

Irrigation reduction resistance mechanisms in the rapid fruit growth stage of pears (*Pyrus communis* L.)

Mecanismos de resistencia en la reducción del riego en la fase de rápido crecimiento del fruto de pera (*Pyrus communis* L.)

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ABSTRACT

Plants adopt physiological defense mechanisms to counteract droughts. In Colombia, there is no information for these mechanisms in pears (*Pyrus communis* L.), cv. Triunfo de Viena. Therefore, the present study aimed to analyze the hydric conditions of this plant in order to determine if it has developed a mechanism to avoid, reduce, or tolerate water stresses as a defense. This experiment used a pear crop located in the municipality of Sesquile (Colombia), with 16-year-old trees that were subjected to three irrigation treatments: a control that received 100% of this crop's evapotranspiration (100%ETc), and 73%ETc and 53%ETc treatments were irrigated at 73% and 53% of crop's evapotranspiration, respectively, for the entire rapid fruit growth period of 2012 to 2013. The results indicated that the irrigation reduction in 53%ETc treatment present an adaptive mechanism in the trees, with a structural change in the cellular wall that allowed for 47% water savings in this fruit growth stage.

Key words: evapotranspiration, irrigation rates, drought resistance, physiological adaptation, cell walls, pome fruits.

RESUMEN

Las plantas adoptan mecanismos fisiológicos de defensa para enfrentar la sequía y en Colombia no existe información sobre estos mecanismos en pera (*Pyrus communis* L.) cv. Triunfo de Viena. Por esta razón, el propósito del presente estudio fue analizar las condiciones hídricas de la planta con el fin de determinar si desarrolla algún mecanismo de resistencia para evitar, retrasar o tolerar en respuesta a un estrés hídrico. El experimento se realizó en un cultivo de pera ubicado en el municipio de Sesquile (Colombia), en árboles de 16 años de edad, que fueron sometidos a tres tratamientos de riego. Un tratamiento control (100%ETc) regado con el 100% de la evapotranspiración del cultivo durante todo el ciclo, y los tratamientos 73%ETc y 53%ETc que fueron regados a 73% y 53% de la evapotranspiración del cultivo, respectivamente, durante el periodo de crecimiento rápido del fruto en el periodo de 2012 al 2013. Los resultados obtenidos mostraron que la reducción de riego en el tratamiento 53%ETc se presenta un mecanismo de adaptación en los árboles, mediante un cambio estructural de la pared celular, permitiendo ahorros de agua de un 47% en esta etapa de crecimiento del fruto.

Palabras clave: evapotranspiración, dosis de riego, resistencia a la sequía, adaptación fisiológica, pared celular, pomáceas.

Introduction

The hydric condition of plants is an important factor due to the function of water in all of the biochemical and physiological processes of growth and development (Ortiz, 2006). The state of a plant reflects the conditions of the soil and the effects of the climate (Cohen *et al.*, 2001; Vélez *et al.*, 2007a).

A decrease in the edaphic moisture and an increase in the evaporative demand unleash a series of events that starts with a decrease in the water potential (Ψ), which is seen in all of the plant organs, causing cellular turgor loss (Ψ_p); followed by a synthesis of abscisic acid (ABA), blockage of the synthesis of cytokinins in the roots, an increase in the

xylematic sap (Vila, 2011), a decrease in foliar expansion, stomatal closure, peroxidation of lipids, changes in the permeability of the membranes, degradation of the proteins and changes in gene expression (Moreno, 2009).

Long drought periods can induce anatomical modifications in plants. Changes in the mesophyll structure of olive and avocado leaves have been observed with hydric stresses, with the start of the drought resulting in a rapid modification of the tree-water ratio, decreasing the water potential of the leaves or stems (Morandi *et al.*, 2014). These changes can affect the water potential gradient between the different tree organs with consequences in the xylem and phloem. At the foliar level, ABA and other molecules

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are transported from the roots for use as signals to reduce stomatal conductance and avoid water loss through excessive transpiration (Morandi *et al.*, 2014).

A multitude of drought resistance mechanisms exist in plants. Evolution has resulted in the development of different responses and adaptations that allow for survival in conditions of constant water deficiency (Moreno, 2009). The principal mechanisms are: escape, avoidance, delay or tolerance to water stress, resulting in adaptation and survival (Cruz *et al.*, 2012).

