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ORIGINAL PAPER

Estimation of stomatal conductance and stem water potential threshold values for water stress in olive trees (cv. Arbequina)

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Abstract

Many irrigation strategies have been proposed in olive orchards to overcome both increasing water scarcity and competition for water with other sectors of society. However, threshold values of stomatal conductance (g_s) and stem water potential (Ψ_{stem}) for use in designing deficit irrigation strategies have not yet been adequately defined. Thus, an experiment was conducted to determine g_s and Ψ_{stem} thresholds for water stress in a super-intensive olive orchard (cv. Arbequina) located in Pencahue Valley (Maule Region, Chile) over three consecutive growing seasons. The experimental design was completely randomized with four irrigation treatments. The stem water potential (Ψ_{stem}) of the T_1 treatment was maintained between − 1.4 and − 2.2 MPa, while the T_2, T_3, and T_4 treatments did not receive irrigation from fruit set until they reached a Ψ_{stem} threshold of approximately − 3.5, − 5.0, and − 6.0 MPa, respectively. Stomatal conductance (g_s), transpiration (T_l), net CO_2 assimilation (A_n), and stem water potential (Ψ_{stem}) were measured fortnightly at midday. A significant nonlinear correlation between A_n and g_s was used to establish different levels of water stress. Water stress was considered to be mild or absent when the g_s values were greater than 0.18 mol m^{-2} s^{-1}, whereas water stress was estimated to increase from moderate to severe as g_s decreased significantly below 0.18 mol m^{-2} s^{-1}. Similarly, water stress using Ψ_{stem} was determined to be mild or absent above − 2.0 MPa. Such categorizations should provide valuable information for maintaining trees well-watered in critical phenological phases.

Introduction

An evaluation of several studies of modern olive orchards in Mediterranean climatic conditions has demonstrated that irrigation benefits fruit and oil yield (Gucci and Fereres 2012). Nevertheless, the water scarcity and competition for water with other sectors of society that occurs worldwide has generated pressure to reduce the water used in agriculture (Fereres et al. 2003; Fernández and Torrecillas 2012). For this reason, several researchers have indicated that regulated deficit irrigation (RDI) is a viable management tool for improving leaf-level water-use efficiency (WUE, µmol CO_2/mol H_2O) and overall crop water productivity (WP, kg/m^3) in fruit trees (Lampinen et al. 2001; Ortega-Farias et al. 2012; Fereres et al. 2014). For RDI to be a practicable solution, adequate water stress indicators are required to properly schedule the timing of water application. Both stomatal conductance (g_s) and plant water potential (Ψ) have been suggested as potential indicators for olive orchards (Moriana et al. 2002, 2012; Tognetti et al. 2009; Agüero Alcaras et al. 2016).

Stomatal conductance is controlled by soil water availability, osmotic adjustment, xylem hydraulic conductivity, and environmental factors such as vapor pressure deficit and involves complex interactions between internal and external leaf factors (Flexas and Medrano 2002; Medrano et al. 2002; Fernández 2014). According to Cifre et al. (2005), g_s has

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been identified as a very good indicator of water stress in vineyards, because a decrease in g_s is an early response to water deficits in grape leaves. In olive trees, leaves have been shown to close their stomata progressively when soil water availability decreases to reduce water loss by transpiration (T_l) (Fernández et al. 1997; Hernandez-Santana et al. 2016). Stomatal closure in olives also reduces CO_2 diffusion into the leaf, thereby affecting net assimilation (A_n) (Giorio et al. 1999; Fernandes-Silva et al. 2016).

Several studies have found significant linear correlations between g_s and A_n for olive trees (Angelopoulos et al. 1996; Moriana et al. 2002; Tognetti et al. 2007). However, some other studies have reported nonlinear correlations between g_s and A_n for olive trees (Sofo et al. 2009; Marino et al. 2018) and vineyards (Medrano et al. 2002; Cifre et al. 2005). In young, potted olive plants, Sofo et al. (2009) found that g_s decreased from an upper limit of approximately 0.20 mol m^2 s^{-1} in well-watered plants as water stress increased and that A_n was more sensitive to water stress in plants exposed to full sunlight than in shaded plants. This suggests that both stomatal limitations and photoinhibition were likely to be of importance in the response to water stress. In vineyards, Cifre et al. (2005) observed a nonlinear correlation between g_s vs. A_n. In this study, the threshold values of $g_s > 0.15$, between 0.15 and 0.05 and < 0.05 mol m^2 s^{-1} indicated null-mild, moderate, and severe water stress, respectively. Under mild water stress conditions, water-use efficiency (WUE) increased, because g_s and transpiration (T_l) had a greater rate of decrease than that of A_n (Cifre et al. 2005). This occurred, because A_n remains relatively high under partial stomatal closure due to limited decreases in the substomatal CO_2 concentration (C_i) (Angelopoulos et al. 1996; Medrano et al. 2002; Cifre et al. 2005). However, under high levels of water stress, C_i further decreases and both stomatal and nonstomatal limitations, such as decreased electron transport rate and carboxylation efficiency, begin to be more important (Medrano et al. 2002). Despite some advances, there is little information about g_s thresholds that define different levels of water stress in olive orchards under field conditions. López-Bernal et al. (2017) recently cautioned against extrapolating g_s values from young potted olive plants to older field-grown plants due to significant stomatal oscillations in young plants under water stress conditions.

