RESEARCH

SENSITIVITY AND VARIABILITY OF TWO PLANT WATER STRESS INDICATORS: EXPLORING CRITERIA FOR CHOOSING A PLANT MONITORING METHOD FOR AVOCADO IRRIGATION MANAGEMENT

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Avocado (*Persea americana* Mill.) is a fruit-tree species highly susceptible to water deficit, which makes irrigation management a difficult task for growers. When irrigation is inadequate, trees suffer growth reduction, fruit losses, and roots damage. This study addressed the question of how to assess water stress in avocado trees and the considerations to choose an indicator to measure the plant water stress. In this work the sensitivity and variability of two water stress indicators in response to water deficit were analyzed: stem water potential (SWP) and maximum daily trunk shrinkage (MDTS). During a period of high water demand, avocado trees planted in a clay loam soil were subjected to water stress by withholding irrigation and compared to control trees irrigated according to the maximal crop evapotranspiration. During the study, avocado trees reached a minimum SWP of -0.9 MPa and a maximum MDTS of ~ 285 μm. To better understand avocado tree response to water deficit, leaf abscisic acid, stomatal conductance, soil moisture, and vapor pressure deficit were also measured. Interestingly, it was found that water stress indicators showed differences with control after 3 d of withholding irrigation. It was possible to observe that MDTS was more sensitive in detecting water stress than SWP, signal strength of 4.5 vs. 1.2 respectively; however, MDTS higher variability counteracted its performance as stress indicator, coefficient of variation of 32% vs. 9%, respectively. This study confirms that monitoring water stress is an important tool for avocado irrigation management and should consider both, the sensitivity and variability of the indicator.

Key words: Dendrometers, stem water potential, environmental stress, *Persea americana*.

Avocado (*Persea americana* Mill.) is a subtropical fruit-tree highly sensitive to lack and excess of water in the root zone (Faber *et al*., 1994; Whiley and Schaffer, 1994). Low soil moisture during days of high evapotranspiration can severely reduce avocado fruit yield and quality (Bower and Cutting, 1988), whereas water logging, caused by excessive irrigation or poor soil drainage (matric potentials lowers than -10 kPa), can cause root hypoxia and provide suitable conditions for *Phytophthora cinnamomi* infection (Sterne *et al*., 1977). Avocado trees can respond to water stress by wilting and/or shedding leaves and fruits, a phenomenon enhanced by their shallow root system (Bower and Cutting, 1988). When grown under optimal conditions, avocado orchards can have an average fruit yield of 22 t ha^{-1} yr^{-1} (Whiley *et al*., 1988). However, if the soil has limited physical properties or irrigation is not managed according to soil limitations, fruit yields can be drastically reduced representing one of the major challenges for avocado growers.

The increasing shortage of water resources in avocado producing regions and the need for optimizing irrigation strategies to avoid excess or lack of water in the root zone, has led growers to use sensors to measure soil moisture and plant water status. The use of soil moisture sensors has to consider the natural variability of soils properties and its effects in water distribution in the soil profile (Van Leeuwen *et al*., 2001). Spatial soil variability occurs in three dimensions, laterally and vertically, and can become a major issue in drip and micro sprinkler irrigation systems where a great number of measurements or probes are required for an accurate representation of soil moisture in the root zone (Van Leeuwen *et al*., 2001). In the other hand, plant monitoring techniques such as stem water potential (SWP) and trunk diameter changes (TDC) have the advantage of measuring plant water status directly and may reduce errors due to soil moisture variability. The data provided by both type of sensors can be used together with weather conditions and crop evapotranspiration allowing a more comprehensive irrigation management strategy.

Plant water stress indicators have to be able to detect stress early and reliably in order to be used for irrigation

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scheduling in avocado orchards. Midday SWP has been shown to be a reliable stress indicator in many fruit trees, as described by Naor *et al*. (1995) for apples (*Malus domestica* Borkh. 'Golden Delicious'); by Naor *et al*. (2001) for nectarine (*Prunus persica* L. 'Fairlane'), and as described by Lampinen (1995; 2001) for prunes (*Prunus domestica* L. 'French') among others. In avocado SWP values of -1.0 to -1.2 MPa have been reported as a water stress indicator (Sterne *et al*., 1977; Bower, 1978; Scholefield *et al*., 1980). However, it is not clear if SWP can detect water stress in avocado early enough to avoid its negative effects in fruit yield and roots. Lately, digital dendrometers to measure TDC have attracted the attention of researchers and growers. Other studies have suggested that maximum daily trunk shrinkage (MDTS), a parameter derived from TDC, is a highly sensitive water stress indicator in deciduous trees (Goldhamer *et al*., 1999; Cohen *et al*., 2001). Maximum daily trunk shrinkage has been used as plant water status indicator in several crop species including table grape and wine grape (Gurovich, 1997; Gurovich and Saggé, 2005), peach (*Prunus persica* [L.] Batsch., Sellés and Berger, 1990; Goldhamer and Fereres, 2001; Naor and Cohen, 2003), avocado (Gurovich *et al*., 2006) and other fruit crops (Cohen *et al*., 2001; Moriana and Fereres, 2002; Fereres and Goldhamer, 2003). The high sensitivity of MDTS could represent an advantage for avocado irrigation scheduling where early detection of stress is critical. However, MDTS in apples was found to be more variable than SWP, making it a less reliable stress indicator (Naor and Cohen, 2003). Importantly, the response of MDTS to environmental conditions and water availability is species dependent which has been attributed to water storage capacity in plant tissues surrounding the xylem and to radial resistance to the water flow in xylem vessels (Huguet *et al*., 1992).