In the escape mechanism, the plant reduces the vegetative cycle and restricts it to the non-drought period, entering dormancy and adapting to very brief periods with edaphic moisture (Torrecillas *et al.*, 1996).

The avoidance mechanisms act on distinct points of the water transport system in the plant and physical action, facilitating the acquisition of water or limiting its loss. To avoid hydric stress, the avoidance mechanisms minimize resistance to the flow of water in the plant, limit transpiration, or promote a reduction in the osmotic potential in order to favor the uptake of symplastic water; furthermore, physical changes occur, such as stomatal closure, increases in water conductance, changes in the tissue elasticity, and morphological changes that decrease the absorbed radiation in order to minimize transpiration (leaf folding, development of impermeable cuticles and hair) (Vila, 2011).

The resistance mechanisms are biochemical in nature and act at the cellular level; tissues suffer the stress and develop biochemical and morphological transformations to counteract it. The morphological transformations result in a decrease in the foliar area, leaf folding or anthocyanin coating, and doubling of the cellular wall and vacuoles that support the cell. Meanwhile, the chemical transformations release thermal energy (xanthophyll cycle) and facilitate the synthesis of compatible solutes, synthesis of antioxidants, and synthesis of antioxidant enzymes (Vila, 2011).

A plant's hydric stress can be monitored through the water potential (Ψ), expressed in megapascals (MPa). It reflects the water tension in the conduction vacuoles of the plant, defining the stress level of the plant (Muñoz, 2005; Arévalo-H. *et al.*, 2013). Another way to look at the hydric state and the mechanisms of adaptation in plants is the volume pressure curve; this technique provides complete information of the hydric state of the leaf, allowing for a determination of a broad spectrum of water parameters in the tissues, such as the total water content, turgor weight/

dry weight ratio, relative water content (RWC), apoplastic water content, symplastic water content, osmotic pressure at zero turgidity and the mean elasticity model (Polanía *et al.*, 2003).

The present study aimed to analyze the hydric conditions of a pear crop (*Pyrus communis* L., cv. Triunfo de Viena) in order to determine if it has developed a mechanism to avoid, reduce, or tolerate water stresses as a defense.

Materials and methods

This experiment was carried out between October of 2012 and March of 2013 with a pear crop (*P. communis*), Triunfo de Viena variety, planted in 1998 with a 4 x 4 m pattern and drip irrigation with six emitters per plant (each giving 8 L h⁻¹) and a frequency of 2 d in a 0.32 ha lot with 17 rows of 10 trees each on the San Benito Farm in the Boitiva district of the municipality of Sesquile (Colombia), at 5°02'53.65" N and 73°48'12.78" W and an altitude of 2,595 m a.s.l., with a mean annual temperature of 14°C (Molina-Ochoa *et al.*, 2015).

Three irrigation treatments were evaluated: a control treatment (100%ETc) with 100% of the crop evapotranspiration (ETc) throughout the year and 73%ETc and 53%ETc treatments with 73% and 53% of the ETc, respectively, throughout the rapid fruit growth period of 2012 to 2013.

A completely random block design was used with three treatments and four replications per treatment (12 lots). Two trees were randomly selected for each lot, taking into account the border effect.

The hydric balance was determined according to the water requirements of the crop, taking into account the mean monthly precipitation, effective precipitation, potential evapotranspiration of the crop and the crop coefficient (Kc) according to the Allen *et al.* (2006), in accordance with the climatic information that was obtained with a portable WS-GP1 weather station (ATdelta-T Devices, Cambridge, UK), installed beside the experiment lot. The climate of the region is temperate with moderate rain throughout the year, with a mean temperature of 14°C and annual precipitation of 890 to 1,500 mm, concentrated in the months of April to May and October to November.

Quantifying the water content and evolution of the soil as a result of rain and irrigation allows for irrigation programming and reveals the effects of water suppression or deficits in the stages of the physiological cycle of the crop (Vélez *et*

al., 2007a). In order to discover the water potential matrix of the soil (Ψ_s), 10 granular matrix sensors per treatment were used for the measurements (Watermark Mod. 200ss Irrrometer Co., Riverside, CA), installed at a depth of 30, 26 cm from the emitter and drip lines, to avoid directly wetting the drip irrigation emitter.

