WATER REQUIREMENTS AND WATER USE EFFICIENCY OF CARROT UNDER DRIP IRRIGATION IN A HAPLOXERAND SOIL

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ABSTRACT

Water management efficiency is a key issue for sustainable agriculture development, since it is necessary to get a higher biomass production per unit of applied water. This study aimed to determine both water requirements and water use efficiency (WUE) and their effect on yield and quality parameters in carrots (*Daucus carota* L.), during the 2006 – 2007 growing season in Chillán, Chile (36º 35' 43.2" S, 72º 04' 39" W, 140 m altitude). The water treatments applied were 25, 50, 75, 100 and 125 % pan evaporation (E_{pan}) in a Haploxerand soil under drip irrigation. The results showed that the highest crop yield was obtained with 100% E_{pan} treatment. However, the highest WUE was found in the 75% E_{pan} treatment equivalent to 3864 m^3 ha^{-1}, which is the recommended water application level in irrigation scheduling. Regarding carrot crop yield and quality parameters, statistical differences between the different water treatments were not significant, but the increase of applied water (125% E_{pan}) reduced plant density and root length. This relationship between yield and applied water will allow to improve the management of water resources under water scarcity.

Keywords: Water content, Roots quality, Water stress, Andisols.

INTRODUCTION

Scarcity of water resources is a worldwide issue due to their increasing demand, as a result of world's growing population and social-economic development (Zapata y Segura, 1995). The pressure on water resources is expected to increase as the requirements for food production and industrial needs go up in parallel with the country's rapidly growing population (Webber *et al*., 2006). Water resources are limited worldwide and there is an urgent need to identify and adopt efficient irrigation management strategies since irrigation of agricultural lands accounts for over 85% of worldwide water usage (Zegbe *et al*., 2006).

Sprinkler and drip irrigation systems can be used to decrease agricultural water demand. Water savings can be achieved either by decreasing the frequency of irrigation events or by a systematic reduction of water inputs (Darwish *et al*., 2006). Richards *et al*.(2002) indicate that crop water use efficiency (WUE) can be increased either by enhancing crop transpiration or by plant breeding to produce greater biomass (CO_2 assimilation) and yield per unit of water used.

Climate change poses significant challenges to agriculture due to increased temperatures, droughts and water scarcity, but it also provides opportunities to improve crop yields in arid and semiarid zones. Yield of water-limited crops is determined by crop water use and WUE, both of which can be affected by the increase in atmospheric carbon dioxide (CO_2) and temperature. At leaf level, the increase in transpiration efficiency may result both from an increase in photosynthetic rate and a decrease in stomatal conductance (Wayne, 2002).

WUE can be maximized by applying deficit irrigation, irrigation technology and irrigation scheduling as well as by improving agricultural practices that can result in the increase of crop yields. Drip irrigation is the response to pressure on limited fresh-water resources and plays an important role in the increase of WUE. Nevertheless, there is still limited information on how to use it on conventional crops. Hassanli *et al*. (2010) found that WUE increased from 4.15 kg m^{-3} with furrow irrigation to 8.2 kg m^{-3} with drip irrigation in a sugar beet crop.
WUE has remained as a research topic of interest to plant, soil and irrigation specialists due to the fact that water shortage for agriculture has generated a strong need to design strategies aimed at improving WUE (Behboudian and Sing, 2001). In addition, it can be used as a tool of plant management to improve crop yield and product quality.

Water use efficiency (WUE) is generally used to express the ratio of total dry matter production to evapotranspiration and it is influenced by a variety of factors, such as crop type, atmospheric environment, cultivation practices and soil conditions (Liu *et al*., 2002). Given the climate characteristics of Chile, droughts occur with frequency and these affect water availability in irrigated zones, resulting in a high risk for crop production (Sellés *et al*., 2003). It is also noteworthy that 84.5 % of the consumptive water rights are used in agricultural land irrigation (Novoa, 2004). Therefore, it is necessary to increase WUE, decreasing the applied water volume without affecting crop yield, especially in water-scarce regions (Bebhoudian and Singh, 2002).