Considering the importance of a water stress indicator for avocado irrigation scheduling, the objective of this study was to compare the sensitivity and variability of SWP and MDTS to detect water stress in avocado trees after withholding of irrigation.

MATERIALS AND METHODS

Experimental conditions

The experiment was conducted in a site located in the Coastal Ranges of Central Chile (32º49' S, 71º15' W; 120 m a.s.l.). The weather is Mediterranean marine humid (Santibáñez and Uribe, 1990) with an annual rainfall of 405 mm, concentrated during winter (June-August). The mean maximum daily temperature in summer is 26 ºC, and the mean maximum temperature in winter is 16 ºC. The mean annual pan evaporation is 1095.3 mm. The experiment was carried out in February and March 2006, months of high crop water demand.

The experiment was conducted in a commercial orchard of 'Hass' avocado trees grafted on 'Mexicola' rootstock, planted in the year 2000. The spacing among trees was 5 × 4 m apart. The irrigation system consisted of one lateral line per row with two pressure-compensated micro sprinklers per tree, with a total flow of 70 L h^{-1} $tree^{-1}$. The soil profile was modified to build up ridges (raised beds) due to a shallow effective depth limited by a C horizon. The soil texture was clay loam with a soil bulk density at 30 cm depth of 1.49 g cm^{-3}. The slope in the orchard was 5%.

Experimental design and irrigation treatments

Trees used in the experiment had similar fruit load, vigor and appearance. Twelve experimental plots consisting of three contiguous trees in the same row were selected and the measurements were made only in the central tree while the other two trees served as border trees. For six randomly selected experimental plots, the irrigation was suspended for 13 d (T1 = 0% ETc, no-irrigation), while the other six experimental plots were irrigated at 100% of crop evapotranspiration (T0 = 100% ETc, control), in order to maintain the soil moisture near to field capacity. The volume of water applied daily to T0 trees was calculated using a Class-A evaporation pan close to the experimental site, using a pan coefficient (Kb) of 0.8 and a crop coefficient (Kc) of 0.72 (Gardiazábal *et al*., 2003). Before initiating the treatments all the trees were irrigated with the same frequency and irrigation depth. During the experiment, T1 trees did not receive water through irrigation or rainfall. Throughout the irrigation treatment several plant water status and soil moisture indicators were measured. After the period of irrigation withholding, T1 trees were irrigated with 30 mm of water until the top ~ 40 cm of soil reached field capacity, in one irrigation event, and thereafter were irrigated the same as T0 trees.

Measurements

Stem water potential. Midday stem water potential was measured every 2 to 3 d between 13:00-15:00 h. Six leaves per tree were selected on the external part of the canopy, on sun-exposed branches. Thirty minutes before the measurement, leaves were enclosed in aluminum plastic bags to allow them to reach equilibrium with the stem water potential (Meyer and Reicosky, 1985). Stem water potential was measured with a pressure chamber (Soil Moisture Co., Santa Barbara, California, USA) as described by Scholander *et al*. (1965).

Daily trunk shrinkage and growth measurements. The trunk radius was measured with electronic dendrometers (Model RS-DE-1A, Phytalk™ System, Phytech, Israel). On each central tree one dendrometer was installed between 20-30 cm above the ground, below the first branch and in the northern face in a flat area of the trunk. Measurements were recorded by a portable data logger (Model CPR-1, Phytalk™ System, Phytech, Israel) every

60 min. Maximum daily trunk shrinkage (MTDS) was calculated by subtracting the minimum radius (~ 17:00 h) from the maximum radius (~ 08:00 h). Trunk growth rate was calculated as the difference between the maximum radiuses of two consecutive days.

Stomatal conductance and transpiration. Midday abaxial stomatal conductance (g_s) and transpiration (T) were measured every 2 to 3 d on mature leaves of 10 randomly selected stems on the sun-exposed side of the central-tree with a steady state porometer (Li-1600, Li-Cor Inc., Lincoln, Nebraska, USA) as described by Raviv *et al*. (2001) and Prive and Janes (2003). The stomatal conductance for each central-tree was determined as the average of 10 leaves (one measurement per leaf) per tree.

