according to the water potential values at the time of measurement (Figure 7). Here it can be seen that water stress induced a drop in the reflectance throughout the entire electromagnetic spectrum (more clearly in figures 8 to 10). It is known that the water content of the leaf cells partly affects the reflectance, especially in the NIR and SWIR regions (Ceccato et al., 2001). This is consistent with what is observed by other authors; for example, Carter (1991) states that when water is lost in a structure the reflectance tends to increase in the range of 400 to 2500nm. Rodríguez-Pérez et al. (2007) indicates that in areas of water absorption, reflectance decreases when the water content is increased in tissues. In this regard, Kim et al. (2011) affirms that stress causes photosynthetic efficiency to fall, which entail reflectance to increase in the VIS region. Finally, Pôças et al. (2015), in vines of the cv. Touriga Nacional, graphically shows that plants with higher water stress have more reflectance between 400 and 1060nm than those without stress.

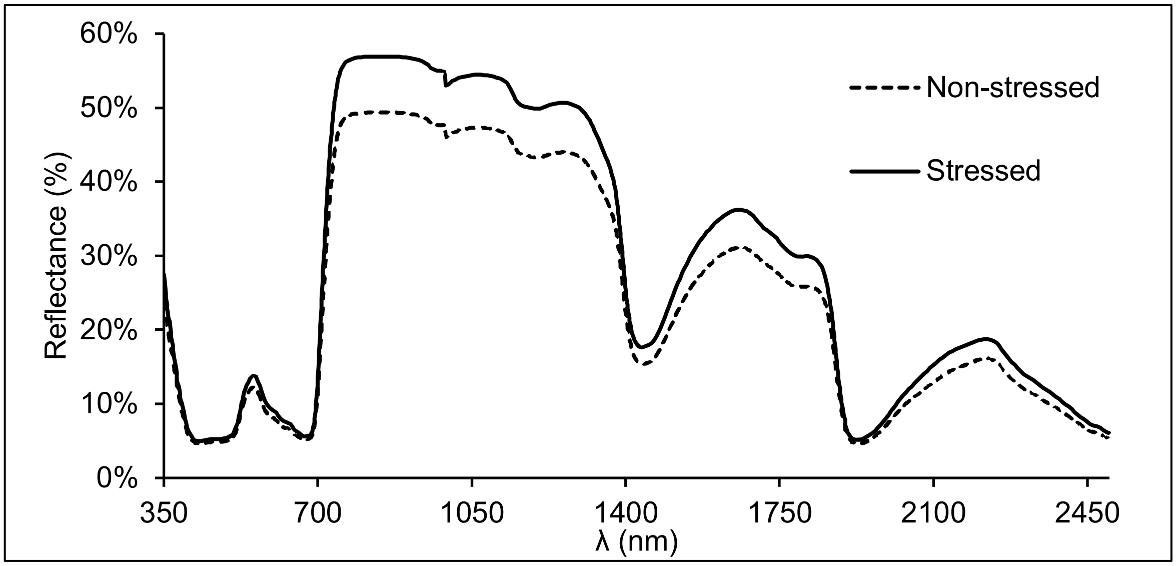


Figure 7. Mean reflectance of stressed (mean of 51 measurements) and non-stressed (mean of 65 measurements) leaves during the season.

However, there are other researchers who have obtained results that partially coincide with those of this work: Rapaport et al. (2015), in a greenhouse experiment over cv. Cabernet Sauvignon, found a progressive reflectance decrease in the 530–550 and 710–750 nm regions, while an increase in the vicinity of 1500 nm. Pôças et al. (2017), on the other hand, saw that between 400 and 700 nm a stressed plant has a lower reflectance than a well-watered one, which is reversed between 700 and 1000 nm.

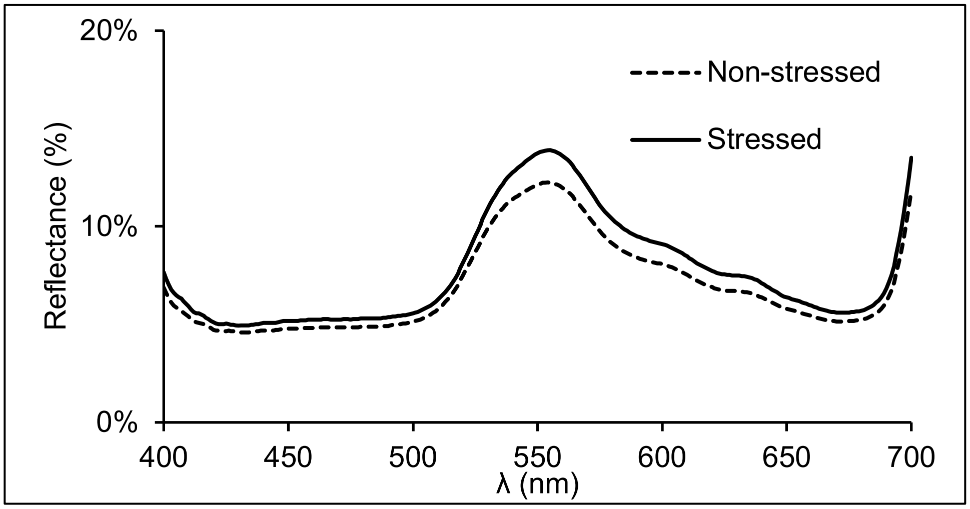


Figure 8. Mean reflectance centered at VIS region of stressed (mean of 51 measurements) and non-stressed (mean of 65 measurements) leaves during the season.