Chile presents a great variety of soils. The Central Zone of the country presents a wide range of soil types from different origins and characteristics, predominating alluvial soils and those derived from volcanic ashes (Honorato, 2000). Carrot is considered as an economically important crop for the country, with a seeded area of 3819.76 ha in the season 2006-2007. This crop is mainly produced in the Bío-Bío Region (999.67 ha), the Metropolitan Area (915.70 ha) and the Valparaiso (822.70 ha) Region (INE 2007). Carrots are cultivated preferably in deep, loam textured, not stony, well drained soils (Giaconi and Escaff, 1993).

Water requirements range from 6000 and 9000 m^3 ha^{-1} with an average pan evaporation of 6 to 7 mm d^{-1}, depending mainly on the crop period, which lasts between 100 and 140 days (Villeneuve and Leteinturier, 1992). A study carried out on a carrot crop showed higher root production, total dry matter and WUE with a water application level of 100 % E_{pan} (Prabhakar *et al*., 1991). Moreover, Gibberd *et al*. (2003) studied water application in a carrot crop cultivated in sandy soils and determined that a higher marketable carrot yield is obtained with water application level of 151% E_{pan}. However, there is little information available in our country regarding carrot irrigation management with high efficiency systems. Therefore, this study aimed at determining water requirements and WUE, by applying different water application levels on a carrot crop under drip irrigation and evaluating their effects on yield and quality parameters in Haploxerand soils.

MATERIALS AND METHODS

Experimental site

This study was performed at El Nogal Experimental Station of the University of Concepcion in Chillán, Chile (36º 35' 43.2” S, 72º 04' 39” W, 144 m above sea level) during 2006-2007 growing season. This area presents a Mediterranean climate, with an annual rainfall of about 1000 mm per year, concentrated between May and August, with a potential evapotranspiration of around 1200 mm. Annual mean temperature is 13.6º C, with an average temperature of 8.0º C in the coldest month (July) and 19.7º C in the hottest month (January). Annual mean relative humidity is 71.3% and the frost-free period is 5 to 6 months. Soil is classified as medial, amorphic, thermic Humic Haploxerands, derived from volcanic ashes, moderately deep, loamy textured, with an average bulk density of 1.18 g cm^{-3}, and with good drainage (Stolpe, 2006). Soil water content (0-30 cm depth) varied between 45.8% BDW (basis dry weight) at field capacity (FC) and 31.3% BDW at permanent wilting point (PWP). Threshold level (TL) corresponds to 50% of plant available water or difference between values for FC and PWP. The carrot crop was sown manually in September. The used variety was Abaco and seeds were sown at rate of 1-2 seeds 5 cm^{-1} (1.7 a 2.5 kg ha^{-1}). Prior to sowing, soil was fertilized with concentrated superphosphate 24 kg ha^{-1}, urea 24 kg ha^{-1} and potassium muriate 50 kg ha^{-1}. Foliar nitrogen was applied at a rate of 30 kg N ha^{-1} in November.

Experimental design

The experiment was set up in a randomized block design with five treatments and four replicates. The plot size was 5 m x 0.7 m. Each plot consisted of eight rows. Water treatments were set as a percentage of E_{pan}: values of 25%, 50, 75, 100 and 125% for 2007-2008 period, according to data provided by the Agrometeorological Station of University of Concepción in Chillán. Crop evapotranspiration was determined as follows:

$$ET_c = E_{pan} * K_{pan} * K_c$$

where: ET_c= crop evapotranspiration; E_{pan} = pan evaporation (mm day^{-1}); K_c = plant coefficient; K_{pan}= pan coefficient (0.75). The used K_c values were initial (0.7); mid-season (1.05) and late season (0.95) (FAO, 2006).

Water was applied by drip irrigation, using tape Queen Gil (Bulgaria) with emitters spaced 10 cm apart, each delivering 4 L h^{-1} m^{-1}, at a pressure of 10 water meter column pumped from a 5 m deep well with Pedrollo (Italy) CPm 158-E of 1 HP.

