Research article

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Phosphorus availability and solar radiation efficiency in carrot (*Daucus carota* L.) cultivation in volcanic soils.

Disponibilidad de fósforo y eficiencia de la radiación solar en el cultivo de zanahoria (*Daucus carota* L.) en suelos volcánicos

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ABSTRACT

The adoption of more efficient management practices, such as recognizing the adequate level of P availability (Olsen) in the soil, can result in improved production efficiency in the carrot (*Daucus carota* L.) cropping system. Complementarily, knowing the behavior of radiation use efficiency (EUR) is relevant in the optimization of resources (P-fertilizer and radiation), due to the continuous concern for environmental impact and for the reduction of production costs. The objective of this work was to evaluate the EUR performance of two commercial carrot cultivars, across five levels of P-Olsen availability, under field conditions (13, 16, 19, 24, 28 ppm). The experiment was established at the Santa Rosa Experimental Station (39º47'S; 73º14'W), belonging to the Universidad Austral de Chile (UACh) located in the city of Valdivia in the Los Ríos Region, during the 2010-2011 growing season. EUR (g DM MJ-1) was calculated using photosynthetically active radiation (RIFA) and biomass (aerial and total). In this study, EUR of D. carota cultivars was not influenced by soil P-Olsen availability ($p>0.05$), but differences ($p<0.01$) were found in photosynthetically active radiation intercepted (RIFA) and specific leaf area.

Keywords: photosynthesis, P-olsen, fertilization, vegetables, napiform root.

RESUMEN

La adopción de prácticas de manejo más eficientes, como reconocer el nivel adecuado de disponibilidad de P (Olsen) en el suelo, puede resultar en una mejora de la eficiencia productiva en el sistema de cultivo de zanahoria (*Daucus carota* L.). Complementariamente, conocer el comportamiento de la eficiencia de uso de la radiación (EUR) es relevante en la optimización de recursos (fertilizante-P y radiación), por la continua preocupación por el impacto ambiental y por la reducción de los costos de producción. El objetivo de este trabajo fue evaluar el comportamiento de la EUR de dos cultivares comerciales de zanahoria, a través de cinco niveles de disponibilidad de P-Olsen, bajo condiciones de campo (13, 16, 19, 24 28 ppm). El experimento se estableció en la Estación Experimental Santa Rosa (39º47´S; 73º14´O), perteneciente a la Universidad Austral de Chile (UACh) localizada en la ciudad de Valdivia en la Región de Los Ríos, en la temporada de crecimiento del 2010-2011. La EUR (g MS MJ-1) se calculó mediante la radiación fotosintéticamente activa (RIFA) y la biomasa (aérea y total). En este estudio, la EUR de los cultivares de D. carota no fue influenciada por la disponibilidad de P-Olsen en el suelo (p>0,05), pero sí se encontraron diferencias (p<0,01) en la radiación interceptada fotosintéticamente activa (RIFA) y en el área foliar específica.

Palabras clave: fotosíntesis, P-olsen, fertilización, hortalizas, raíz napiforme

1. Introduction

Carrot (*Daucus carota* L.) is one of the main horticultural crops due to its high content of carotenes (pro-vitamin A), carbohydrates and other nutrients. This umbellifer has gained importance due to the growing preference of consuming natural products, a situation that opens new perspectives and opportunities to grow in surface with this crop, due to the tendencies towards a healthier life.

In Chile, the main regions that grow carrots, according to the National Institute of Statistics (INE) (2007), are Valparaíso, Bío-Bío and Metropolitana, with a small cultivated area (33 ha) in the region of Los Ríos (southern part of the country). This is probably due to the scarcity of updated information on this crop, since this area has favorable soil and climatic conditions, where root crops, bulbs and tubers grow more efficiently. In Valdivia, D. carota is traditionally grown on a small scale, with some research on this species carried out by Krarup et al. in 2000. Rosas (2011), evaluated the performance of new cultivars of D. carota observing yields of 43.3 t ha-1 in the Borec cultivar (Chantenay type) and 73.5 t ha-1 in the hybrid Miraflores. These yields are higher than those reported in central Chile, where the average yield is 35 t ha-1 (Giaconi and Escaff, 2001).

Crop productivity with adequate supplies of water and nutrients depends on the capture of solar radiation. Therefore, having a precedent of Radiation Use Efficiency (EUR) is important for the D. carota crop, since its response under any source of variation in this crop has not been reported so far. EUR has an important focus in the understanding of plant growth and is defined as the ability of crops to intercept radiation and convert it into biomass (Monteith, 1977). In other words, EUR is the interaction between photochemical-biochemical and assimilate transport processes. Graphically, it is the slope between crop biomass produced per unit of intercepted solar radiation (IR) or photosynthetically active intercepted radiation (PAR) (Sinclair and Muchow, 1999).

The purpose of studying EUR in D. carota arises for multiple reasons, among them, the special characteristics of the plant such as the foliar architecture and the storage root as its organ of agronomic interest, the crop production objective (carbohydrates); the napiform root architecture, of limited exploration and root deepening; short absorption time, because the crop is harvested in vegetative state (in fresh matter) and therefore it could be more sensitive to the varied availability of P. Particularities, which make it a totally contrasting crop to the traditional crops studied, under conditions of limited nutrient availability. In other words, harvestable crops in the reproductive phase where grain is the objective. Studies conducted in the area have evaluated purely agronomic characteristics. This research seeks to complement them by understanding the physiological processes involved in the plant growth of carrot, associated with the efficiency of solar radiation use (EUR) through the different inputs of phosphorus (P-Olsen) available in the soil, in a vegetable crop harvestable in vegetative stage in order to analyze the possible restrictions in the capture of solar radiation in two cultivars (Miraflores and Royal Chantenay).