Using a pressure chamber to determine water potential (Ψ) has been suggested as a good method for monitoring irrigation scheduling in vineyards and orchards, because it integrates the effects of soil water content, atmospheric conditions, and cultivar on leaf water status (Scholander et al. 1965; Meyer and Reicosky 1985; Williams and Araujo 2002; Naor 2006; Ortega-Farías and López-Olivari 2012). The measurement of water potential can be carried out using three different measurements: (1) the predawn leaf water potential (Ψ_{pd}); (2) midday leaf water potential (Ψ_{leaf}) in leaves exposed to the full sun; and (3) midday stem water potential (Ψ_{stem}) measured in leaves previously enclosed in plastic and aluminum foil to obtain equilibrium with the plant xylem (Ahumada-Orellana et al. 2017; Tognetti et al. 2005; Fulton et al. 2001). Several researchers have suggested that Ψ_{stem} can be used to evaluate water deficit, because it is very sensitive to water deficit, has low variability between measurements in a given tree, and is highly correlated with other physiological variables such as g_s and A_n (Williams and Trout 2005; Naor 2006; Tognetti et al. 2007; Ennajeh et al. 2008; Ben-Gal et al. 2010).

Recent studies have indicated that Ψ_{stem} values between -2.5 and -3.5 MPa are appropriate to maintain adequate olive oil yield and quality (cv. Arbequina) (Naor et al. 2013; Trentacoste et al. 2015; Marra et al. 2016; Ahumada-Orellana et al. 2017, 2018). Such values likely represent mild-to-moderate water stress when applied over extended portions of the growing season. Moriana et al. (2002) also proposed that Ψ_{stem} values < -4.0 MPa represent severe water stress in cv. Picual. Nevertheless, more information is still needed regarding Ψ_{stem} thresholds in order for effective application of RDI in olive trees (Marino et al. 2018). As one step in defining such Ψ_{stem} thresholds, it is necessary to understand the effects of different water deficit levels on leaf gas exchange. Defining the relationships among leaf gas exchange variables (A_n, g_s and T_l) and Ψ_{stem} can help to establish threshold values that affect oil quality and yield. Therefore, the objective of this study was to determine g_s and Ψ_{stem} threshold values for water stress in a super-intensive, drip-irrigated olive orchard (cv. Arbequina) in Mediterranean climatic conditions. Gas exchange relationships were developed for olive trees under different irrigation treatments, which generated different degrees of water stress.

Materials and methods

Site description and experimental design

The experiment was conducted during three consecutive growing seasons (2011–2012 to 2013–2014) in a 6-year-old drip-irrigated olive orchard (*Olea europaea* L. cv. Arbequina) established in 2005 and located in the Pencahue Valley, Maule Region, Chile (35°, 232′L.S; 71°442′W; 96 m altitude). The olive trees were trained under a hedgerow system with a planting framework of 1.5 × 5.0 m (1333 tree ha^{-1}) and irrigated using two 2.0 L h^{-1} drippers per tree. The climate is Mediterranean with an annual rainfall of 620 mm that is concentrated in the winter period (Ortega-Farías and López-Olivari 2012).

The experimental design was described in detail by Ahumada-Orellana et al. (2017). Briefly, the control treatment

(T_1) was maintained by irrigation at Ψ_{stem} values between − 1.4 and − 2.2 MPa during the growing season, with the most negative values tending to occur in the summer when crop demand was greatest. Irrigation was cutoff in the other treatments from fruit set (20 days after full bloom) until reaching Ψ_{stem} thresholds of approximately − 3.5 MPa for T_2, − 5.0 MPa for T_3, and − 6.0 MPa for T_4. Upon reaching the specific thresholds, irrigation was reinitiated, so that Ψ_{stem} recovered to values close to those of T_1. The seasonal irrigation amount for T_1 averaged approximately 245 mm over the three growing seasons, and was 200, 180, and 160 mm for the T_2, T_3, and T_4 treatments, respectively. There were four replicate plots per treatment with each plot consisting of five trees.

Plant water status measurements

To evaluate olive water status between 12:30 and 14:00 h, the midday stem water potential (Ψ_{stem}) was measured weekly during each growing season using a Scholander-type pressure chamber (Model 1000, PMS Instrument Company., Albany, Oregon, USA) (Moriana and Fereres 2002). Two apical stems per plot were used for this measurement. The stems were located in the center of the hedgerow with at least five leaf pairs per stem (Secchi et al. 2007; Rousseaux et al. 2008), and they were covered with plastic bags and aluminum foil for 1–2 h before measurement (Meyer and Reicosky 1985).

Leaf gas exchange measurements

Gas exchange was measured during each growing season, between 12:00 and 14:00 h every 7–14 days, from December to February. Measurements were performed on two mature, sun-exposed leaves per plot, located at chest height on the hedgerow exterior (Tognetti et al. 2007).