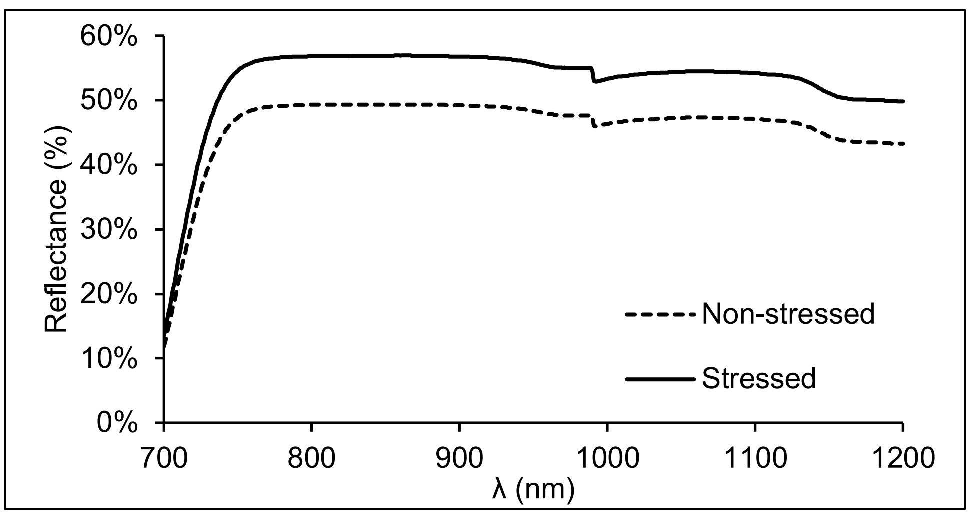


Figure 9. Mean reflectance centered at NIR region of stressed (mean of 51 measurements) and non-stressed (mean of 65 measurements) leaves during the season.

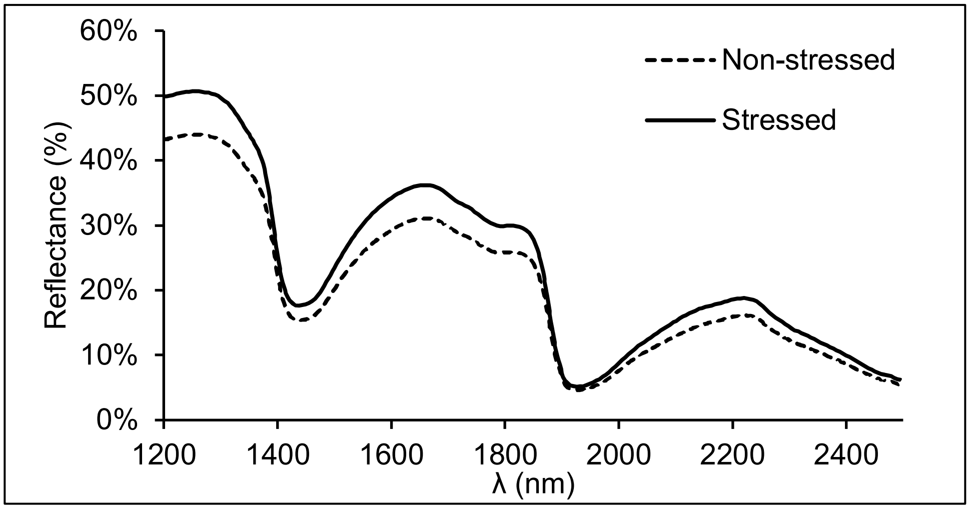


Figure 10. Mean reflectance centered at SWIR region of stressed (mean of 51 measurements) and non-stressed (mean of 65 measurements) leaves during the season.

The dissimilar results that these authors have obtained indicate that evaluating water stress through the spectral signature is not the best approach. For this reason, in this work the spectral reflectance indices (SR) have been used.

Table 3. Best correlations indices for MSWP.

Index	*Formulation*	*R^2 MSWP*	*R^2 MLWP*
PRI2	(528-567)/(528+567)	0.48***	0.29**
SR7	(545)/(538)	0.46***	0.30**
SR6	(553)/(537)	0.46***	0.33***
NDSI40	(1650-2215)/(1650+2215)	0.44***	0.31***
PRI5	(570-531-670)/(570+531+670)	0.43***	0.25**
PRI4	(570-530)/(570+530)	0.43***	0.30**
PRI_2_WATER	(531-570)/(531+570)	0.42***	0.31**
PRI_CI	((531-570)/(531+570))*((760/700)-1)	0.41***	0.30**
PRI_NORM	((570-531)/(570+531))/(((800-670)/(SQRT(800+670)))*700/670)	0.35***	0.24**
NDg_b	(573-440)/(573+440))	0.33***	0.09

(Significance level: * P < 0.05; ** P < 0.01; *** P < 0.001)

The analyzes through the SR indices methodology indicates that there were significant linear correlations between MSWP and SR indices with values of R^2 ranging between 0.02 to 0.48 (Only the best 10 correlations are presented in Table 3). The highest values of R^2 were observed for linear regression between MSWP and PRI2 (Photochemical Reflectance Index 2), followed by SR7 and SR6 (Simple Ratio) and NDSI40 (Normalized Difference Spectral Index) (Figures11 to 14).

As can be seen, most of the best results were obtained by indices that only consider bands of the VIS region of the spectrum, especially around 500 nm, what agrees with other authors findings, such as Carter y Knapp (2001), Dobrowski et al. (2005), Pôças et al. (2015), Rallo et al. (2014), Suárez et al. (2009) and Sun et al. (2008), who have determined that leaf reflectance is modified by stress more significantly at visible wavelengths (400–720 nm) than in the rest of the incident solar spectrum (730–2500 nm), probably due to the fact that these bands are associated with photosynthetic pigments.