The hydric state of the plants was determined through the stem water potential (Ψ_t), using a Scholander pressure chamber (Model 600, PMS Instrument Co., Corvallis, OR) at midday every 15 d, following the procedure described by Scholander *et al.* (1965), in three mature leaves on two trees per repetition, for a total of 24 per treatment, which were located on the northern side of the trees and covered with aluminum-wrapped, hermetic plastic bags for 2 h before the measurement in order to prevent transpiration.

In order to observe the daily evolution of the foliar water potential of the pear crop (*P. communis*), 75 days after full (DAF), four leaves with a normal transpiration state were collected per repetition, for a total of 16 leaves in the 100% ETC treatment, starting the measurement before sunrise (4:00 AM) and repeating it every 2 h until the potential recovery was observed in the plant (7:00 PM).

In order to reveal the drought resistance mechanisms that the pear trees have adapted, the volume pressure curve was graphed with measurements of the water restriction. For this, 20 completely developed leaves were selected and cut per repetition and immediately hydrated for 24 h in a dark chamber in order to saturate them and observe the total turgidity at the time of measurement. After 24 h, the water potential was determined with a Scholander pressure chamber and the fresh weight was determined with an electronic precision balance, X73%ETC20A (0.001 g precision). This procedure was repeated successively during the dehydration of the tissue in the natural environmental conditions until the variations in the water loss and water potential were minimal (Cruz *et al.*, 2012).

At the end of this process, the leaves were dried in an oven at 80°C for 48 h in order to determine the dry weight and, finally, the relative water content (RWC, %) (Eq. 1) and the total water content (WC, %) (Eq. 2) were calculated.

$$\text{RWC (\%)} = \frac{\text{Fresh weight} - \text{Dry weight}}{\text{Saturated weight} - \text{Dry weight}} * 100 \quad (1)$$

$$\text{WC (\%)} = \frac{\text{Saturated weight} - \text{Dry weight}}{\text{Saturated weight}} * 100 \quad (2)$$

In order to obtain the saturated foliar osmotic potential (Ψ_{os}), fourth leaves were selected per repetition, wrapped in aluminum foil, and frozen at -50°C with liquid nitrogen to detect the metabolic activity (Azcón-Bieto and Talón, 2008). In order to measure the Ψ_{os} , the leaves were thawed and centrifuged with an International device for 10 min at 10,000 rpm to obtain the cellular juice to determine the Ψ_{os} with a Wescor 5520 vapor pressure osmometer (Wescor Inc., Logan, UT).

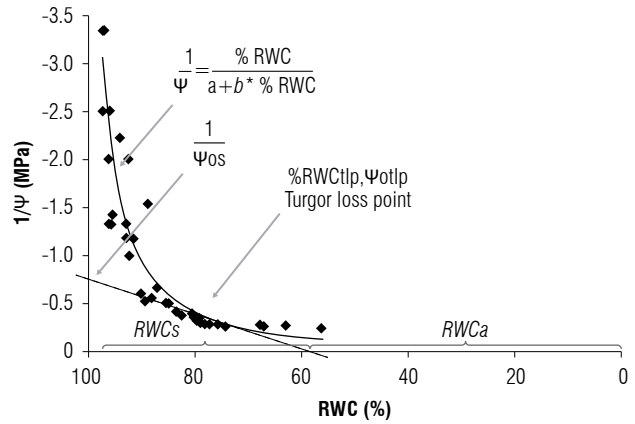


FIGURE 1. Isothermal pressure volume and indicators for the rapid fruit growth stage of pears, where RWC is the relative water content, RWC_a is the relative apoplastic water content, RWC_s is the relative symplastic water content, RWC_{tIp} is the relative water content at the turgor loss point, and Ψ_{oPtIp} is the osmotic potential at the turgor loss point.

The inverse of the leaf water potential (Ψ) was graphed against the relative water content (RWC), obtaining the volume pressure curve for each replication of the three treatments for the evaluated period (Fig. 1).