Leaf abscisic acid (ABA) content. A sample of three mature leaves per central-tree was collected at the beginning and the end of the experiment. The samples were stored and kept in liquid nitrogen before they were transported to the laboratory. The ABA was measured by the monoclonal antibodies indirect method (ABA indirect ELISA Assay) according to the methodology described by Walker-Simmons *et al*. (1989), and the kit ABA Phytodetek (AGDIA Inc., Elkhart, Indiana, USA).

Leaf stomatal impressions. Immediately after measuring g_s, silicone (Polysiloxane) for high accuracy impressions (Oranwash L, Zhermack, Badia Polesine, Italy) was mixed with a hardener (Indurent gel, Zhermack) and spread in a 10 cm^2 area of the abaxial surface of same leaves used for stomatal conductance measurements. The mixture was allowed to dry for 5 min and then pulled off the leaf. After the material hardened, it was painted with clear nail polish to obtain an impression of the surface of the leaf which was then observed with an optical microscope (at 400X) to determine if the stomata were open or closed.

Vapor pressure deficit. Air temperature (T) and the relative humidity (RH) were recorded every 5 min by an automatic device (Hobo datalogger, Onset Computer Corporation, Pocasset, Massachusetts, USA). The vapor pressure deficit (VPD) was calculated from T and RH.

Soil moisture. Soil water content was monitored using a frequency domain reflectometry probe (FDR) (Diviner 2000, Sentek Sensor Technologies, Stepney, Australia) installed at 100 cm from the micro sprinkler in the same line as the trees and irrigation lines. One probe access tube was installed to a 60-cm depth per central-tree. Soil volumetric moisture was calculated using a standard calibration equation provided by the manufacturer. To compare soil moisture between treatments, we used values relative to initial soil moisture before irrigation withholding for each central-tree.

Soil moisture was also measured by gravimetry. One soil sample per central-tree was collected from a position close to the FDR access tube at a 30 to 40-cm depth. The soil samples were collected five times during the course of the experiment.

Sensitivity and variability of water stress indicators. As defined by Goldhamer *et al*. (2000), the "sensitivity" of an indicator relates to the degree of change in water status that can be detected statistically for a given number of measurements. Thus, the "signal" of an indicator is the extent of response of the water stress indicator to changes of water status or water availability; "noise" is the variability between readings of different sensors; and consequently "sensitivity" is the signal-to-noise ratio. The signal of MDTS and SWP was calculated by dividing the average value of T1 trees by the average value of the T0 trees for each day. The noise was calculated as the variation coefficient of T1 trees.

Statistical analysis. Differences between treatment averages were determined by a T-test at $P \leq 0.05$. Data were analyzed by ANOVA using the SAS statistical package (SAS Institute, Cary, North Carolina, USA).

RESULTS AND DISCUSSION

Before the study started midday SWP was measured to show that all the trees in both treatments were in a non-stress condition with an average SWP value of -0.45 MPa (Figure 1B, day 47). After day 47, irrigation continued for T0 trees and was withheld for T1 trees as explained in Materials and Methods. Although T1 trees did not receive more water after day 47, SWP values were not significantly different on days 49 and 51 (Figure 1B). From day 53 to day 60, SWP was significantly different between the two treatments (Figure 1B). The SWP for T0 trees remained between -0.45 and -0.6 MPa while in T1 trees there was a steady decrease in SWP from -0.5 to -0.9 MPa. After the irrigation was resumed at day 61, the SWP of T1 trees reached non-stress values.

The maximum daily trunk shrinkage (MDTS) was greater in T1 trees after day 52 with significant differences among treatments between days 53 to 61 (Figure 2A). Between days 55 and 56 both treatments showed a decrease in the MDTS which coincided with the lower VPD values (1.21 and 1.86 kPa, Figure 1A). During the course of the experiment, there was an increase in the variability of MDTS in T1 trees. After irrigation was resumed (day 61), MDTS immediately recovered to control values showing no significant differences between treatments.

Daily trunk growth was similar for both treatments until day 52 (Figure 2B) with the only exception of day 49. After day 52, trunk daily growth was significantly different between the two treatments with the exception of days 57 and 60, where T0 trees grew less compared to previous days. Although there were significant differences