Soil water measurements

Soil water tension was measured in each treatment on a weekly basis and after each irrigation, using tensiometers Irrometer at 30 cm deep. In addition, the volumetric soil water content was measured by dielectric sensor TDR, Delta Devices model Profile Prob-PR2 (England) at 30 cm deep. The calibration curve was performed during the trial period, obtaining the following regression equation (R^2= 0.8597)

$$\theta = 0.0991 x - 2.1002$$

where: θ= volumetric water content(%); x = volumetric water content dielectric sensor (m^3 m^{-3})

Crop yield parameters

Crop yield parameters were measured in three dates during the crop period

(December 28, 2006 and January 15 and 25, 2007). Measurements were carried out in 5 plant samples per replicate and treatment in a 50 cm x 50 cm square, and the following determinations were made: (a) plant number, (b) marketable yield, (c) biomass accumulation, and (d) root basal diameter. Fresh weight and dry weight of roots and foliage was also measured in order to determine biomass accumulation. Foliage samples were dried at 60ºC for 48 hours to foliage, and root samples were dried at 60° C for 96 hours in SL Shel Lab ventilation oven, model 1370 FX (United States).

WUE was determined by the relationship between kg fresh matter and m^3 applied water. In addition, the harvest index (HI) or relationship between cropping biomass and total biomass was also determined.

Root quality parameters

Soluble solid concentration (ºBrix) of roots was determined at physiological maturity, using a KRUSS refractometer(Germany) model HRT-32. Measurements were also made at harvest time by evaluating the length of the main root.

Statistical analysis

Data were analyzed using analysis of variance (ANOVA). Comparisons between averaged values from the different treatments were made by the Duncan's test at 0.05 probability significance level (Infostat, 2004). Plant density data were subjected to non-parametric ANOVA by Kruskal-Wallis ($p \leq 0.05$).The conversion of data to percentage was made by the relationship $(x + 0.5)^{½}$ to adjust them to normal distribution (Steel and Torrie, 1992).

RESULTS AND DISCUSSION

Applied water volume

The applied water volumes were 2379 m^3 for 25 %; 3122 m^3 for 50 %; 3864 m^3 for 75 %; 4607 m^3 for 100 %, and 5349 m^3 for 125 % E_{pan} (Table 1), including rainfall from November 9, 2006 to January 24, 2007.

Table 1. Water requirements and water use efficiency in carrot with different water treatments under drip irrigation in a Haploxerand soil. Columns with different letters differ significantly, Duncan's test ($p \leq 0.05$).

Treatments	Yield (kg ha⁻¹)	Applied water (m³ ha⁻¹)	WUE (kg m^{-3})	ΔY/ΔW (kg m^{-3})
25 % Eb	67,434 a	2379	28.3 a	-
50 % Eb	80,490 ab	3121	25.8 a	17.58
75 % Eb	94,891 b	3864	24.6 a	19.40
100 % Eb	103,632 b	4606	21.4 a	11.77
125 % Eb	98,456 b	5349	19.4 a	-6.97

WUE= Water use efficiency; ΔY/ΔW = Marginal yield / Marginal water applied

Spring rainfall reached 90.99 mm prior irrigation, and during the period of plant growth, which allowed a good level of soil moisture. The total rainfall was 163.68 mm (Figure 1). The total pan evaporation was 537.79 mm, with an average of 5.54 mm d^{-1} during crop growing season. In contrast, Galeano (2003) determined that with a water application level of 7 mm day^{-1} and adding the season rainfall, applied water was 9261 m^3 ha^{-1} with drip irrigation in carrots. These differences can be explained by the number of irrigations, level of water applications and soil water retention capacity.