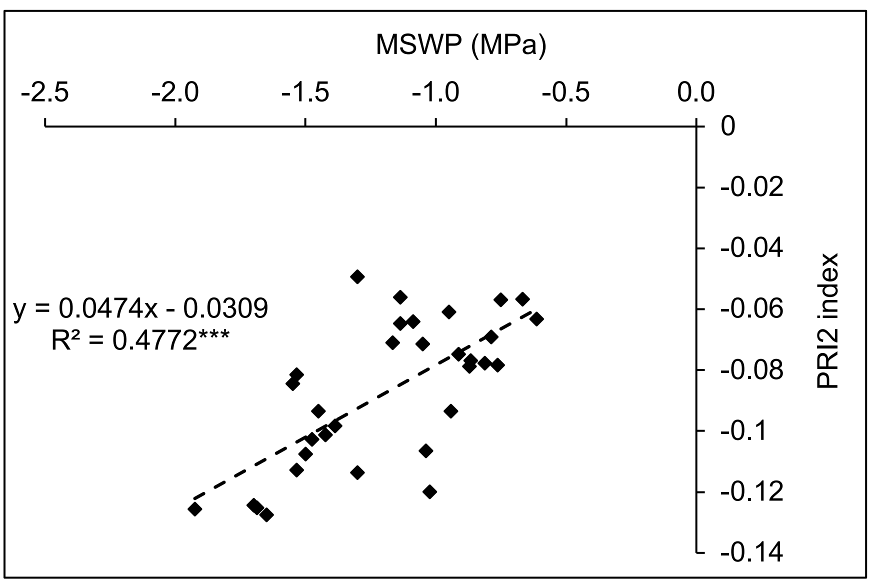


Figure 11. Linear regression between MSWP and PRI2 index ((528-567)/(528+567)). (***Significant at $P < 0.001$)

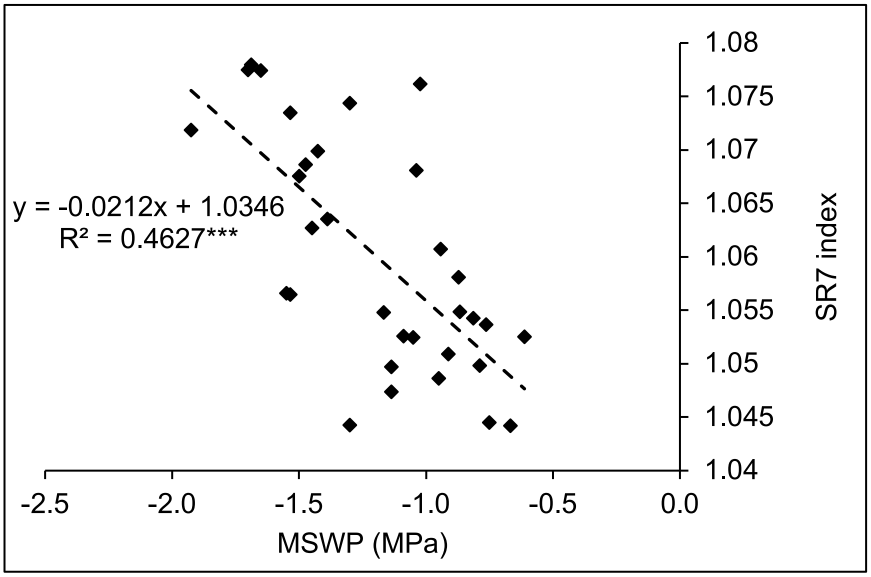


Figure 12. Linear regression between MSWP and SR7 index (545/538). (***Significant at $P < 0.001$)

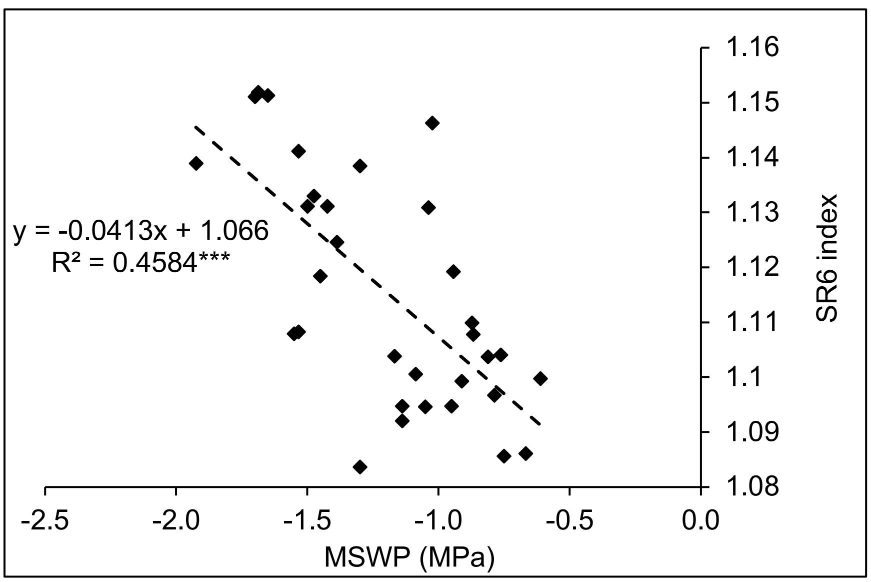


Figure 13. Linear regression between MSWP and SR6 index (553/537). (***Significant at $P < 0.001$)