The modified hyperbolic equation II was used to fit the curve (Eq. 3).

$$f = \frac{x}{(a + b * x)} \quad (3)$$

Where, f is the inverse of the potential in MPa, x is the relative water content, a and b are the regression parameters.

A dotted, straight line was graphed, separating the point of the observed $1/\Psi_{os}$, intercepting the curve and extending to the %RWC axis point where $1/\Psi_{os}$ was zero (Rodríguez *et al.*, 2012) because the dependence of Ψ_{os} on the cellular volume was approximately linear (Azcón-Bieto and Talón, 2008), in order to determine the inverse of the osmotic potential at the turgor loss point ($1/\Psi_{oPtIp}$), the relative apoplastic water content (RWC_a), and the elasticity model (ϵ), which indicated the rigidity of the cellular walls, which, when higher, results in higher resistance to deformation in the wall (Azcón-Bieto and Talón, 2008), as determined with Eq. 4 from Patakas and Nortsakis (1999).

$$\epsilon \text{ (MPa)} = \frac{(\Psi_{os} - \Psi_{stlp}) * (100 - RWCa)}{(100 - RWCtp)} \quad (4)$$

To determine the influence of the irrigation restriction on the fruit setting, a quantitative evaluation was carried out (Garzón *et al.*, 2013). The BBCH scale was used for the selection criteria (Bleiholder, 1996). Principal stage 5 (appearance of floral organs) was selected, code 55 (female flowers, visible (still closed)). In November, two branches were selected and marked at the cardinal point (eight per tree) in two trees per replication, for a total of 64 per treatment, counting the number of flowers every 15 d until the fruit harvest.

The results were analyzed with Statistics IBM (IBM Corp. Released, 2011) through an analysis of variance (ANOVA) and a Duncan mean comparison test, with a 5% significance level.

Results

During the restriction period, the mean daily maximum and minimum temperatures were 15.37°C (79 DAF) and 10.71°C (77 DAF), respectively. The daily vapor pressure deficit (VPD) values had a range of 0.183 and 0.696 KPa at 58 and 94 DAF, respectively, demonstrating a tendency to increase in the days with higher temperatures, as expected. The daily ETo demonstrated an oscillating behavior with a tendency to increase starting at 20 DAF, decreasing with precipitation, as seen between 51 and 58 DAF, as well as at 107 DAF, when there was a new tendency to decrease for the same reason (Fig. 2).

During the irrigation restriction in the experiment period, the water potential matrix in the soil (Ψ_s) (Fig. 3) reached

minimum values of -111.40; -123.00 KPa at 119 DAF and -145.40 KPa at 106 DAF in treatments 100%ETC, 73%ETC and 53%ETC, respectively. The lower Ψ_s values were seen in the treatment with the biggest reduction of the water lamina (53%ETC), with significant differences ($P \leq 0.05$) when compared to the properly irrigated treatment (100%ETC) throughout the period, except at 53, 147 and 161 DAF, due to precipitation that prompted recovery and leveling of the treatments. These results corroborated the sensitivity and precision of the sensors that were used to monitor the soil moisture in this experiment for the drying cycle. In a general sense, the Ψ_s can be defined as having had an expected behavioral relationship with the irrigation application, with recovery when the rains arrived, reaching a balance at 161 DAF, corresponding to the difference of the potential matrix of the soil in accordance with the applied irrigation lamina.

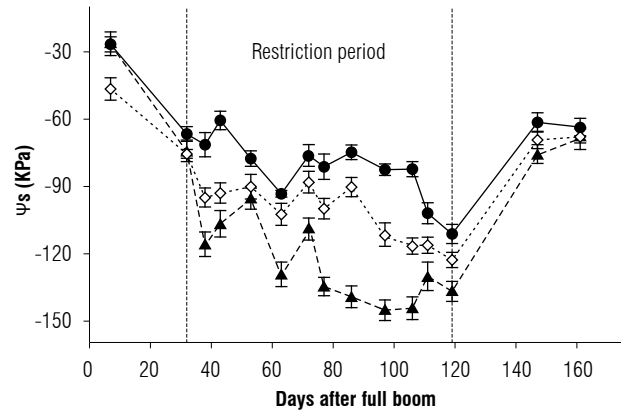


FIGURE 3. Soil potential matrix (Ψ_s) at a depth of 0.6 m for treatments irrigated at 100% of crop's evapotranspiration (continuous, thick line), 73% (dashed lined), and 53% (dotted line) in the rapid fruit growth stage of pears. Means with different letters indicate significant differences according to the Duncan test ($P \leq 0.05$). Error bars indicate standard error.