An infrared gas analyzer (Model LI-6400, Li-Cor, Inc., Lincoln, NE, USA) was used to estimate values of stomatal conductance (g_s), transpiration (T_l), substomatal CO_2 concentration (C_i), and net photosynthesis (A_n). Measurements were made on sunny days with PAR and CO_2 concentration ranging between 1100–1700 µmol m^{-2} s^{-1} and 380–400 µmol mol^{-1}, respectively. Moreover, the leaf chamber temperature was maintained between 25 and 35 °C, molar air flow rate was 400 µmol s^{-1}, and relative humidity was between 40 and 50%.

Data analysis

Relationships between g_s and the other gas exchange variables, including Ψ_{stem}, were evaluated. In addition, g_s threshold values were obtained by plotting the relationship between A_n and g_s using a piecewise linear regression, which is an effective technique for modeling changes in slope (Toms and Lesperance 2003). In this analysis, g_s values were segmented and regression analyses were done separately for each segment (Malash and El-Khaiary 2010). Finally, Ψ_{stem} vs g_s relationship was used to obtain Ψ_{stem} and g_s thresholds that defined water stress.

Results

The overall relationship between A_n and g_s was curvilinear with a r^2 value = 0.88 (Fig. 1). Piecewise linear regression analysis indicated that there were three lines segments of different slopes over the range of g_s values explored, which coincided with: $g_s > 0.18$ (Zone I), g_s between 0.18 and 0.09 (Zone II), and $g_s < 0.09$ mol m^{-2} s^{-1} (Zone III). A change in slope at a g_s value of 0.18 mol m^{-2} s^{-1} indicated an upper threshold above which water stress was mild or absent. This threshold value was consistent among seasons (Table 1). However, the point of inflection between the lower two line segments (Zones II, III) could not be determined the first season (2011–2012) and was different among seasons for 2012–2013 and 2013–2014. In Zone I, A_n was not significantly affected when $g_s > 0.18$ mol m^{-2} s^{-1}, presenting a clear plateau at 17.3 µmol m^{-2} s^{-1}. Values of A_n for Zone II decreased linearly from 17.2 to 10.5 µmol m^{-2} s^{-1} as g_s values declined from 0.18 to 0.09 mol m^{-2} s^{-1}, while A_n in Zone III decreased linearly from 10.5 to 1.00 µmol m^{-2} s^{-1} as g_s decreased from 0.09 to nearly 0.01 mol m^{-2} s^{-1}. For Zones II and III, the ratios of A_n to g_s were 78.2 and 107.2 µmol m^{-2} s^{-1}/mol m^{-2} s^{-1} with a r^2 of 0.55 and 0.63,

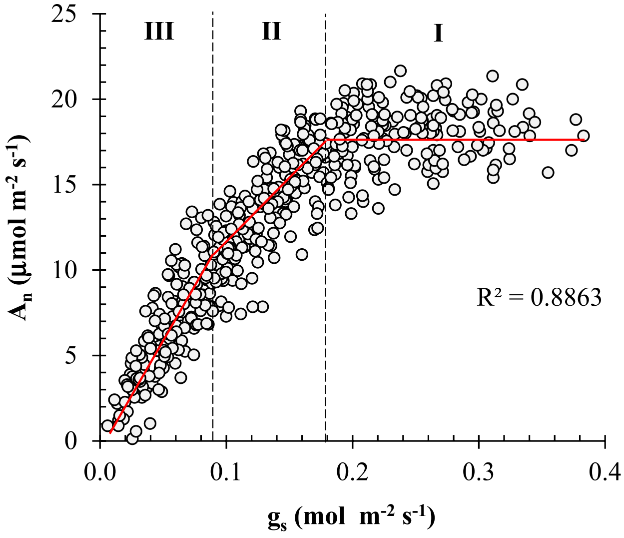

Fig. 1 Relationship between stomatal conductance (g_s) and net assimilation (A_n). Vertical dashed lines separate three line segments into zones (I, II, III) using piecewise regression

Table 1 Estimation of stomatal conductance (g_s) thresholds using piecewise linear regression

Water condition	Season	Threshold	Lower limit (95%)	Upper limit (95%)	Value *p*
Non water stress	2011–2012	0.19	0.18	0.21	0.00
	2012–2013	0.18	0.17	0.18	0.00
	2013–2014	0.18	0.17	0.19	0.00
	Overall	0.18	0.17	0.19	0.00
Water stress	2011–2012	n.f.	n.f.	n.f.	n.f.
	2012–2013	0.08	0.02	0.14	0.00
	2013–2014	0.06	0.04	0.08	0.00
	Overall	0.09	0.07	0.11	0.00

n.f. data were not fitted to the model

respectively. Therefore, Zones I, II, and III were used to interpret the behavior of the leaf gas exchange relationships (g_s vs C_i and T_l vs g_s).