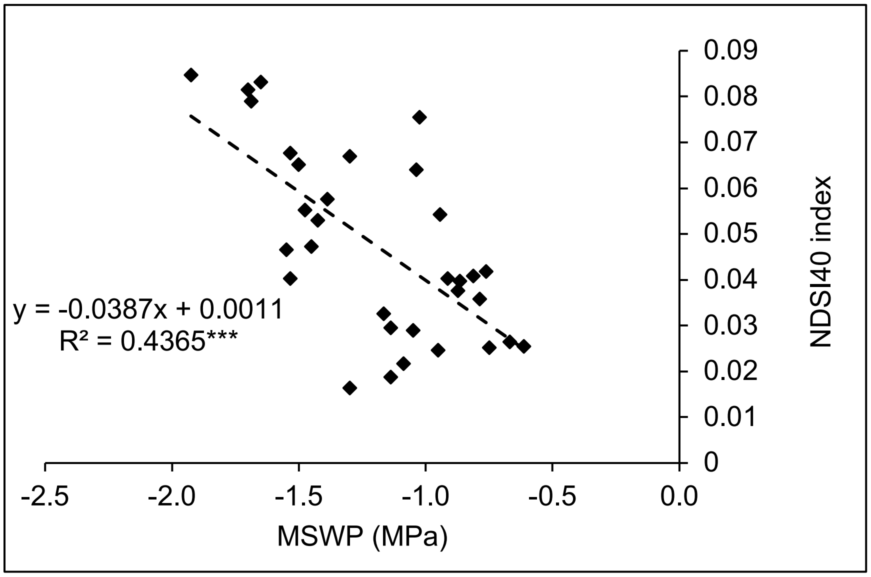


Figure 14. Linear regression between MSWP and NDSI40 ((1650-2215)/(1650+2215)). (***Significant at $P < 0.001$)

It is known that drought stress can reduce photosynthesis in three ways: limiting the entrance of CO_2 into the leaf (stomatal limitation), decreasing the CO_2 diffusion within the mesophyll (mesophyll limitation) or inhibiting the photochemical and metabolic processes associated with photosynthesis (photochemical and enzymatic limitations) (Peguero-Pina et al., 2008).

The latter explains the good correlations that were obtained with indices based on the VIS region of the electromagnetic spectrum, because these indices measure changes in photosynthetic activity, and water stress is defined as the loss of photosynthetic capacity of the plant (Sarlikioti et al., 2010; Stagakis et al., 2012). However, variations in chlorophyll content can not only be caused by water stress but also by phenological status, atmospheric pollution, nutrient deficiency, toxicity, disease and radiation stress (Ceccato et al., 2001), so a good detection of water stress would be better obtained when plants are in healthy conditions.

Problems related with the measurement of SR are probably due to the multi-collinearity of the data, because a large number of spectral bands are being modeled with a small number of biophysical variables, like the MSWP (Mirzaie et al., 2014). Moreover, SR is influenced not only by the plant water status, but also by leaf thickness (Sims y Gamon, 2003), differences in leaf surface properties, soil background, and non-water stress related variation in leaf angle, canopy structure, leaf area (Sims y Gamon, 2003), leaf age (Thenot et al., 2002), measuring angle, solar zenith, canopy architecture, and row spacing (Jackson y Huete, 1991). Performing measurements with a leaf clip and with a controlled light source many of these uncertainties can be overcome. Despite this, it is necessary to standardize the leaf selection and measurement as a way to minimize this source of variability.

CONCLUSIONS

Good correlations were obtained between several SR indices and MSWP for those who make use of the VIS region of the spectrum. This makes it possible to estimate with high confidence the water status of plants based on spectral information.

Considerations regarding the leaf selection and measurement procedure has to be taken into account to obtain better results.

Nevertheless, these good results in the VIS spectrum open up the possibility of developing a low-cost device capable of measuring MSWP for irrigation management at a fraction of the cost of complex research equipment, such as the used in this study.

Work remains to be done to improve these estimates. For example, the spectral signature of the same leaves could be taken during the experiment to verify if the predictive power of the spectral indices degrades over time. Also, other approaches could be used to analyze the data, such as multivariate analysis or artificial intelligence.

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ANEXOS

Anexo 1. Relaciones entre potencial hídrico y distintos índices espectrales obtenidos de la literatura.

Especie	***Potencial***	***Índice***	***Valor R^2***	***Comentario***	***Referencia***
Vid cv. Cabernet Sauvignon	ψ_{hoja}	PRI-1	0.19	Ensayo en macetas en invernadero	(Rapaport *et al.*, 2015)
		PRI-2	0.32		
		REIP	0.34		
		dREP	0.14		
		mNDVI	0.28		
		SIPI	0.17		
		NDVI	0.03		
		NDII	0.24		
		NDWI	0.04		
		WI	0.12		
		MDWI	0.34		
		MSI	0.31		
		WABI-1	0.72		
		WABI-2	0.89		
		WABI-3	0.61		
Olivo cv. Nocellara del Belice	ψ_{hoja}	NDVI	0.36	Reflectancia a nivel de dosel	(Rallo *et al.*, 2014)
		GNDVI	0.41		
		NDGI	0.62		
		NDWI	0.63		
		SRWI	0.5		
		GI	0.59		
		WI	0.38		
		MSI	0.62		
		NDVI	0.09	Reflectancia a nivel de hoja	
		GNDVI	0.02		
		NDGI	0.15		
		NDWI	0.47		
		SRWI	0.42		
		GI	0.13		
		WI	0.09		
		MSI	0.47		
Vid cv. Chardonnay	$\psi_{amanecer}$	NDVI	0.8 (2007) 0.71 (2008)	A nivel de dosel. Se presenta R	(Serrano, González-Flor and Gorchs, 2012)