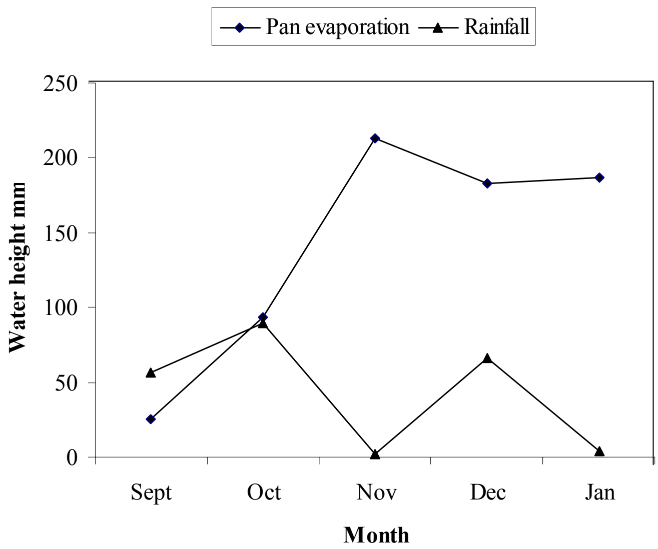

Figure 1. Pan evaporation and rainfall during the 2006-2007 growing season in Chillán, Chile.

Soil water tension

Soil water tension (Figure 2) shows an increase in 25 and 50 % E_{pan} treatments due to a rapid and constant loss of soil water content, as a result of a low water application, with tensions between 60 and 70 cb. On the other hand, soil presents higher water availability and tensions between 15 to 20 cb with the 100 % and 125 % E_{pan} treatments, during the whole growing period of carrots. Therefore, a better development and higher crop yield was obtained, the same as with 75 % E_{pan}, where tension ranged between 15 and 50 cb. These results agree with the findings of Thompson *et al.* (2004) who determined that the highest yields in vegetables are obtained with tensions between 15 and 45 cb. In this study, critical tensions varied between 40 and 50 cb and between 15 and 20 cb, demonstrating that the energy status of soil water is a good indicator of scheduling irrigation in high frequency systems (Taylor *et al.*, 2004).

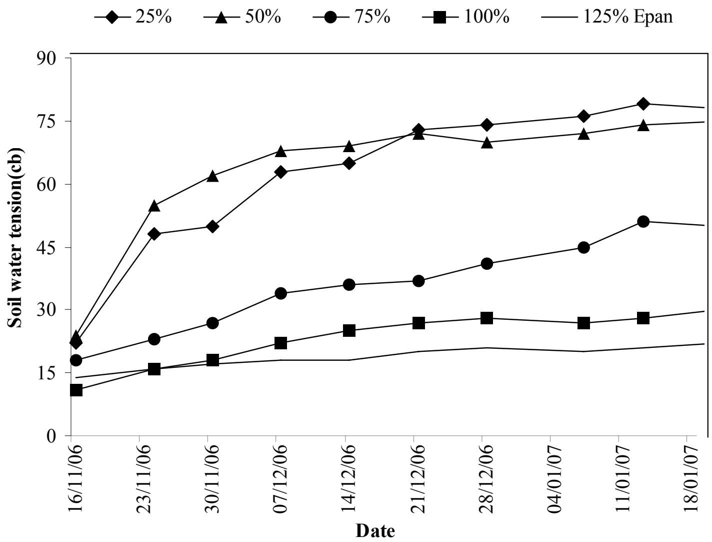

Figure 2. Soil water tension (cb) under the different water treatments measured at 30 cm deep during the study period in a Haploxerand soil.

Volumetric water content

The volumetric water content (Figure 3) measured at 30 cm of soil depth shows that E_{pan} treatments the soil water remained during all the season close to FC in the 100 % and 125 %. With 75 % E_{pan}, a constant loss of soil water content is observed, coming under the threshold level (TL), while with 25 % and 50 % E_{pan} the level of soil water content decreased rapidly under the TL, reaching levels close to the PWP.