There were linear relationships between C_i and g_s for Zones I and II, with r^2 values equal to 0.79 and 0.48, respectively (Fig. 2). C_i values for Zone I increased linearly from 170 to 250 µmol m^{-2} s^{-1} for $g_s > 0.18$ mol m^{-2} s^{-1}, while those for Zone II decreased linearly from 170 to 150 µmol m^{-2} s^{-1} as g_s diminished from 0.18 to 0.09 mol m^{-2} s^{-1}. For Zone III, there was not a significant relationship between C_i and g_s, since the data were highly scattered. Finally, the relationship between T_l and g_s was curvilinear ($r^2 = 0.82$) with highly scattered data for Zone I and low scattering for Zone III (Fig. 3). The r^2 values for Zones II and III were 0.25 and 0.81, respectively.

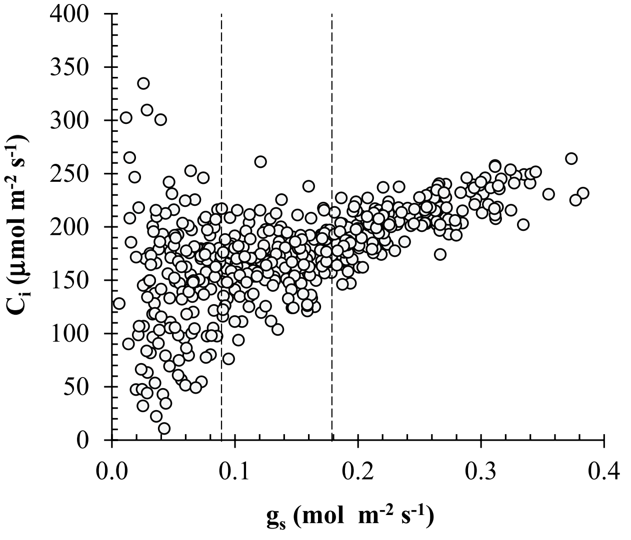

Fig. 2 Relationship between stomatal conductance (g_s) and internal CO$_2$ concentration (C_i)

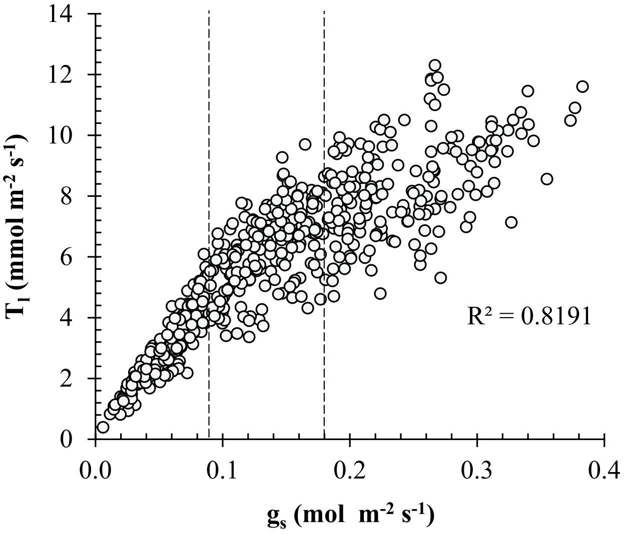

Fig. 3 Relationship between stomatal conductance (g_s) and leaf transpiration (T_l)

Significant nonlinear relationships were observed between A_n and Ψ_{stem} and g_s and $\Psi_{stem,}$ with r^2 values of 0.65 and 0.67, respectively (Fig. 4). Values of g_s and A_n decreased rapidly at first and then more gradually as water status became more negative. The relationship between Ψ_{stem} and g_s was used to establish threshold values of Ψ_{stem}. This relationship was developed using values of Ψ_{stem} and g_s ranging from −0.9 to −6.5 MPa and 0.05 to nearly 0.395 mol m^{-2} s^{-1}, respectively. A piecewise linear regression indicated that a break point in the g_s–Ψ_{stem} relationship (i.e., a significant change in slope) occurred when g_s was 0.12 mol m^{-2} s^{-1} and Ψ_{stem} was −2.3 MPa (Fig. 4b), and two linear equations were obtained ($\Psi_{stem} = -2.77 + 4.36g_s$ for $g_s > 0.12$ mol m^{-2} s^{-1} and $\Psi_{stem} = -5.29 + 25.54g_s$ for $g_s < 0.12$ mol m^{-2} s^{-1}). A more detailed analysis of the g_s–Ψ_{stem} relationship indicated that crop load did not significantly affect the relationship for the range of crop load (6–10 kg tree^{-1}) evaluated (Fig. 5).