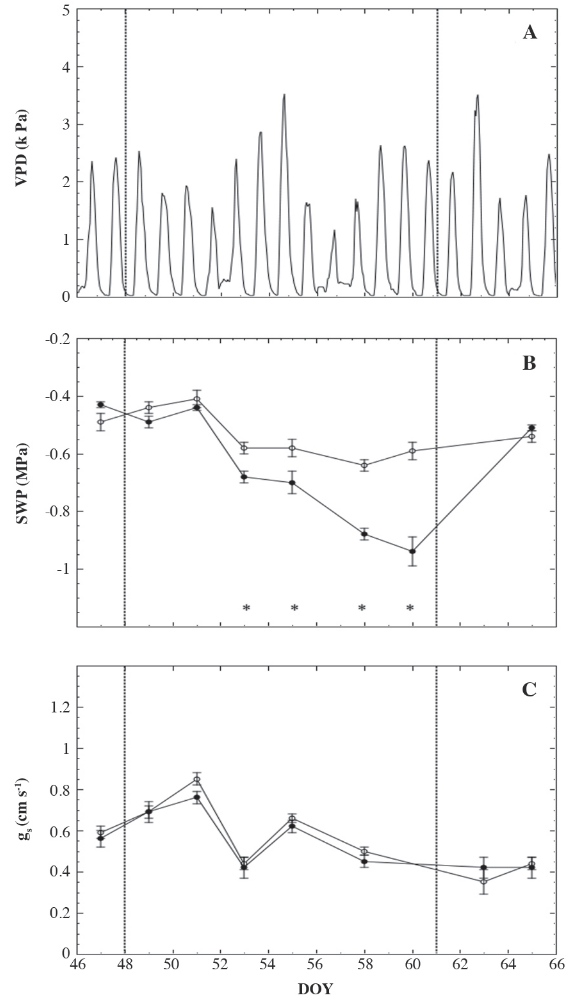

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Figure 1. Variation of vapor pressure deficit (VPD) (A) and comparison of midday stem water potential (SWP) (B) and stomatal conductance (g_s) (C) for T0 (open circles) and T1 (closed circles) avocado trees during the course of the experiment. Vertical dotted lines represent the beginning and end of the irrigation withholding period for T1 trees. Vertical bars indicate standard errors and asterisks indicate significant differences between treatments (T-Test, P≤ 0.05).

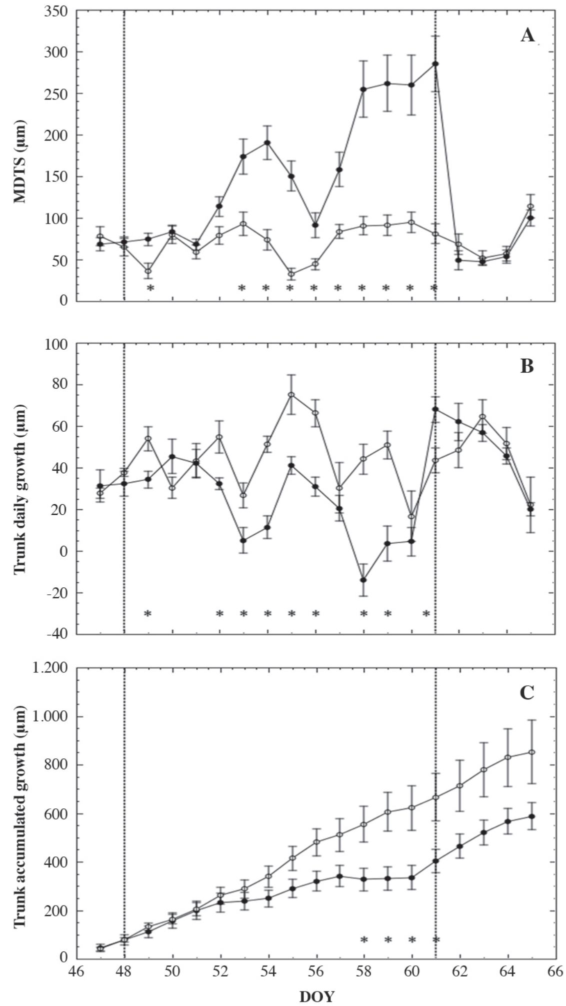

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Figure 2. Comparison of maximum daily trunk shrinkage (MDTS) (A), Daily trunk growth (B) and accumulated trunk growth (C) for T0 (open circles) and T1 (closed circles) trees during the course of the experiment. Vertical dotted lines represent the beginning and end of the irrigation withholding period for T1 trees. Vertical bars indicate standard error and asterisks indicate significant differences between treatments (T-Test, P ≤ 0.05).

in absolute values of trunk daily growth, between days 48 and 57 the two treatments had slopes of the same value, showing a parallelism between T0 and T1 trees influenced by VPD. Only after day 57 can be observed a divergence between the two curves, showing a positive slope for T0 trees and a negative slope for T1 trees.

The accumulated trunk growth (Figure 2C) was similar for both treatments until day 53. After day 53, the two trunk growth curves separate but with no significant differences until day 58. Between days 58 and 61 included, the accumulated trunk growth was significantly different between treatments. After day 61, when the irrigation was resumed, differences observed between treatments were not significant. After day 57, trunk growth in T1 trees ceased while the T0 trees continued growing. When the irrigation was resumed, T1 trees resumed trunk growth at similar rates as T0 trees; however, T1 trees did not reach the accumulated growth of the T0 trees.

The stomatal conductance (g_s) varied between 0.8 and 0.4 cm s^{-1} and was not significantly different between treatments throughout the experiment (Figure 1C). Consistently, there was no significant difference between treatments in ABA levels in leaves neither at the beginning of the experiment, nor at the end of the experiment after 12 d of water stress in T1 trees (Table 1). Consistent with these results, the percentage of open stomata at the beginning of the experiment was 42% for T0, and 45% for T1 trees, condition that did not change significantly at the end of the irrigation withholding period where they were 45% and 32%, respectively.