		SR	0.75 (2007) 0.74 (2008)	(coef. de correlación de Pearson)	
		WI	0.03 (2007) 0.3 (2008)		
		G (Lich)	0.3 (2007) -0.51 (2008)		
		NPQI	0.05 (2007) -0.53 (2008)		
		TCARI_OSAVI	0.64 (2007) -0.39 (2008)		
		CAR_{black}	0.14 (2007) -0.44 (2008)		
		SIPI	-0.73 (2007) 0.14 (2008)		
		ANT_{Gamon}	-0.02 (2007) -0.52 (2008)		
Trigo línea SBS-II	ψ_{hoja}	NWI-3	0.81	Combinando fenologías (datos sin combinar se obtienen valores más bajos)	(Gutierrez, Reynolds and Klatt, 2010)
Trigo línea SYNDER		NWI-3	0.76		
Trigo línea SBS-I	ψ_{hoja}	WI	-0.47	Coeficiente correlación Pearson	
		NWI-1	-0.47		
		NWI-2	-0.46		
		NWI-3	-0.49		
		NWI-4	-0.48		
Trigo línea ALN	ψ_{hoja}	WI	-0.58		
		NWI-1	-0.58		
		NWI-2	-0.56		
		NWI-3	-0.58		
		NWI-4	-0.55		
Trigo (todas las líneas combinadas)	ψ_{hoja}	NWI-3	0.56	Combinando líneas y años (2006, 7 y 8)	
Olivo cv. Arbequino	ψ_{xilema}	PRI	0.84	Reflectancia de corona (superior)	(Suárez *et al.*, 2009)
Vid cv. Thompson Seedless	ψ_{hoja}	NDVI	0.34 (13:00 hrs) 0.38 (13:00 + 15:30 hrs) 0.03 (13:00 + 15:30 + 18:00 hrs)	A nivel de dosel mediante UAV	(Zarco-tejada *et al.*, 2013)
		RDVI	0.49 (13:00 hrs)		

			0.38 (13:00 + 15:30 hrs) 0.01 (13:00 + 15:30 + 18:00 hrs)		
		TCARI	0.13 (13:00 hrs) 0.1 (13:00 + 15:30 hrs) 0.11 (13:00 + 15:30 + 18:00 hrs)		
		TCARI/OSAVI	0.01 (13:00 hrs) 0.01 (13:00 + 15:30 hrs) 0.05 (13:00 + 15:30 + 18:00 hrs)		
		R_{700}/R_{670}	0.14 (13:00 hrs) 0.15 (13:00 + 15:30 hrs) 0.17 (13:00 + 15:30 + 18:00 hrs)		
		PRI	0.53 (13:00 hrs) 0.49 (13:00 + 15:30 hrs) 0.37 (13:00 + 15:30 + 18:00 hrs)		
		PRI_{norm}	0.82 (13:00 hrs) 0.77 (13:00 + 15:30 hrs) 0.44 (13:00 + 15:30 + 18:00 hrs)	A nivel de dosel mediante UAV. Índice PRI fue normalizado por el contenido de clorofila de la dosel. El nuevo índice daría cuenta de cambios en el pigmento xantófilas como función del estrés hídrico.	
Vid cv. Cabernet Sauvignon	ψ_{xilema}	WABI	0.92 (training period) 0.85 (testing period)		(Rapaport *et al.*, 2017)
Olivo cv. Leccino	ψ_{hoja}	PRI NDVI WI	0.066 0.668 0.576	Combina plantas de secano y bien regadas en la misma regresión	(Marino *et al.*, 2014)
Populus deltoides x Populus nigra (OP-367)	ψ_{hoja}	MDWI	0.34 (Leaf level) 0.32 (Canopy level)	Ensayo a nivel de invernadero	(Eitel *et al.*, 2006)
		NDWI	0.00 (Leaf level) 0.08 (Canopy level)		
		REIP	0.13 (Leaf level) 0.08 (Canopy level)		

		WI	0.15 (Leaf level) 0.14 (Canopy level)			
			ÍNDICES ESTÁNDAR	ÍNDICES OPTIMIZADOS		
		VARI	0.55 (bloque 1) 0.58 (bloque 2)	0.80 (bloque 1) 0.79 (bloque 2)		
		GI	0.37 (bloque 1) 0.51 (bloque 2)	0.78 (bloque 1) 0.81 (bloque 2)		
		NDGI	0.45 (bloque 1) 0.54 (bloque 2)	0.79 (bloque 1) 0.79 (bloque 2)		
		PRI	0.39 (bloque 1) 0.39 (bloque 2)	0.82 (bloque 1) 0.79 (bloque 2)		
		RGRI	0.50 (bloque 1) 0.54 (bloque 2)	0.79 (bloque 1) 0.77 (bloque 2)		
		TCARI	0.03 (bloque 1) 0.02 (bloque 2)	0.50 (bloque 1) 0.55 (bloque 2)		
Vid cv. Tempranillo	$\psi_{amanecer}$	MCARI	0.01 (bloque 1) 0.01 (bloque 2)	0.59 (bloque 1) 0.61 (bloque 2)	5 fechas, medición de dosel con optimización de índices	(Pôças *et al.*, 2015)
		ARVI	0.44 (bloque 1) 0.46 (bloque 2)	0.73 (bloque 1) 0.66 (bloque 2)		
		WI	0.00 (bloque 1) 0.59 (bloque 2)	0.36 (bloque 1) 0.71 (bloque 2)		
		SR	0.04 (bloque 1) 0.29 (bloque 2)	0.36 (bloque 1) 0.55 (bloque 2)		
		NDVI	0.09 (bloque 1) 0.20 (bloque 2)	0.36 (bloque 1) 0.55 (bloque 2)		
		SAVI	0.23 (bloque 1) 0.17 (bloque 2)	0.42 (bloque 1) 0.44 (bloque 2)		
		MSAVI	0.25 (bloque 1) 0.17 (bloque 2)	0.46 (bloque 1) 0.43 (bloque 2)		
		RDVI	0.22 (bloque 1)	0.37 (bloque 1)		