Discussion

In comparison with other agronomic species such as grapevines, there has been little emphasis on establishing water stress thresholds in olive trees using gas exchange measurements (Cifre et al. 2005; Medrano et al. 2002; Marino et al. 2018). Stomatal conductance values have been used successfully as an integrative parameter for determining the degree of water stress in vineyards (Zsófi et al. 2009). The water stress thresholds of 0.015 and 0.05 mol m^{-2} s^{-1} for g_s, observed by Medrano et al. (2002) and Cifre et al. (2005) in grapevines, have also been proposed for other C$_3$ plants

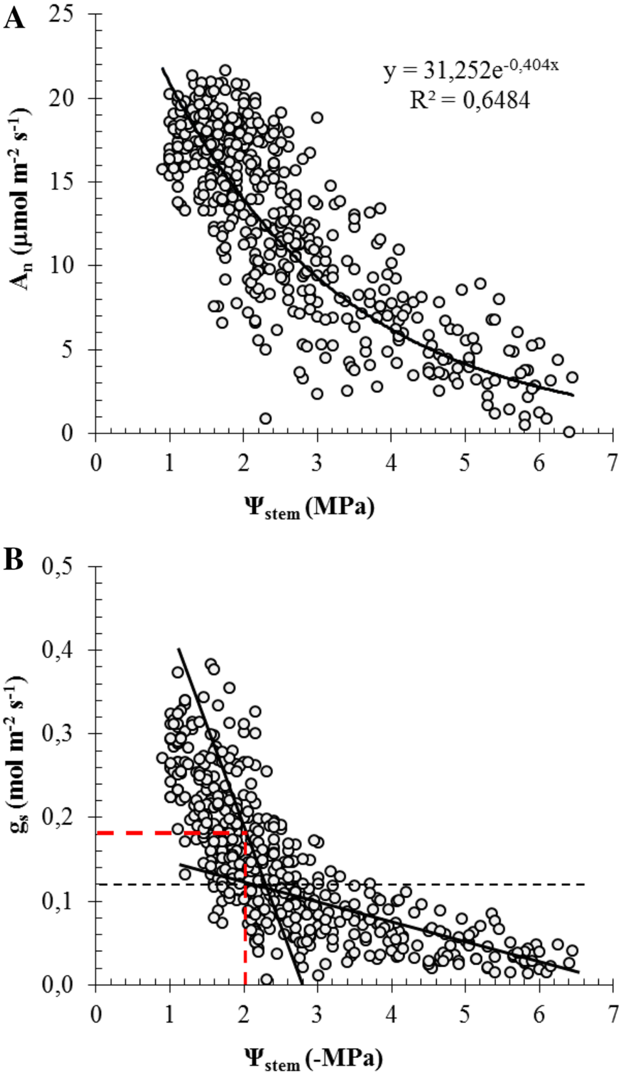

Fig. 4 Relationships between **a** net assimilation (A_n) and midday stem water potential (Ψ_{stem}) and **b** stomatal conductance (g_s) and midday stem water potential (Ψ_{stem}). The intersection of the black solid lines indicates a Ψ_{stem} threshold value (−2.3 MPa) at $g_s = 0.12$. The red dashed line indicates the Ψ_{stem} value (−2.0) that separates different zones in the g_s vs A_n relationship in Fig. 1

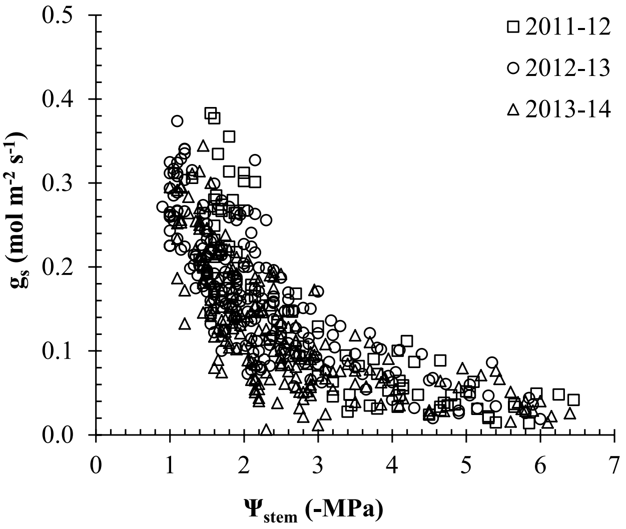

Fig. 5 Relationship between stomatal conductance (g_s) and midday stem water potential (Ψ_{stem}) for different growing seasons. Crop load was 8.3, 6.5, and 10.3 kg tree^{-1} in 2011–2012, 2012–2013, and 2013–2014, respectively. The range of crop load evaluated did not affect the g_s vs. Ψ_{stem} relationship

In our study, as water deficit progressed, values of g_s, A_n, C_i, and T_l decreased, but at different rates. In addition, the g_s–A_n relationship has been described in olives and other species, because the decrease in photosynthesis is greatly controlled by stomatal closure (Naor and Wample 1994; Angelopoulos et al. 1996; Medrano et al. 2002; Cifre et al. 2005; Galmés et al. 2007; Tognetti et al. 2007). Moriana et al. (2002) observed that the relationship between g_s and A_n was linear in olive trees. However, the relationship was nonlinear in our study (Fig. 1). This difference can likely be explained by the range of g_s values evaluated in the two studies. Moriana et al. (2002) evaluated the g_s vs A_n relationship up to maximum g_s values of about 0.2 mol m^{-2} s^{-1}. In contrast, g_s reached values of 0.4 mol m^{-2} s^{-1} under our field conditions, but A_n did not increase when g_s was greater than 0.18 mol m^{-2} s^{-1}.