Crop yield parameters

The results obtained in yield parameters are similar to the findings reported by Gray and Benjamin (1994) who explained that the variation in root weight at harvest can be influenced by plant size at emergence and by the degree of competition between plants. The water treatments did not show significant effects on plant density, root size and discarded roots (quality loss for cracking, deformity, insect damage or diseases). The highest yields were obtained with 75 and 100 % E_{pan}, probably due to a low density (Table 2) and roots of greater size. The 125 % E_{pan} treatment showed lower plant density and smaller root size due to the fact that water excess in the soil decreases the oxygen diffusion rate in the root zone (Wan and Kang, 2006) affecting crop yield. However, these results presented no statistically significant differences ($p > 0.05$) in discarded roots, but there was a significant effect on the total marketable yield of carrot roots (Figure 4). The analysis of the effect of the water treatments on dry weight of roots and foliage (Figure 5) demonstrated that the highest increases were obtained with 100 % and 125 % E_{pan}, but with no statistically significant differences ($p \leq 0.05$) were found between the treatments during the season. The curve of fresh weight (data not shown) presented the same shape as the dry weight curve.

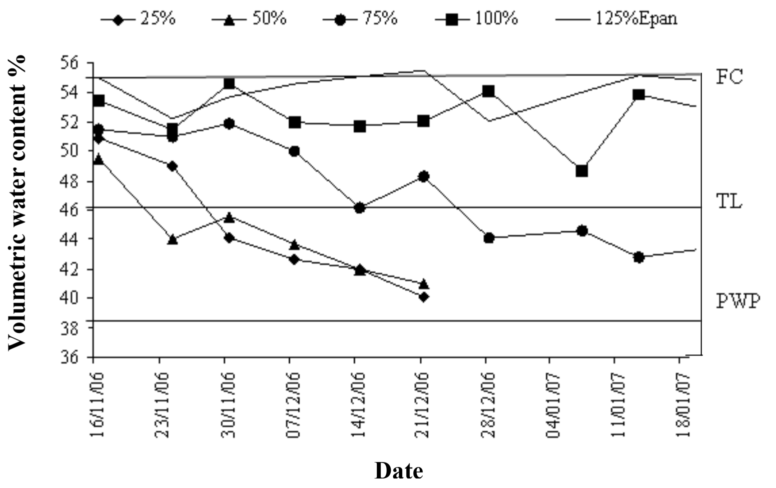

Figure 3. Volumetric water content under different water treatments measured at 30 cm deep during the study period in a Haploxerand soil. FC: field capacity, TL: threshold level; PWP: permanent wilting point.

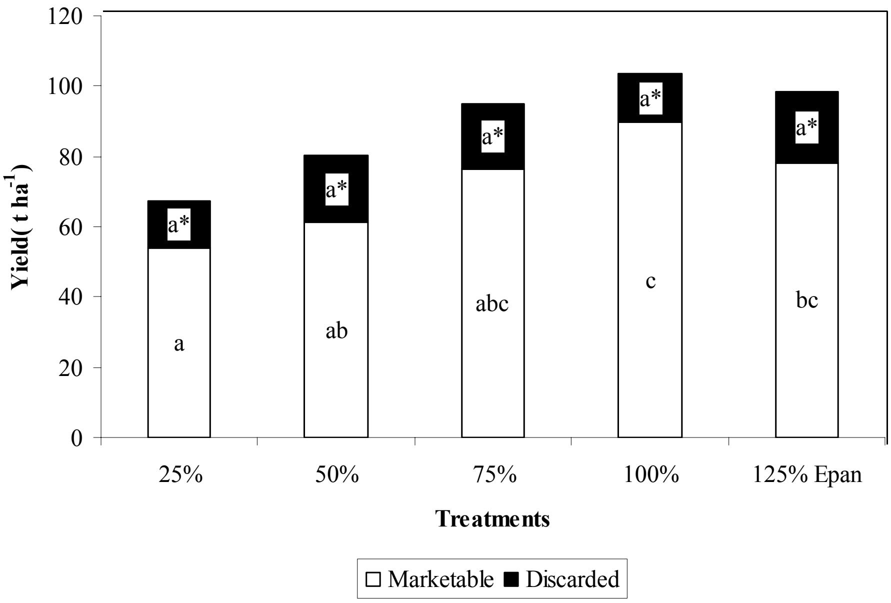

Figure 4. Total, marketable and discarded root yield (t ha^{-1}) of different water treatments in carrots under drip irrigation in a Haploxerand soil. Columns with different letters differ significantly, Duncan´s test ($p \leq 0.05$). Capital letters refer to total yield, lowercase letters refer to marketable yield and lowercase letters with asterisk refer to discarded yield.