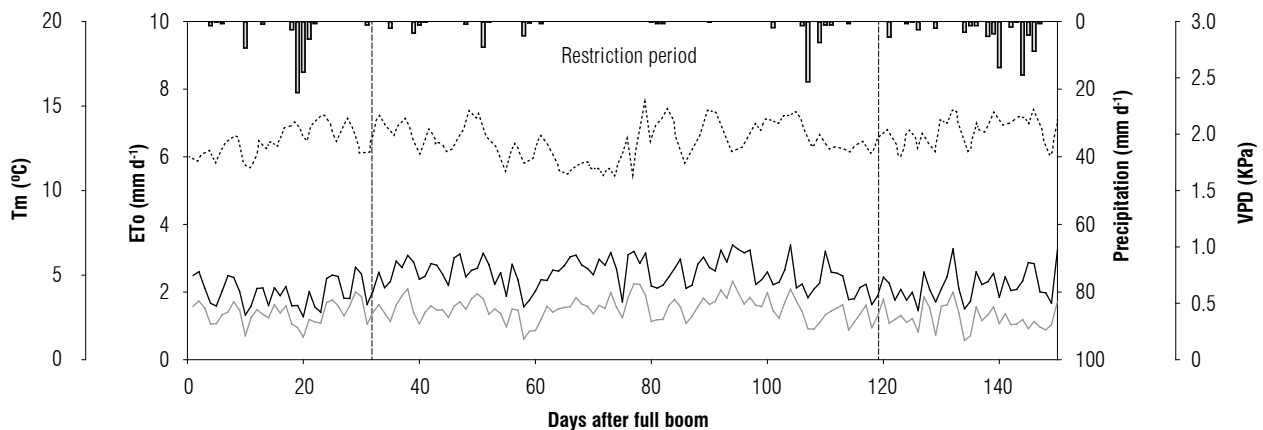


FIGURE 2. Mean daily temperature (dashed line), daily evapotranspiration potential (continuous, thick line), daily precipitation (vertical bars) and daily vapor pressure deficit (continuous, thin line) during the rapid fruit growth stage of pears.

During the irrigation restriction, the Ψ_t (Fig. 4) demonstrated a behavior that was similar in all of the treatments, with some exceptions in the treatment with the lowest water lamina (53%ETC) when there was no precipitation. The higher values were seen at the start of the irrigation restriction.

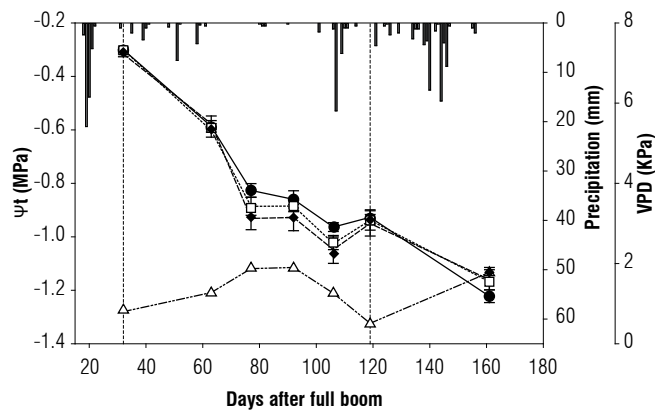


FIGURE 4. Precipitation (vertical bars), vapor pressure deficit (continuous, thin line), plot of the stem potential (Ψ_t) in treatments irrigated at 100% of crop's evapotranspiration (continuous, thick line), 73% (dotted line) and 53% (dotted line) during the rapid fruit growth stage of pears. The values correspond to the mean of three leaves per tree from eight trees per treatment. Error bars indicate standard error.

Treatment 53%ETC, which had the lowest irrigation lamina, had the lowest Ψ_t value (-1.05 MPa) and the control (100%ETC) had the highest (-0.96 MPa) at 106DAF; these values are lower than the ones observed by Molina (2014) in the same lot during the 2011 to 2012 cycle, applying irrigation lamina that corresponded to 67 and 55% of the ETC, with a mean Ψ_t of -0.65 and -0.42 MPa, respectively.