Based on the g_s–A_n relationship, two zones of water stress were identified with water stress being mild or absent in Zone I ($g_s > 0.18$ mol m^{-2} s^{-1}) and water stress increasing from moderate to severe as g_s decreased significantly below 0.18 mol m^{-2} s^{-1} in Zone II. In Zone I, A_n presented a constant value of approximately 17.0 µmol m^{-2} s^{-1}, which is similar to the maximum value obtained by Marino et al. (2018), although a higher g_s (> 0.25 mol m^{-2} s^{-1}) was needed to reach the highest A_n rates. Fernández (2014) has reported that A_n values of C_3 plants usually do not exceed 25 µmol m^{-2} s^{-1}. In contrast to A_n, C_i did not appear to reach maximum values within the measured range (i.e., up to g_s of 0.4 mol m^{-2} s^{-1}). In Zone II, A_n decreased linearly to 10.5 µmol m^{-2} s^{-1} at g_s of 0.09 mol m^{-2} s^{-1}. In this zone, stomatal closure is likely to limit photosynthesis due to diminishing C_i in the leaf mesophyll (Flexas and Medrano 2002). Finally, with g_s under 0.09 mol m^{-2} s^{-1}, A_n decreased steeply, but C_i did not show any pattern as a result of highly scattered data. Nonstomatal limitations to photosynthesis become dominant in this range, as has been reported by several studies (Medrano et al. 2002; Cifre et al. 2005; Zsófi et al. 2009).

Given the above discussion, the value of 0.18 mol m^{-2} s^{-1} could be used as a g_s threshold for determining water stress in olive trees (cv. Arbequina). With the decrease in Ψ_{stem}, the A_n and g_s values decreased rapidly at first; later, as Ψ_{stem} became more negative, the decreases were more gradual (Fig. 4a, b). Such a nonlinear response coincides with the results reported by other studies with olive trees (Angelopoulos et al. 1996; Ennajeh et al. 2008; Marino et al. 2018). In addition, our results showed that g_s values were highly scattered when Ψ_{stem} was greater than − 2 MPa. Similar results were observed by Marino et al. (2018), who suggested that a Ψ_{stem}–g_s model for low-level stress ($\Psi_{stem} > -2$ MPa) is not reliable. This data scattering at high Ψ_{stem} values is caused by the sensitivity of g_s to other factors such as temperature, vapor pressure deficit, and radiation influx under well-watered conditions (Ennajeh et al. 2008; Marino et al. 2018). Later, as stress intensified ($\Psi_{stem} < -2$ MPa), g_s decreased more gradually. Based on these physiological responses, the − 2.0 MPa value of Ψ_{stem} could be the break point between well-watered and water stress conditions. Therefore, − 2.0 MPa of Ψ_{stem} is proposed as the threshold value for programming irrigation in super-intensive 'Arbequina' olive orchards.

These results complement the previous studies in the same orchard in Chile under Mediterranean climate conditions (Ahumada-Orellana et al. 2017, 2018). Fruit and oil yield were not affected in this orchard under 4 years of water deficit treatment when irrigation was cutoff after fruit set each year until reaching a Ψ_{stem} value of − 3.5 MPa (Ahumada-Orellana et al. 2017). Moreover, the quality of the olive oil was not affected negatively by this level of water stress (Ahumada-Orellana et al. 2018). Similar results were observed by Marra et al. (2016) who suggested maintaining a Ψ_{stem} between − 3.5 and − 2.5 MPa for moderate, sustainable yields with good oil quality.

When interpreting Ψ_{stem} and g_s values in field situations, it should be recognized that crop load in a given year can influence such variables with Ψ_{stem} tending to decrease late in the season as crop load increases (Naor et al. 2013). This indicates that agronomic factors, as well as climatic conditions may influence target Ψ_{stem} and g_s values to some degree. In our study, crop load did not influence the g_s–Ψ_{stem} relationship (Fig. 5) likely because the range of crop load was fairly narrow (6.5–10.3 kg tree^{-1}) in the three seasons evaluated. Ψ_{stem} of − 2.0 MPa and g_s of 0.18 mol m^{-2} s^{-1} found in this study are proposed to provide a guideline as to when water stress occurs under moderate yields in Mediterranean climates. The empirical relationships obtained between these variables and photosynthetic rate could be of use in validating simulation models addressing different aspects of irrigation and global change such as OliveCan (López-Bernal et al. 2018). The obtained Ψ_{stem} and g_s thresholds also give valuable information for maintaining trees well-watered in critical phenological stages such as flowering, and could be used in baseline, reference plots when RDI is implemented in super-intensive 'Arbequina' olive orchards.

Conclusion

Results obtained in the present study over three growing seasons showed that there were significant nonlinear correlations between A_n vs g_s, A_n vs Ψ_{stem}, and g_s vs Ψ_{stem} with r^2 values ranging between 0.65 and 0.88. Water stress was considered to be mild or absent when g_s and Ψ_{stem} values were above 0.18 mol m^{-2} s^{-1} and above − 2.0 MPa, respectively. These threshold values should provide valuable information for maintaining trees well-watered in critical phenological stages such as flowering, and could be used in establishing baseline or reference plots when regulated deficit irrigation is implemented in super-intensive 'Arbequina' olive orchards. Further research is necessary to establish threshold values of g_s and Ψ_{stem} for olive trees under severe water stress.