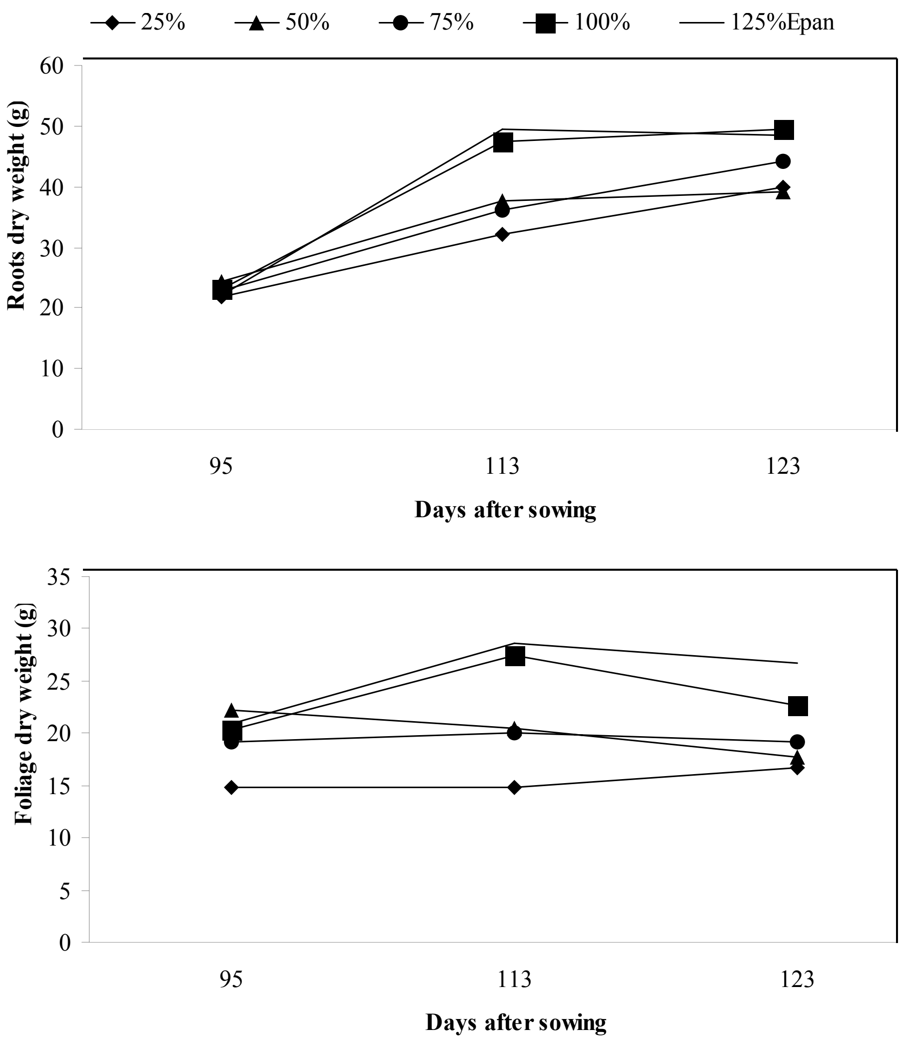

Figure 5. Root and foliage dry weight (g) of carrot in the different water treatments measured at 95, 113 and 123 days after sowing, in a Haploxerands soil.