			0.17 (bloque 2)	0.41 (bloque 2)		
		SIPI	0.50 (bloque 1)	0.64(bloque 1)		
			0.35 (bloque 2)	0.56 (bloque 2)		
		OSAVI	0.27 (bloque 1)	0.44 (bloque 1)		
			0.21 (bloque 2)	0.56 (bloque 2)		
		mRESR	0.31 (bloque 1)	0.49 (bloque 1)		
			0.66 (bloque 2)	0.73 (bloque 2)		
Vid cv. Pinot noir	ψ_{xilema}	SIPI	-0.59		Reflectancia de una fecha a nivel de dosel. Se presenta coef. de correlación de Pearson.	(Rodríguez-Pérez *et al.*, 2007)
		SIPI1	-0.55			
		NDWI	0.57			
		NDWI1	0.57			
		fWBI	0.55			
		SRWI	0.57			
		Lic	0.56			
	$\psi_{xilema}-\psi_{amanecer}$	NPCI	-0.62			
		SRPI	0.61			
		SIPI	-0.74			
		SIPI1	-0.72			
		NDNI	0.61			
		NDWI	0.58			
		NDWI1	0.58			
		WBI	-0.56			
		WI	0.56			
		fWBI	0.57			
		SRWI	0.57			
		MCARI	0.62			
		MTVI2	0.63			
		MTVI3	-0.56			
		MSR	0.64			
		Crt2	-0.66			
		Lic	0.7			
		GM2	0.6			
		EVI	0.57			
Vid cv. Cabernet Sauvignon y cv. Chardonnay	ψ_{xilema}	NDVI	0.2		Solo 3 mediciones en la temporada. Relaciones	(Romero *et al.*, 2018)
		NDGI	0.18			
		NDRE	0.05			
		GI	0.14			

		RGRI	0.2	son polinomiales.	
		SR	0.27		
		RDVI	0.05		
		OSAVI	0.42		
		MSAVI	0.25		
		DVI	0.23		
Limón (*Citrus jambhiri*) cv. Hamlin	ψ_{xilema}	NDVI	0.31		(Waldo and Schumann, 2009)
Vid cv. Chardonnay	$\psi_{amanecer}$	NDVI	0.64 (2007) 0.48 (2008) 0.57 (2007 + 2008)	Dos temporadas. Mediciones a nivel dosel.	(Serrano, González-Flor and Gorchs, 2010)
Algodón cv. Deltapine	ψ_{hoja}	Simple Ratio 1689/1657	0,68	A nivel de hoja. Mediciones desde yema floral (squaring) a apertura de cápsulas (boll opening)	(Kakani, Reddy and Zhao, 2007)
Triticum aestivum cv. Sakha 93 y cv. Sakha 61	ψ_{hoja}	NDSI (614/542)	0.45 (Sakha 93) -> cuadrática 0.64 (Sakha 61) -> exponencial	Durante 2 temporadas, con 2 variedades en tres condiciones de salinidad. Vista de dosel.	(El-Hendawy *et al.*, 2019)
		NDSI (722/542)	0.45 (Sakha 93) -> lineal 0.65 (Sakha 61) -> exponencial		
		NDSI (1193/701)	0.65 (Sakha 93) -> cuadrática 0.69 (Sakha 61) -> exponencial		
		NDSI (2309/2261)	0.30 (Sakha 93) -> cuadrática 0.79 (Sakha 61) -> exponencial		
		NDSI (2309/614)	0.54 (Sakha 93) -> cuadrática 0.52 (Sakha 61) -> exponencial		
		NDSI (2261/701)	0.53 (Sakha 93) -> cuadrática 0.55 (Sakha 61) -> cuadrática		
Vid cv. Moscato Reale	ψ_{xilema}	NDVI	0.32 → Alto vigor 0.05 → Bajo vigor	Reflectancias obtenidas de satélite Landsat 8. 1 temporada. Se presenta R (coef. correlación de Pearson).	(Borgogno-Mondino *et al.*, 2018)
		NDWI	0.36 → Alto vigor 0.04 → Bajo vigor		
Olea europaea cv. Arbequino	ψ_{xilema}	PRI	0,7→ 9:30 GMT	2 años (1 medición por año)	(Suárez *et al.*, 2008)
		NDVI	0,28→ 9:30 GM		
		TCARI/OSAVI	0,07→ 9:30 GM		

	PRI	0,19→ 7:30 GM	Imágenes satelitales
	PRI	0,34→ 12:30 GM	

Anexo 2. Índices espectrales que en la literatura han sido relacionados con el agua en la planta.

Índice	***Sigla***	***Fórmula***	***Referencia***
Normalized difference vegetation index 1	NDVI_1	NDVI=((R800-R680)/(R800+R680))	
Simple ratio index	SRI	SRI=(R900/R680)	
Enhanced vegetation index	EVI	EVI=(2,5*((R800-R680)/(R800+6*R680-7,5*R450+1)))	
Atmospherically resistant vegetation index	ARVI	ARVI=((R800-(2*R680-R450))/(R800+(2xR680-R450)))	
Red edge NDVI =	*reNDVI"	reNDVI=((R750-R705)/(R750+R705))	
Modified red edge NDVI	"MreNDVI"	MreNDVI=((R750-R705)/(R750+R705-2*R445))	(Kim *et al.*, 2011)
Modified Red Edge SR	"MRESRI"	MRESRI=((R750-R445)/(R705-R445))	
Vogelmann Red Edge Index 1	VOG_REI_1	VOG_REI_1=(R740/R720)	
Vogelmann Red Edge Index 2	VOG_REI_2	VOG_REI_2=((R734-R747)/(R715+R726))	
Vogelmann Red Edge Index 3	VOG_REI_3	VOG_REI_3=((R734-R747)/(R715+R720))	
plant senescence reflectance index	PSRI	PSRI=((R680-R500)/R750)	
water index	WI	WI=(R900/R970)	
Ratio Generic Index 1	RGI1	RG1=(R1600/R820)	
Ratio Generic Index 2	RGI2	RGI2=(R900/R970)	
Ratio Generic Index 3	RGI3	RGI3=(R860/R1240)	
Normalized Difference Water Generic Index 1	NDWGI1	NDWGI1=((R820-R1650)/(R820+R1650))	
Normalized Difference Water Generic Index 2	NDWGI2	NDWGI2=((R860-R1240)/(R860+R1240))	
Normalized Multi-band Drought Generic Index	NMDGI	NMDGI=((R860-(R1640-R2130))/(R860+(R1640-R2130)))	(Pasqualotto *et al.*, 2018)
Multi-band Simple Generic Ratio	MSGR	MSGR=((R753-R708)/(R708-R681))	
Triangular Difference Generic Index	TDGI	TDGI=((0,02(R670-R550))+(0,01(R670-R480)))	
Water Line Height Generic Index	WLHGI	WLHGI=(R676-0,5(R746+R665))	
Depth Water Index	DWI	DWI=((2,044*(R1080))-((0,044*(R850))-R970-R1200))	
moisture stress index_1	MSI_1	MSI=(R1600/R820)	(Zhang *et al.*, 2012)