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References

Agüero Alcaras LM, Rousseaux MC, Searles PS (2016) Responses of several soil and plant indicators to post-harvest regulated deficit irrigation in olive trees and their potential for irrigation scheduling. Agric Water Manag 171:10–20. https://doi.org/10.1016/j.agwat.2016.03.006

Ahumada-Orellana LE, Ortega-Farías S, Searles PS, Retamales JB (2017) Yield and water productivity responses to irrigation cut-off strategies after fruit set using stem water potential thresholds in a super-high density olive orchard. Front Plant Sci 8:1–11. https://doi.org/10.3389/fpls.2017.01280

Ahumada-Orellana LE, Ortega-Farías S, Searles PS (2018) Olive oil quality response to irrigation cut-off in a super-high density orchard. Agric Water Manag 202:81–88. https://doi.org/10.1016/j.agwat.2018.02.008

Angelopoulos K, Dichio B, Xiloyannis C (1996) Inhibition of photosynthesis in olive trees (*Olea europaea* L.) during water stress and rewatering. J Exp Bot 47:1093–1100

Ben-Gal A, Kool D, Agam N et al (2010) Whole-tree water balance and indicators for short-term drought stress in non-bearing "Barnea" olives. Agric Water Manag 98:124–133

Cifre J, Bota J, Escalona JM et al (2005) Physiological tools for irrigation scheduling in grapevine (*Vitis vinifera* L.): an open gate to improve water-use efficiency? Agric Ecosyst Environ 106:159–170

Ennajeh M, Tounekti T, Vadel AM et al (2008) Water relations and drought-induced embolism in olive (*Olea europaea*) varieties "Meski" and "Chemlali" during severe drought. Tree Physiol 28:971–976

Fereres E, Goldhamer DA, Parsons LR (2003) Irrigation water management of horticultural crops. HortScience 38:1036–1042

Fereres E, Orgaz F, Gonzalez-Dugo V, Testi L, Villalobos FJ (2014) Balancing crop yield and water productivity tradeoffs in herbaceous and woody crops. Funct Plant Biol 41:1009–1018. https://doi.org/10.1071/FP14042

Fernandes-Silva AA, López-Bernal Á, Ferreira TC, Villalobos FJ (2016) Leaf water relations and gas exchange response to water deficit of olive (cv. Cobrançosa) in field grown conditions in Portugal. Plant Soil 402:191–209. https://doi.org/10.1007/s11104-015-2786-9

Fernández JE (2014) Understanding olive adaptation to abiotic stresses as a tool to increase crop performance. Environ Exp Bot 103:158–179

Fernández JE, Torrecillas A (2012) For a better use and distribution of water: an introduction. Agric Water Manag 114:1–3

Fernández JE, Moreno F, Girón IF, Blázquez OM (1997) Stomatal control of water use in olive tree leaves. Plant Soil 190:179–192

Flexas J, Medrano H (2002) Drought-inhibition of photosynthesis in C_3 plants: stomatal and non-stomatal limitations revisited. Ann Bot 89:183–189

Fulton A, Buchner R, Olson B, Schwankl L, Gilles C, Bertagna N, Walton J, Shackel K (2001) Rapid equilibration of leaf and stem water potential under field conditions in almonds, walnuts, and prunes. HortTechnology 11:609–615

Galmés J, Medrano H, Flexas J (2007) Photosynthetic limitations in response to water stress and recovery in Mediterranean plants with different growth forms. New Phytol 175:81–93

Giorio P, Sorrentino G, d'Andria R (1999) Stomatal behaviour, leaf water status and photosynthetic response in field-grown olive trees under water deficit. Environ Exp Bot 42:95–104

Gucci R, Fereres E (2012) Fruit trees and vines. Olive. In: Crop yield response to water. FAO irrigation and drainage paper 66. Food and Agriculture Organization of the United Nations, Rome, pp 300–313

Hernandez-Santana V, Fernández JE, Rodriguez-Dominguez CM, Romero R, Diaz-Espejo A (2016) The dynamics of radial sap flux density reflects changes in stomatal conductance in response to soil and air water deficit. Agric For Meteorol 218–219:92–101. https://doi.org/10.1016/j.agrformet.2015.11.013

Lampinen BD, Shackel KA, Southwick SM, Olson WH (2001) Deficit irrigation strategies using midday stem water potential in prune. Irrig Sci 20:47–54

López-Bernal A, García-Tejera O, Testi L, Orgaz F, Villalobos FJ (2017) Stomatal oscillations in olive trees: analysis and methodological implications. Tree Physiol. https://doi.org/10.1093/treephys/tpx127

López-Bernal Á, Morales A, García-Tejera O, Testi L, Orgaz F, De Melo-Abreu JP, Villalobos FJ (2018) OliveCan: a process-based model of development, growth and yield of olive orchards. Front Plant Sci 9:632. https://doi.org/10.3389/fpls.2018.00632