Table 1. **Abscisic acid (ABA) concentration in avocado leaves. Data express means (n = 6). ABA concentration was measured before and at the end of the irrigation withholding period. Three mature leaves per tree were randomly sampled in a sun exposed branch and stored as in liquid nitrogen. ABA was measured by the monoclonal antibodies indirect method.**

	ABA (ρmol mL^{-1})	
	Day 46	Day 60
Treatment T0	1.9	1.4
Treatment T1	1.2	1.5

T0: 100% evapotranspiration (ETc); control T1: 0% ETc, no-irrigation.

Gravimetric soil moisture at field capacity was of 19%. Similar gravimetric moisture was recorded for both treatments on day 47 before the irrigation withholding period (Figure 3A). T0 trees maintained a gravimetric soil moisture around field capacity throughout the study, while T1 trees showed a steady decrease in gravimetric soil moisture until day 58, when it reached the lowest level. At this point, approximately 80% of the available water content was depleted at 30-40 cm depth. After day 58, soil water content stabilized around 12% and stopped decreasing. Gravimetric soil moisture after day 61 showed an increase due to the resumption of irrigation with the application of 30 mm of water in one irrigation event.

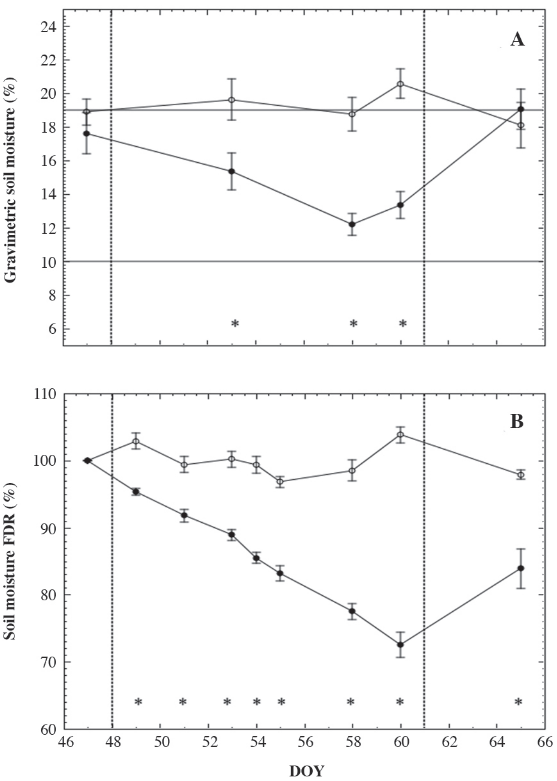

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Figure 3. Soil moisture measured by gravimetry at 30-40 cm depth for T0 and T1 trees (A), and soil moisture measured by frequency domain reflectometry (FDR) (B) (from 0-60 cm depth, values relatives to initial reading) for T0 (open circles) and T1 (closed circles) trees. Vertical dotted lines represent the beginning and end of the irrigation withholding period for T1 trees. Vertical bars indicate standard errors and asterisks indicate significant differences between treatments (T-Test, P ≤ 0.05).

Soil moisture measured with FDR (Figure 3B), showed an overall similar pattern as gravimetric soil moisture. However, the FDR curve continued to decrease after day 58, suggesting that at this point of the experiment roots extracted water from deeper soil layers. After resumption of irrigation in day 61, FDR soil moisture in the T1 treatment did not reach the same soil water content of T0 treatment (Figure 3B), but it was sufficient to leave the top 30 to 40 cm at field capacity (Figure 3A).

Among all the variables measured, SWP and soil moisture measured with FDR had a correlation of r^2 = 0.73 (Figure 4A). The MDTS was also correlated with soil moisture (r^2 = 0.58). The increase in VPD had an effect on both SWP and MDTS, in both treatments between days 51 and 55 (Figures 1 and 2). The effect was stronger in T1 trees. In order to isolate the effect of VPD without the interference of soil moisture, the relationships between SWP vs. VPD and MDTS vs. VPD were analyzed only in T0 trees. In this analysis MDTS had a higher correlation to VPD (r^2 = 0.38) than SWP (r^2 = 0.28). However, this overall weak correlation suggests that SWP and MDTS in avocado do not depend strongly on weather conditions.

The signal-strength of a stress indicator is the response of the variable measured to the stress condition. In this study, the signal-strength of water stress indicators was measured as the ratio of the indicator in T1 trees vs. T0 trees. As indicated in Figure 5A, the signal-strength for MDTS showed a greater sensitivity to water stress compared to SWP. The MDTS signal for T1 trees was 4.5 times greater than T0 trees on day 55, whereas SWP was only 1.2 times greater. However, this greater response to water stress was hindered by the variability of the MDTS signal. Throughout the experiment, SWP showed a lower noise, or variability, compared to MDTS (Figure 5B). The ratio between the response to water stress (signal-strength) and signal variability, named as "signal-to-noise" ratio, allows the determination of the best indicator in terms of its sensitivity and variability. As it can be seen in Figure 5C, the signal-to-noise ratio for MDTS was consistently lower than SWP, except for day 55.