normalized difference water index 1	NDWI_1	NDWI_1=((R860-R1240)/(R860+R1240))	
1650/2220 nm ratio	????	????=(R1650/R2220)	
Simple ratio water index 1	SRWI_1	SRWI=(R858/R1240)	
water index 1	WI_1	WI_1=(R900/R970)	
normalized difference spectral index 1	NDSI1	NDSI1=((R1347-R2307)/(R1347+R2307))	
normalized difference spectral index 2	NDSI2	NDSI2=((R1650-R1801)/(R1650+R1801))	
normalized difference spectral index 3	NDSI3	NDSI3=((R1300-R2308)/(R1300+R2308))	
ratio spectral index 1	RSI1	RSI1=(R2307/R1347)	
ratio spectral index 2	RSI2	RSI2=(R1801/R1650)	
Photochemical reflectance index 1	PRI_1	PRI_1=((R531-R550)/(R531+R550))	(Rapaport *et al.*, 2015)
Photochemical reflectance index 2	PRI_2	PRI_2=((R531-R570)/(R531+R570))	
	mNDVI	mNDVI=((R750-R705)/(R750+R705))	
Structure-independent pigment index	SIPI	SIPI=((R800-R445)/(R800+R680))	(Penuelas, Baret and Filella, 1995)
	NDVI_2	NDVI_2=((R800-R675)/(R800+R675))	(Rapaport *et al.*, 2015)
Normalized difference infrared index 1	NDII_1	NDII=((R820-R1650)/(R820+R1650))	
water balance index	WABI_1	WABI_1=((R1490-R531)/(R1490+R531))	
water balance index	WABI_2	WABI_2=((R1500-R538)/(R1500+R538))	
water balance index	WABI_3	WABI_3=((R1485-R550)/(R1485+R550))	
Green Normalized Difference Vegetation Index	GNDVI	GNDVI=((R800-R550)/(R800+R550))	(Rallo *et al.*, 2014)
Normalized Difference Greenness Vegetation Index	NDGI	NDGI=((R550-R680)/(R550+R680))	
Normalized Difference Water Index 2	NDWI_2	NDWI_2=((R858-R1240)/(R858+R1240))	
Simple Ratio Water Index 2	SRWI_2	SRWI_2=(R680/R1240)	
Green Index	GI	GI=(R550/R680)	
Water Index 2	WI_2	WI_2=(R680/R858)	
Moisture Stress Index 2	MSI_2	MSI_2=(R858/R1240)	
Water content reflectance index	WCRI	WCRI=(R1455/(R1272-R1455))	(Sun *et al.*, 2008)

Red/green index	RGI	RGI=(R695/R554)	(Rodríguez-Pérez *et al.*, 2018)
Simple ratio water index 3	SRWI_3	SRWI_3=(R1350/R870)	
Normalized difference vegetation index	NDVI_3	NDVI_3=((R858-R645)/(R858+R645))	
Normalized difference water index 3	NDWI_3	NDWI_3=((R870-R1260)/(R870+R1260))	
Shortwave infrared water stress index	SIWSI	SIWSI=((R858,5-R1640)/(R858,5+R1640))	
Normalized difference infrared index 2	NDII_2	NDII_2=((R835-R1650)/(R835+R1650))	
Zarco Tejada Miller Index	ZTM	ZTM=(R750/R710)	
Photochemical reflectance index_3	PRI_3	PRI_3=((R570-R531)/(R570+R531))	
water balance index 4	WABI_4	WABI_4=((R1500-R531)/(R1500+R531))	(Rapaport *et al.*, 2017)
Blue/Red 2	BRI_2	BRI_2=(R440/R690)	(Rodríguez-Pérez *et al.*, 2007)
Normalized Green/Red Ratio 1	NGRR_1	NGRR_1=((R673-R554)/(R673+R554))	
Normalized Green/Red Ratio 2	NGRR_2	NGRR_2=((R673+R554)/(R673-R554))	
Simple Ratio 1	SR1	SR1=(R695/R760)	
Simple Ratio 2	SR2	SR2=(R1070/R1340)	
Simple Ratio 3	SR3	SR3=(R678/R880)	
Simple Ratio 4	SR4	SR4=(R678/R1070)	
Red/Blue (RBI)	RBI	RBI=(R695/R445)	
Moisture Stress 3	MSI_3	MSI_3=(R870/R1350)	
Normalized Difference Vegetation Index 4	NDVI_4	NDVI_4=((R858,5-R645)/(R858,5+R645))	
Normalized Difference Vegetation Index 5	NDVI_5	NDVI_5=((R870-R673)/(R870+R673))	
Normalized Difference Vegetation Index 6	NDVI_6	NDVI_6=((R884-R680)/(R884+R680))	
Simple Ratio Water 4	SRWI_4	SRWI_4=(R880/R1265)	
Simple Ratio Water 5	SRWI_5	SRWI_5=((R1350/R870))	
Simple Ratio Water 6	SRWI_6	SRWI_6=((R880/R1265))	
Modified triangular VI	MTVI	MTVI=(1.2*[1.2*(R880−R554)−2.5*(R758−R554)])	
Triangular VI	TVI	TVI1=(0.5*[120*(R758−R554)−200*(R674−R554)])	
Carter	Crt	Crt=(R700/R420)	

Normalized PRI	PRI_{norm}	PRI_norm=((R570-R531)/(R570+R531))/(((R800-R670)/(SQRT(R800+R670)))*R700/R670)	(Zarco-Tejada *et al.*, 2013)
Simple Ratio 5 Simple Ratio 6 Simple Ratio/NDVI	SR5 SR6 SR/NDVI	SR5=(R940/R960) SR6=(R1000/R1100) SR/NDVI=(R940/R960)/NDVI	(Elsayed, Mistele and Schmidhalter, 2011)

*sigla creación propia

Anexo 3. Características de los espectroradiómetros de campo más utilizados en diversos artículos.