The treatments with lower applications of water showed a constant growth, probably because the root is less sensitive to water stress than the aerial part of the plant. This could be explained by a higher activity of xiloglucan endotransglicosilasa enzyme (XET), which decreases the tension of the molecules of hemicellulose at low water potential, and it allows root growth (Reigosa *et at*., 2003). Moreover, Westerveld *et al*. (2006) determined that dry matter (DM) accumulation in the roots was generally linear after 53 days sowing (DAS) on the organic soil. Only 5 % of DM accumulation occurred before this period.

In relation to foliage, the highest values in fresh and dry weight were obtained with the 100 % and 125 % E_{pan} treatments at 113 DAS, due to the fact that a higher water application allowed an optimum transpiration, hence, a high growth of the aerial part of the plant. In the rest of the treatments the effect of water deficit decreased the photo-synthetic capacity (assimilation of CO^2), resulting in a decrease of the leaf stomatal conductance due to stomatal closure and decrease of transpiration, as it has been found in other plants (Sato *et al*., 2006). Statistical differences ($p \leq 0.05$) were not significant, except for fresh weight of the foliage at 113 DAS. Westerveld *et al*. (2006) found that DM accumulation in the foliage was higher than in the roots before 60 DDS and that the peak DM content occurred between 115 and 135 DDS. Then, it gradually decreased on both organic and mineral soil.

The harvest index did not present significant differences between treatments ($p \leq 0.05$). However, a high harvest index was obtained with the 25 % E_{pan} treatment when compared to the rest of the treatments, probably because of the scarce foliage produced (Table 2, due to water stress to which it was submitted. This may be the result of an increase of net synthesis of absicic acid (ABA), that causes the stomatal closure and decreases photosynthesis, as it has been reported in other plants (Azcón-Bieto and Talón, 2000). Results obtained by Klocker (1997) and Ebner (1995) differ from these results. These authors reported harvest indices around 80% under rainfed conditions, indicating that plants had a lower foliage development.

Table 2. Plant density, harvest index, soluble solids and root length of carrots with different water treatments under drip irrigation in a Haploxerand soil.

Treatments	**Plant density (10^3 ha^{-1})**	**Harvest index (%)**	**Soluble solids (º Brix)**	**Root length (cm)**
25% E_{pan}	1410	72	6.9	10.8
50% E_{pan}	1520	68	6.5	10.7
75% E_{pan}	1510	70	6.4	10.6
100% E_{pan}	1400	67	5.8	11.1
125% E_{pan}	1300	63	6.0	10.2
Significance	ns *	ns **	ns **	ns **

(*) Kruskal-Wallis test; (**) Duncan´s test , ns: no significant.

Root quality parameters

The concentration of soluble solids (Table 2) showed no significant differences in any of the treatments, even though a higher value in degrees ºBrix (6.9) was obtained with the 25% E_{pan} treatment, when compared with the 100 and 125 % E_{pan} (ºBrix about 6.0). In order to support the potential gradient required for water absorption in soils under water stress, the plant decreases the osmotic potential by increasing the levels of organic solutes (Azcón-Bieto and Talón, 2000). The soluble solid concentration obtained in this study is in accordance with data reported by Carlton and Peterson (1963), who obtained a range from 4.5 to 9 % of soluble solids with different carrot cultivars.

Environmental growth conditions affect directly the quality and the production of carrots, while plant density has more influence on yield parameters than in the internal root quality (Evers *et al*., 1997). Root length (Table 2) presented no significant differences ($p \leq 0.05$) between the treatments of water applications. The 100 % E_{pan} treatment presented the highest length (11.1 cm), probably because the length of the principal root was reached close to 35 DAS, period in which there were no differences in water applications. Klocker (1997) and Ebner (1995) reported similar
The highest values of carrot basal diameter were found in the 75, 100 and values in length and diameter to the ones obtained in this study.