Malash GF, El-Khaiary MI (2010) Piecewise linear regression: a statistical method for the analysis of experimental adsorption data by the intraparticle-diffusion models. Chem Eng J 163:256–263. https://doi.org/10.1016/j.cej.2010.07.059

Marino G, Caruso T, Ferguson L, Marra FP (2018) Gas exchanges and stem water potential define stress thresholds for efficient irrigation management in olive (*Olea europea* L.). Water 10:1–10. https://doi.org/10.3390/w10030342

Marra FP, Marchese GM, Caruso A T (2016) Effects of different irrigation regimes on a super-high-density olive grove cv. "Arbequina": vegetative growth, productivity and polyphenol content of the oil. Irrig Sci 34:313–325

Medrano H, Escalona JM, Bota J et al (2002) Regulation of photosynthesis of C3 plants in response to progressive drought: stomatal conductance as a reference parameter. Ann Bot 89:895–905

Meyer WS, Reicosky DC (1985) Enclosing leaves for water potential measurement and its effect on interpreting soil-induced water stress. Agric For Meteorol 35:187–192

Moriana A, Fereres E (2002) Plant indicators for scheduling irrigation of young olive trees. Irrig Sci 21:83–90

Moriana A, Villalobos FJ, Fereres E (2002) Stomatal and photosynthetic responses of olive (*Olea europaea* L.) leaves to water deficits. Plant Cell Environ 25:395–405. https://doi.org/10.1046/j.0016-8025.2001.00822.x

Moriana A, Pérez-López D, Prieto MH et al (2012) Midday stem water potential as a useful tool for estimating irrigation requirements in olive trees. Agric Water Manag 112:43–54

Naor A (2006) Irrigation scheduling and evaluation of tree water status in deciduous orchards. Hortic Rev 32:111–163

Naor A, Wample RL (1994) Gas exchange and water relations of field-grown concord (*Vitis labruscana* Bailey) grapevines. Am J Enol Vitic 45:333–337

Naor A, Schneider D, Ben-Gal A, Zipori I, Dag A, Kerem Z, Birger R, Peres M, Gal Y (2013) The effects of crop load and irrigation rate in the oil accumulation stage on oil yield and water relations of 'Koroneiki' olives. Irrig Sci 31:781–791

Ortega-Farias S, Fereres E, Sadras VO (2012) Special issue on water management in grapevines. Irrig Sci 30:335–337

Ortega-Farías S, López-Olivari R (2012) Validation of a two-layer model to estimate latent heat flux and evapotranspiration in a drip-irrigated olive orchard. Am Soc Agric Biol Eng 55:1169–1178

Rousseaux MC, Benedetti JP, Searles PS (2008) Leaf-level responses of olive trees (*Olea europaea*) to the suspension of irrigation during the winter in an arid region of Argentina. Sci Hortic 115:135–141

Scholander PF, Bradstreet ED, Hemmingsen EA, Hammel HT (1965) Sap pressure in vascular plants. Science 148:339–346

Secchi F, Lovisolo C, Schubert A (2007) Expression of OePIP2.1 aquaporin gene and water relations of *Olea europaea* twigs during drought stress and recovery. Ann Appl Biol 150:163–167

Sofo A, Dichio B, Montanaro G, Xiloyannis C (2009) Shade effect on photosynthesis and photoinhibition in olive during drought and rewatering. Agric Water Manag 96:1201–1206

Tognetti R, D'Andria R, Morelli G, Alvino A (2005) The effect of deficit irrigation on seasonal variations of plant water use in *Olea europaea* L. Plant Soil 273:139–155

Tognetti R, D'Andria R, Sacchi R et al (2007) Deficit irrigation affects seasonal changes in leaf physiology and oil quality of *Olea europaea* (cultivars Frantoio and Leccino). Ann Appl Biol 150:169–186

Tognetti R, Giovannelli A, Lavini A et al (2009) Assessing environmental controls over conductances through the soil–plant–atmosphere continuum in an experimental olive tree plantation of southern Italy. Agric For Meteorol 149:1229–1243. https://doi.org/10.1016/j.agrformet.2009.02.008

Toms JD, Lesperance ML (2003) Piecewise regression: a tool for identiying ecological thresholds. Ecology 84:2034–2041. https://doi.org/10.1890/02-0472

Trentacoste ER, Puertas CM, Sadras VO (2015) Effect of irrigation and tree density on vegetative growth, oil yield and water use efficiency in young olive orchard under arid conditions in Mendoza, Argentina. Irrig Sci 33:429–440

Williams LE, Araujo FJ (2002) Correlations among predawn leaf, midday leaf, and midday stem water potential and their correlations with other measures of soil and plant water status in *Vitis vinifera*. J Am Soc Hortic Sci 127:448–454

Williams LE, Trout TJ (2005) Relationships among vine- and soil-based measures of water status in a thompson seedless vineyard in response to high-frequency drip irrigation. Am J Enol Vitic 56:357–366

Zsófi Z, Gál L, Szilágyi Z et al (2009) Use of stomatal conductance and pre-dawn water potential to classify terroir for the grape variety Kékfrankos. Aust J Grape Wine Res 15:36–47