Modelo	***Año***	***Rango espectral***	***Resolución espectral (nm)***	***Número de bandas***	***Ángulo de visión (FOV)***	***Peso (kg)***
ASD FieldSpec-FR	1994	350 - 2500	3 @ 700 10 @ 1400/2100	512 o 1024, 750	1/25/2π	8
ASD FieldSpec 4 Standard-Res	2014	350 - 2500	3 @ 700 10 @ 1400/2100	2151	25	5.44
ASD FieldSpec HandHeld 2	2014	325 - 1075	<3 @ 700	512	25	1.2
Ocean Optic USB2000+	2014	200 - 1100	0.1 – 10	2048	-	0.19
SVC HR-1024i	2005	350 - 2500	3.5 @ 700 9.5 @ 1500 6.5 @ 2100	1024	25	3.9

Adaptado de Pu (2017)

Anexo 4. Poster presentado en el IX International Symposium on Irrigation of Horticultural Crop. International Society for Horticultural Science (ISHS), Matera, Italia, 17 – 20 de junio de 2019.

Development of linear models to estimate vine water status using spectral indices

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I. Introduction

Measurement of Midday Stem Water Potential (MSWP) has been suggested as an excellent tool for monitoring water status in drip-irrigated vineyards[1, 2, 3]. However, practical application of this measurement is limited by the high cost and time consuming[4, 5, 6, 7]. As an alternative, the use of Spectral Reflectance (SR) indices has been proposed as a good predictor of vine water status in a non-invasive way[8, 9, 10]. The aim of this study was to identify the relationships between MSWP and several SR indices in a drip-irrigated vineyard growing under semiarid conditions as an alternative to traditional monitoring techniques.

II. Material and Methods

A study was conducted in a drip-irrigated vineyard (cv. Cabernet Sauvignon) located in the Pencahue Valley of Chile during 2018/19 growing season. The 5 year-old vines were trained on a vertical shoot positioned system (Fig 1). A completely randomized design with four irrigation treatments with four replications was established to develop relationships between MSWP and several SR indices.

Figure 1. Spectral reflectance measurements and equipment (SVC HR-1024i and Scholander pressure chamber).

Both MSWP and SR indices were measured at midday using a pressure chamber (PMS Instrument Co., model 1000, Corvallis, Oregon, USA) and a portable spectroradiometer (SVC HR-1024i, USA), respectively. More than 74 SR indices were calculated based on visible (VIS), near-infrared (NIR) and shortwave infrared (SWIR) spectral measurements. In addition, linear regression analyses between MSWP and SR indices were performed using 10 days of measurements during season.

III. Results

Results indicated that there were significant linear correlations between MSWP and SR indices with values of R^2 ranging between 0.02 to 0.58. The highest values of R^2 was observed for linear regression between MSWP and PRI_CI (Photochemical Reflectance Index X Chlorophyll index) (Fig 2).

Figure 3 shows measured and predicted values of MSWP for non and stressed vines during season. In this case, values of MSWP ranged between -0.5 and -0.74 MPa for non stressed vines and between -0.81 and -1.4 MPa for stressed vines. Statistical analysis indicated that the best agreement between observed and estimated MSWP was obtained for stressed vines with highest differences less than 0.31 MPa. The worst agreement was found for non-stressed vines with maximum errors found at the end of the growing season (Fig 3).

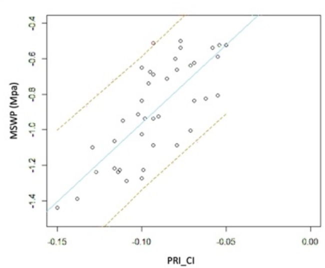

Figure 2. Correlation between MSWP and PRI_CI index for grapevine leaves.

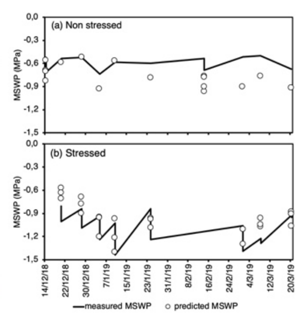

Figure 3. Measured and predicted values of MSWP using the PRI_CI index.

IV. Discussion and Conclusions

We found significant correlations between MSWP and PRI_CI index with a $R^2 = 0.58$. The best estimation of MSWP was observed in stressed vines with difference less than 0.31MPa. This opens up the possibility of developing a low-cost device capable of measuring MSWP for irrigation management.

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Anexo 5. Captura de correo electrónico de aceptación de artículo “Development of linear models to estimate vine water status using spectral indices” para publicación en Acta Horticulturae.

De: symposiacontributions@ishs.org
Asunto: Acta Horticulturae - fulltext accepted : Development of...
Fecha: 9 de octubre de 2020 a las 17:13
Para: rvega@utalca.cl, ffuentesp@utalca.cl, Karengutter@gmail.com, Albornoz.ignacio.gonzalez@gmail.com

Dear co-author,

This is to confirm that the article:
Development of linear models to estimate vine water status using spectral indices
has been reviewed and is accepted by the editorial board of:
IX International Symposium on Irrigation of Horticultural Crops
for publication in Acta Horticulturae

Presenting Author: Dr. Samuel Ortega-Farias sortega@utalca.cl

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