The highest values of carrot basal diameter were found in the 75, 100 and 125 % E_{pan}, treatments, being growth and development more intensive between the 95 and 113 DAS (Figure 6), which is likely to be the result of greater water application. According to Reigosa *et al*. (2003), diameter growth of the principal root begins close to 35 DAS, where the roots of the plants with water deficit will continue growing, especially those who have available water levels. In this study, root diameter growth presented statistical differences ($p \leq 0.05$) that were significant at 113 and 123 DAS. In contrast, lower values were obtained with 25 % and 50 % E_{pan} treatments. This can be explained because small changes in turgidity, during the process of cell growth can reduce the cell enlargement and growth (Azcón-Bieto and Talón, 2000).

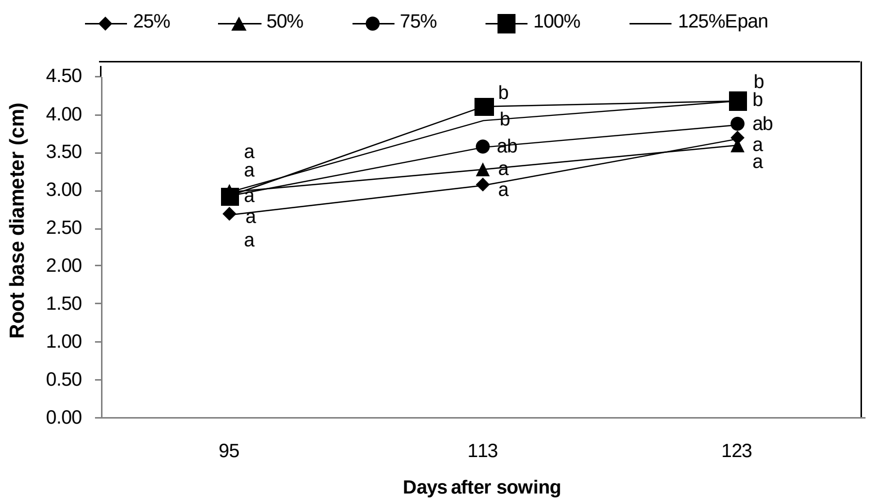

Figure 6. Root base diameter (cm) of carrot in the different water treatments measured at 95, 113 and 123 days after sowing, in a Haploxerand soil. Different letters in vertical order differ significantly, Duncan´s test ($p \leq 0.05$).

Crop water production function

The analysis of the relationship between crop yield (Y) in response to different levels of water input (W) showed that the highest yield was obtained in the 100 % E_{pan} treatment, with a water application of 4606 m^3 ha^{-1}. Nevertheless, as the water application level increased from 25 % to 125 % E_{pan}, it decreased the WUE (Table 1). Crop yield did not decrease and statistical differences ($p \leq 0.05$) were not significant among treatments. These results are in agreement with Kirschbaum *et al*. (2004) in raspberry. They determined that WUE presents no significant differences between treatments of irrigation and that WUE decreases with the increase of applied water. In contrast, Gibberd *et al*. (2003) obtained a higher marketable yield in carrot with a water application level of 151 % E_{pan} in sandy textured soils, but with a 97 % E_{pan}, WUE increased 17 % and the marketable yield decreased from 73 % to 63 %. The marginal analysis of water production function ($\Delta Y/\Delta W$) shows that the highest yield was obtained for the 75 % E_{pan} treatment with a value of 19.4 kg m^{-3} (Table 2) that, according to Liu *et al*. (2002)), corresponds to the point of maximum water use efficiency; therefore, it is the recommended water level.

CONCLUSIONS

We found that the highest yield of carrot crop in a Haploxerand soil was obtained with the 100 % E_{pan} treatment. The maximum WUE corresponded to 75 % E_{pan} treatment, with an applied water volume of 3864 m^3 ha^{-1}, which corresponds to the water application level recommended for drip irrigation scheduling in carrot. The decrease applied in the water volume did not affect crop yield nor quality parameters significantly. On the other hand, the excess of soil water caused a decrease in plant density and root size. The relationship between crop yield and applied water volume obtained for the carrot crop with drip irrigation will help to improve the management of the water resources for this crop under water scarcity conditions.

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