According to Wolstenholme (2002) Mexican and Guatemalan avocado ecotypes originated from subtropical/tropical highland environments with rainfall in the summer and autumn and dry winters and springs. The rainfall in the area of origin of avocado is moderated to high, ranging from 650 mm to 1500 mm. In this context, the results of this study are somewhat unexpected and showed that avocado trees have a greater capacity to tolerate semi-arid environments and to cope with water stress. This conclusion is consistent with previous observations made by Wolstenholme and Whiley (1999), who observed that avocado trees have the ability to tolerate water stress to some degree despite their predominantly mesic adaptation. In this study, MDTS and SWP values changed consistently with the continuous decrease in soil moisture for T1 trees indicating that water was taken up

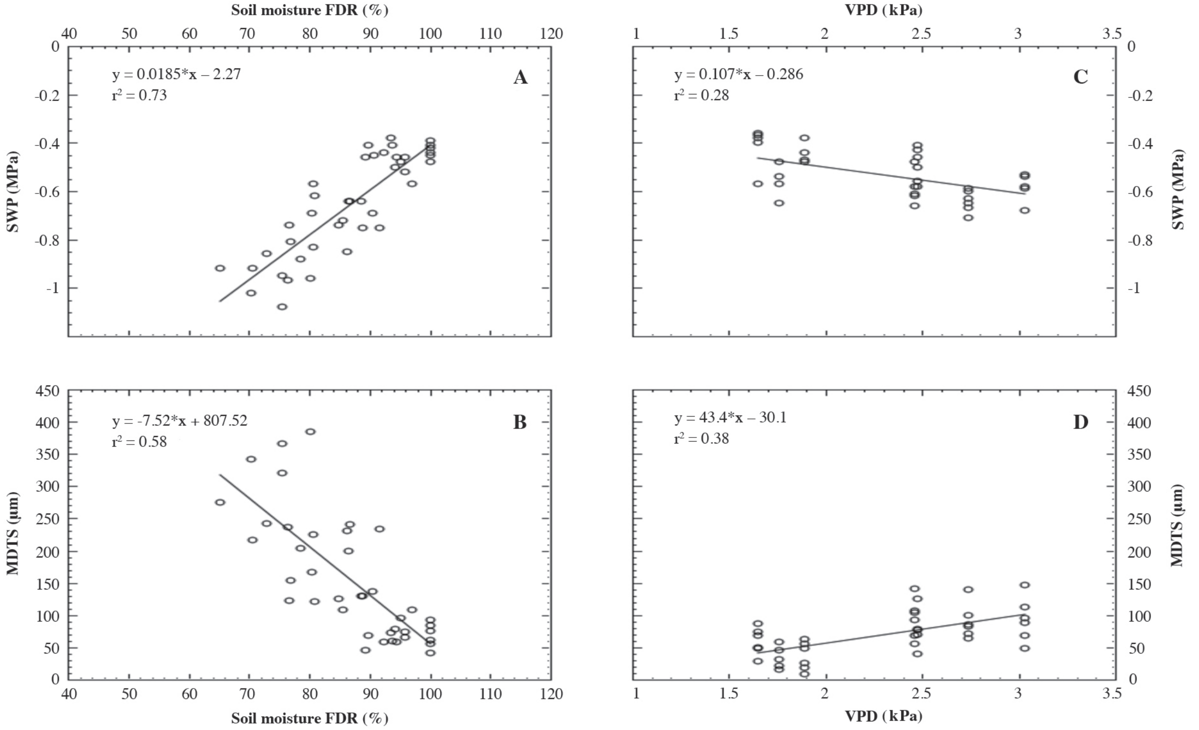

Figure 4. First order regression equations of best fit between soil moisture measured with frequency domain reflectometry (FDR) at 0-60 cm depth and stem water potential (SWP) for T1 trees (A). First order regression equations of best fit between soil moisture measured with FDR at 0-60 cm depth and maximum daily trunk shrinkage (MDTS) for T1 trees (B). First order regression equations of best fit between vapor pressure deficit (VPD) and SWP for T0 (C). First order regression equations of best fit between VPD and MDTS for T0 trees (D).

by the roots and released through the stomata even at the end of the irrigation withholding period. Also, leaf ABA concentrations and stomatal opening were not affected by soil moisture during the course of the experiment, further supporting the idea that T1 trees continued transpiring throughout the irrigation withholding period.

Recent studies to evaluate the effect of different soil aeration levels in avocado physiology and biomass, reported leaf xylem sap ABA concentrations of 341 ρmol mL^{-1} for plants growing under low soil aeration and showing a lower biomass (Gil, 2008). In another study with root hypoxia stressed plants, Gil *et al*. (2009) reported ABA concentrations of leaf tissue of 18.21 ρmol mL^{-1}. ABA concentrations measured in this study for both T0 and T1 trees were well below this value suggesting non-stressed plants.