During the 87 d of irrigation restriction, the Ψ_t decreased similarly in the three treatments, with recovery when the precipitation was 17.80; 6.20; 1.00 and 1.00 mm at 107, 109, 110 and 111 DAF, respectively, with values between -0.93 and -0.95 MPa (119 DAF). The stem potential values (Ψ_t) during the experiment were considered typical for fruit trees with these characteristics when properly irrigated. Similar results were obtained by Galindo *et al.* (2014) and Rodríguez *et al.* (2012) in pomegranate, by Cruz *et al.* (2012) in jujube (*Zizyphus jujuba*), and by Mellisho *et al.* (2011) when studying the hydric stress resistance mechanisms in peach trees exposed to different irrigation levels in the Mediterranean region. These studies were carried out in the rapid fruit growth phase. Morandi *et al.* (2014) observed a Ψ_t range of -1.22 to -0.30 MPa in pears, Ab-béfétel variety, with a 25% ETC application, results that agree with those of the present study, independent of the applied treatments.

Figure 5 shows the daily evolution of the foliar water potential (Ψ) in the control treatment (100%ETC) under suitable irrigation conditions, which were directly proportional to the evaporative demand, oscillating between -0.22 and -1.42 MPa between 4:00 and 14:00, gradually decreasing in the morning, stabilizing at midday and starting recovery at 14:00; the same behavior was observed in the Mediterranean climate by Cruz *et al.* (2012) in *Z. jujuba* and by Vélez *et al.* (2007b) in Nules clementine.

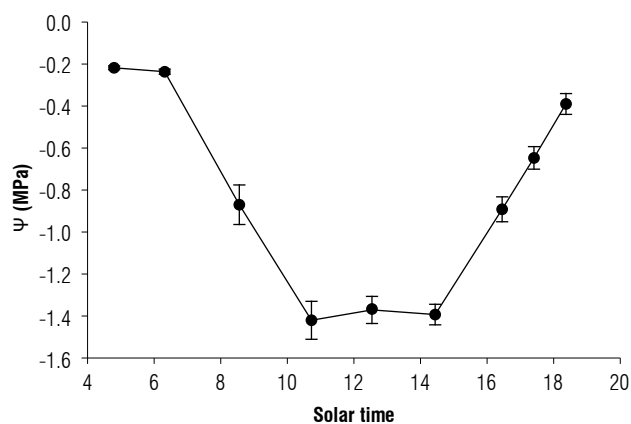


FIGURE 5. Daily plot of the leaf water potential (Ψ) in the control treatment irrigated at 100% of crop's evapotranspiration under conditions with adequate water supply. Error bars indicate standard error.

It was also observed that the foliar water potential (Ψ) had an inverse relationship with the vapor pressure deficit, with higher Ψ values when the VPD decreased (Fig. 4), similar results were found by Measham *et al.* (2014) in sweet cherries (*Prunus avium*); by Vélez *et al.* (2007a) in clementines; by Morandi *et al.* (2014) in the pear variety Abbéfétel and by Molina (2014) in the same crop.

Figure 6 presents the volume pressure curve for the three treatments, plotted with the mean values that were obtained in each replication with the modified hyperbolic equation II and the coefficient of significance determination (R^2) for each of the treatments.

The osmotic potential (Ψ_{os}) (Tab. 1) was not affected by the irrigation lamina, with values of -2.29; -2.36 and -2.36 MPa for 100%ETC, 73%ETC and 53%ETC, respectively, without significant differences ($P \leq 0.05$) between the treatments.

The isothermal volume pressure of the replications of each treatment was used to obtain the leaf water content (LWC), the relative water content at the turgor loss point (RWCltp), the relative apoplastic water content (RWCa), the osmotic potential at the turgor loss point (Ψ_{optlp}) and the maximum elasticity (ϵ_{max}) (Tab. 1).