In avocado, it has been reported that in response to drought, g_s begins to decline when SWP reaches -0.4 MPa and continues to decline until stomatal closure occurs at SWP of -1.0 to -1.2 MPa (Sterne *et al*., 1977; Bower, 1978; Scholefield *et al*., 1980). Also, according to Gil (2008) significant stomatal closure in avocado happens with g_s values lower than 0.125 cm s^{-1}. In this experiment g_s varied between 0.8 and 0.4 cm s^{-1} and was not significantly different between treatments throughout the experiment. Also, there was no significant difference between treatments in ABA levels in leaves neither at the beginning of the experiment, or at the end of the experiment after 12 d of water stress in T1 trees (Table 1). These results indicate that 13 d of soil water depletion in a heavy clay loam soil, reaching 20% of the water availability at 30-40 cm depth, did not highly affect avocado tree water relations.

This study supports the idea that irrigation management could allow some degree of water depletion in the soil without affecting tree growth, i.e. irrigation frequency of 3-4 d (Figure 2C). Both MDTS and SWP indicated an increase in plant water stress level as a result of withholding water from the soil, whereas other physiological parameters, like g_s, did not show significant differences between treatments. An interesting observation was that T1 trees were able to resume growth in the middle of the stress period when the VPD values were low. Such behavior suggests that a deficit irrigation strategy could be useful in soils with poor aeration, restricted drainage and/or large water storage capacity as long as it is implemented when VPD values are low, i.e. early spring, or fall.

Soil moisture measured with FDR (0-60 cm) showed a constant decrease throughout the irrigation withholding period. However, gravimetric soil moisture (30-40 cm) stabilized approximately at day 58. This suggests that

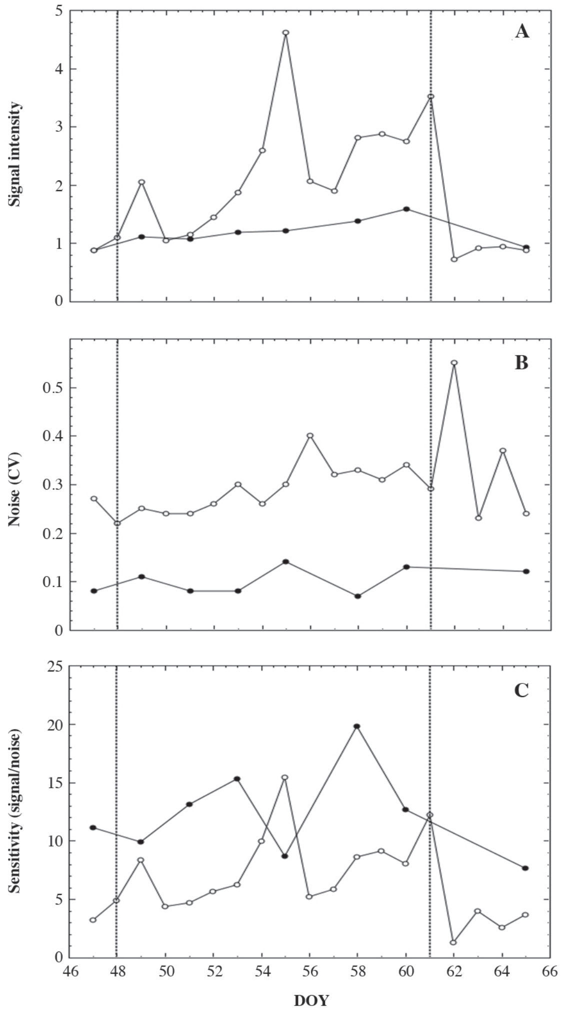

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Figure 5. Signal strength for stem water potential (SWP) (closed circles) and maximum daily trunk shrinkage (MDTS) (open circles) during the course of the experiment (A). Noise (variation coefficient) for SWP and MDTS during the course of the experiment (B). Sensitivity (signal/noise) for MDTS and SWP (C). Vertical dotted lines represent the beginning and end of the irrigation withholding period for T1 trees.

roots may have continued extracting water in deeper soil layers to maintain a transpiration rate of ~ 8.98 μg cm^{-2} s^{-1} (SD 0.6) during the study (data not shown), and that soil moisture did not restrict water uptake by the root system. Similarly, transpiration rate of control trees was 8.95 μg cm^{-2} s^{-1} (SD 0.8) during the study (data not shown).

On day 53 a significant difference in plant water status between T0 and T1 trees was detected by both MDTS and SWP but each indicator presented a different variability. The variability of both indicators increased as the soil moisture was depleted; however, MDTS had a higher variation coefficient (32%) than the SWP (9%) in T1 trees, resulting in a lower signal/noise ratio for MDTS. This was similar to what Naor and Cohen (2003) reported for apple trees but different to what Goldhamer *et al.* (2000) reported in peach trees, where they observed a higher signal-to-noise ratio for MDTS than SWP at the end of the stress period.

The better correlation observed between MDTS and VPD compared to that between SWP and VPD is consistent with the data reported in almond by Fereres and Goldhamer (2003). However, MDTS and SWP in avocado trees depend more on soil moisture than on VPD. The stronger effect of VPD on T1 trees compared to T0 trees was also reported by Sellés and Berger (1990) in table grapes.

The variability in MDTS and SWP increased due to the effect of water stress as the soil moisture decreased. Chartzoulakis *et al*. (2002) found the same trend with avocado stomatal conductance. According to Naor and Cohen (2003) SWP, MDTS and transpiration also showed the same behavior in apple trees. The higher variability of MDTS could be explained by different water conductivities in the xylem tissue that are independent of the plant water status (Naor and Cohen, 2003). Xylem water potential is the main driving force of trunk diameter changes (Klepper *et al*., 1971) but its amplitude is modulated by several factors including the elastic and water diffusion properties of the phloem tissue (Parlange *et al*., 1975; Génard *et al*., 2001), bark-xylem osmotic pressure gradients (Cochard *et al*., 2001), and different organs growth rates (McBurney and Costigan, 1984). In addition, the fact that dendrometers measure the radius in a small region in the trunk and that SWP is representative of a whole branch, may also explain why SWP is less variable than MDTS (Fereres and Goldhamer, 2003).

The variability of an indicator determines the number of sensors or measurements required to have a representative value of tree water stress in an orchard. Therefore, MDTS would need more dendrometers per hectare to achieve the same level of confidence to be used in irrigation scheduling compared to SWP (Goldhamer *et al*., 2000). Our results show that when considering both, sensor sensitivity and variability, SWP is a better stress indicator than MDTS. However, the possibility of automation and low labor costs associated with dendrometers compared to the high labor requirements of SWP measurements should also be taken into account.

This study suggests that a deficit irrigation strategy could be useful in the avocado production management. Future experiments should test the effect of water stress on fruit size and quality, since both could be affected negatively when water supply is restricted. On the other hand, the sensitivity and variability of several water status instruments should be tested when avocado plants are submitted to root hypoxia, a very common problem in the avocado production (Gil *et al*., 2009).

CONCLUSIONS

Monitoring plant water stress is an important tool for irrigation management of avocado orchards. The two indicators tested in this study, SWP and MDTS, showed significant differences between T1 and control trees after 3 d of withholding irrigation. MDTS was a more sensitive indicator to detect stress than SWP (signal strength of 4.5 vs. 1.2); however, it also had a higher variability that counteracted its performance as stress indicator (CV of 32% vs. 9%). The results of this study also showed that avocado trees growing in a clay loam soil can tolerate water deficit better than expected as indicated by similar growth-curves after 4 d of withholding irrigation. This study suggests that monitoring water stress is an important tool in avocado irrigation management and should consider the sensitivity and variability of the indicator at the same time.

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Sensibilidad y variabilidad de dos indicadores de estrés hídrico en plantas: explorando criterios para la elección de métodos de fitomonitoreo para manejo del riego en palto. El palto (*Persea americana* Mill.) es una especie frutal altamente sensible al estrés hídrico, haciendo el manejo del riego una tarea difícil para los productores. Cuando el riego es inadecuado, los árboles reducen el crecimiento, pierden fruta y sufren daño radical. Este estudio aborda el tema de cómo evaluar el estrés hídrico en palto y las consideraciones para elegir un indicador de estrés hídrico de la planta. Este trabajo analizó la sensibilidad y variabilidad de dos indicadores de estrés en respuesta al déficit hídrico: potencial hídrico xilemático (SWP) y contracción máxima diaria del tronco (MDTS). Durante un período de alta demanda hídrica, un grupo de árboles de palto establecidos en suelo franco-arcilloso fue sometido a estrés hídrico mediante suspensión del riego y comparado con árboles control regados según la evapotranspiración máxima de cultivo. Durante el estudio, los árboles alcanzaron un SWP mínimo de -0.9 MPa y un MDTS máximo de ~ 285 μm. Para entender mejor la respuesta de los arboles al estrés hídrico también se midió concentración foliar de ácido abscísico, conductancia estomática, humedad del suelo y déficit de presión de vapor. Los indicadores de estrés hídrico mostraron diferencias entre los árboles tratados y control después de 3 d de tratamiento. Fue posible observar que MDTS fue un indicador más sensible que SWP, intensidad de la señal de 4.5 vs. 1.2 respectivamente; sin embargo, la mayor variabilidad de MDTS disminuyó su capacidad como indicador de estrés, coeficiente de variación de 32% vs. 9% respectivamente. Este estudio confirma que monitorear el estrés hídrico es una herramienta importante para el manejo de riego en palto y que la elección del método debiera considerar tanto la sensibilidad como la variabilidad del indicador.

Palabras clave: dendrómetros, potencial hídrico xilemático, estrés ambiental, *Persea americana*.

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