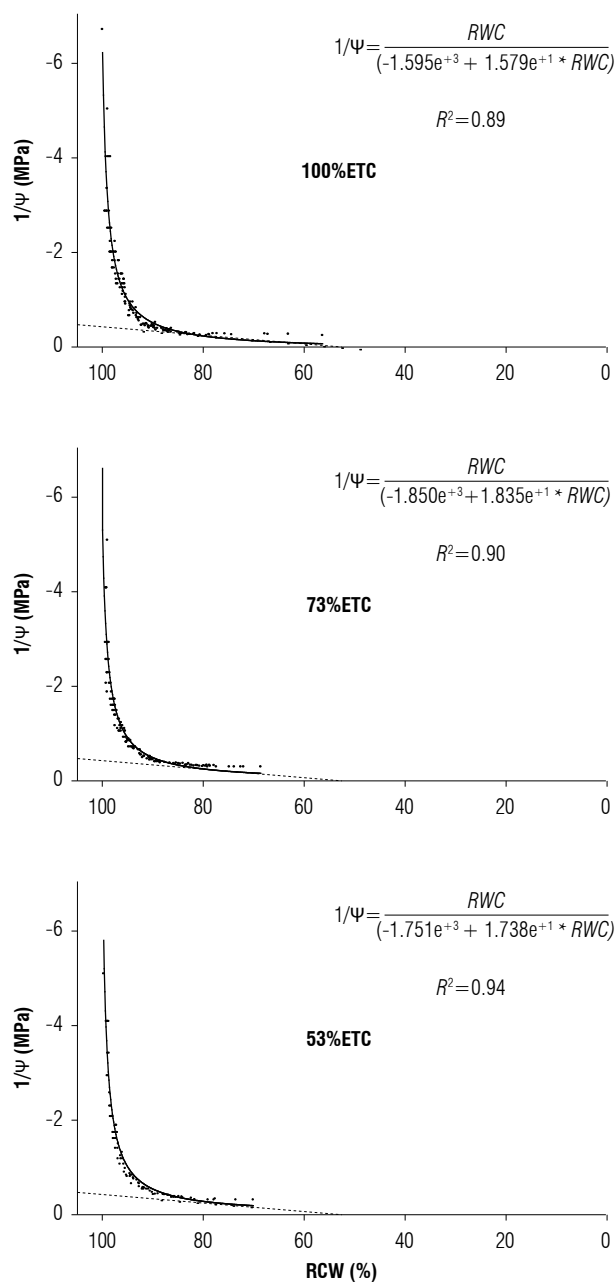


FIGURE 6. Isothermal pressure volume, fit slope (continuous line) and fit slope intercept (dotted line) in the rapid fruit growth stage of pears. The adjustment equation and coefficient of determination for the treatments irrigated at 100% of crop's evapotranspiration (100%ETC), 73% (73%ETC) and 53% (53%ETC).

The osmotic potential at the turgor loss point (Ψ_{optlp}) did not have significant differences ($P \leq 0.05$) between the treatments, which indicated that the plants did not exhibit a tolerance mechanism that involved adjusting the osmotic potential in order to maintain the water gradient from the soil to the leaves, possibly because the hydric stress did not occur for a prolonged period and was not very severe (Cruz

TABLE 1. Effects of the irrigation restriction in the rapid fruit growth stage of pears.

Parameter	100%ETC	73%ETC	53%ETC
MCf (%)	63.847 a	63.036 a	62.492 a
Ψ_{os} (MPa)	-2.294 a	-2.355 a	-2.357 a
RWCtlp (%)	74.121 a	75.452 a	78.070 a
RWCa (%)	49.020 a	51.690 ab	59.920 b
Ψ_{optlp} (Mpa)	-4.728 a	-4.715 a	-5.140 a
ϵ_{max} (Mpa)	13.890 a	13.900 a	13.870 a

MCf, foliar moisture content; Ψ_{os} , osmotic potential at full saturation; RWCtlp, relative water content at the turgor loss point; RWCa, relative apoplastic water content; Ψ_{optlp} , osmotic potential at the turgor loss point; ϵ_{max} , maximum elasticity model. Means with different letters indicate significant differences according to the Duncan test ($P \leq 0.05$).

et al., 2012; Arndt *et al.*, 2001); in this case, the restriction period to the measurement point was only 92 DAF.

The ϵ_{max} values were similar between the treatments, without significant differences ($P \leq 0.05$), which indicated that an elasticity adjustment response to the hydric stress was not developed, a similar behavior to that seen for the RWCtlp. Savé *et al.* (1995) confirmed that the RWCtlp is directly influenced by the ϵ_{max} .

It is important to note the significant difference ($P \leq 0.05$) observed between the control treatment (100%ETC) and 53%ETC for the relative apoplastic water content (RWCa), which can be interpreted as an adaption mechanism for hydric stresses (Serrano and Peñuelas, 2005) because there was a structural change in the cellular wall that allowed for a higher accumulation of apoplastic water (Cruz *et al.*, 2012). The RWCa values were high (49-60%) when compared to those observed by Cruz *et al.* (2012) in jujube (*Z. jujuba*) (29-41%) and by Rodríguez *et al.* (2012) in pomegranate (41-54%); this may have been due to the semiarid climate of the crops or to the high resistance to hydric deficits in this species.

There were no significant differences ($P \leq 0.05$) between the treatments for the percentage of fruit set or physiological fruit drop, which indicates that the restriction applied during the 2011 to 2012 cycle with irrigation lamina that corresponded to 67 and 55% of the ETC for treatments 73%ETC and 53%ETC did not affect the fruit set or drop in the second year of the applied restrictions (Fig. 7). Similar results were reported by Pierantozzi *et al.* (2013) in olive trees (*Olea europea* L. cvs. Arbequina and Manzanilla) with irrigation lamina applications that were 75 and 50% of the ETC for 2 years.

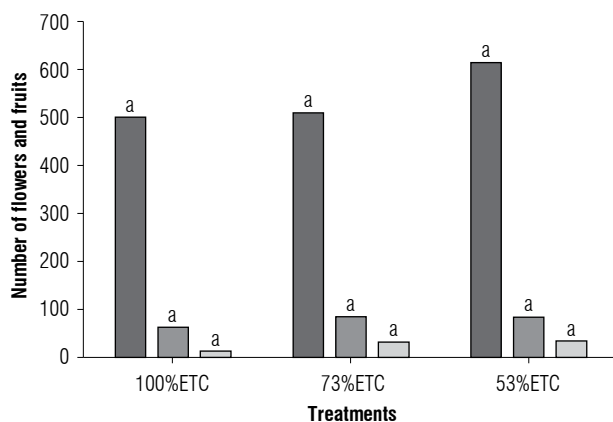


FIGURE 7. Mean number of flowers (black bars), number of set fruits (gray bars with diagonal lines), and number of fruit drops (white bars with diagonal lines) in the rapid fruit growth stage of pears irrigated at 100% of crop's evapotranspiration (100%ETC), 73% (73%ETC) and 53% (53%ETC).

The percentage of fruit drop was 12.72, 16.79 and 13.77% for treatments 100%ETC, 73%ETC, and 53%ETC, respectively. The physiological fruit drop was higher in the more deficient treatment (40%) as compared to the control treatment (21%). Girona *et al.* (2003) found that a hydric stress in peach trees decreases the fruit drop before the last growth phase, similar to the findings of Intrigliolo *et al.* (2013) for pomegranate fruits that received a regulated deficit irrigation application during the flowering and fruit set periods.

Conclusions

The parameters obtained with the isothermal volume pressure demonstrated a clear methodology for the study of hydric stress tolerance mechanisms in these crops. The pear (*P. communis*) did not carry out an osmotic adjustment nor did it adjust the elasticity in the treatments that had a reduced irrigation lamina. The leaf water content remained at a similar level, while the relative apoplastic water content (RWC_a) presented an increase in the treatment with the lowest irrigation lamina (53%ETC), as compared to the properly irrigated treatment (100%ETC), which can be defined as an adaptation mechanism for *P. communis* for hydric stresses and explains the hydric state of the trees exposed to the irrigation conditions of 53%ETC.

The differences in the fruit drop and set between the treatment with the least irrigation (53%ETC) and the control treatment (100%ETC) were not significant.

Further studies on the mechanisms adopted by *P. communis* in other production periods with inferior irrigation lamina are recommended in order to determine if other adjustments are carried out for resistance to hydric deficits.

Acknowledgements

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