2. Materials and Methods

The experiment under field conditions was established at the Santa Rosa Experimental Station (39º47'S; 73º14'W), belonging to the Universidad Austral de Chile (UACh) located in the city of Valdivia in the Los Ríos Region, during the 2010-2011 growing season. The climate of the area is temperate-rainy with Mediterranean influence, with an average annual rainfall of 2,500 mm that fluctuates between 1,800 and 3,100 mm (Montaldo, 1983). The average annual temperature is 12 °C, with January and July being the warmest and coldest months, with maximum averages of 16.9 and minimum averages of 7.9 °C, respectively (Estación Meteorológica UACh, 2006). Especially from August 1 to March, precipitation averages 834 mm, with a RIFA of 9 MJ m-2 and a temperature of 14 °C (Valle et al., 2009).

The total area of the field trial was 168 m2 with an experimental area of 108 m2. The plots were 4 m x 1.8 m, i.e., 7.2 m2 and the subplots were 3.6 m2. A split-plot design was used. The soil used was a Duric Hapludand, Valdivia series, of flat topography, with a depth greater than 2 m, with class II potential use capacity (Chile, Centro de Información de Recursos Naturales, CIREN, 2003). It has usable humidity of 20% volume base, bulk density of 0.7 g/cm3 and total porosity of 65%, as described by Chile, Instituto Nacional de Investigación de Recursos Naturales (IREN) and UACh (1978).

The planting material used for planting were seeds of the Royal Chantenay (RC) variety, considered traditional in Chile, and the Miraflores F1 (M) hybrid from the French company Clause, with the following physical characteristics: M of the Kuroda type (annual), noted for its more intense root color than the traditional ones, with a cylindrical-conical shape of 18 to 22 cm, diameter 4.5 to 5.5 cm, with smooth skin and a very high level of soluble solids. The growing cycle is 100 to 130 days from planting to harvest depending on temperatures (Clause, 2010). RC of Chantenay type, has high yields, conical-cylindrical root of 10 to 15 cm, thick, blunt tip, reddish orange color on the outside and dark orange inside, thick epidermis, smooth and with good quality. The crop cycle is variable according to climatic parameters (Herrera and Moreno, 1995).

The phosphorus source used in the field trial was triple superphosphate (P2O5, 46%) broadcast before planting. The levels under study were considered from the dose typically applied in traditional use (30 kg P ha-1). Measurements of available P-Olsen in the soil were made 3 days after the application of the phosphorus fertilizer. Table 1 shows the P levels used in the experiment.

Table 1. *P levels used in the field experiment on Andisol soils.*

P (kg ha-1)	**P-Olsen (mg kg-1)1**		
Applied	**Increment2**	**Base3**	**Available**
0	0	12,99	12,99
	2,50	12,99	15,49
	6,25	12,99	19,24
135	11,25	12,99	24,24
	15,00	12,99	27,99

1 It was determined according to the method of Olsen et al (1954).

2 Equivalence for the soil used in the tests.

3 Base soil value before P applications.

Mineral fertilizers N and K were applied to all treatments in both trials as follows: In the field, 100 kg K ha-1 as muriate of potash (K2O, 60%) broadcast before sowing and 150 kg N ha-1 as calcium ammonium nitrate (27% N, 6% Ca and 4% Mg), partitioned at 40 kg ha-1 at sowing, 60 kg ha-1 at 46 days after sowing (dds) at full root elongation and 50 kg ha-1 at 63 dds at the beginning of root accumulation, incorporated in a continuous stream near the row.

For sowing in the field, the Planet Jr. (Model B73-09B, Cole, USA), calibrated at a rate of 2.7 kg ha-1. The distance between rows was 30 cm, for subsequent thinning at a distance between plants of 4 cm, in order to ensure a population of approximately 96 pl m-2.

Weed control was manual and chemical (Linurex at a dose of 2.5 L ha-1). Preventive applications of insecticides and fungicides were made according to local practices. Irrigation was carried out according to atmospheric demand, rainfall and crop demand in both growing conditions.

The decision to harvest under field conditions (1,156 degree cumulative days after planting, GDAs, °Cd), was made according to the root shoulder diameter (2.5 cm) required for the commercialization of D. carota in the area. Harvesting was also done at this time, considering that periods greater than 1,450 °Cd could influence the loss of root quality.

Sampling of plants in the field was carried out at 1,156 °Cd to record the basic variables (yield, biomass and P absorbed) of the experiment. A 1 m2 was collected to quantify the fresh yield and a line of 10 plants was collected to determine the fresh and dry variables.

For the fresh growth parameters of the plants in the laboratory, plant height (from stem to top of leaf, cm pl-1), root length (from stem to root tip, cm pl-1) and root diameter (at the shoulder, cm pl-1) were measured with a foot meter. Fresh matter (FM) was then separated by plant organs (leaf, petiole and root) to be weighed with a precision analytical balance (Mettler Toledo, XP205DR, Switzerland) and expressed in kg MF ha-1. The FA (cm2 pl-1) was measured with a leaf area meter (LI 3100; LI-COR, Lincoln, Nebraska, USA), and the IAF and AFE (cm2 g-1) were estimated without petiole.

Total carrot root yield was determined at 1,230 °Cd, harvesting that took place within 1 m2 (kg MF m2) of each treatment, yield was expressed in t MF ha-1.

To determine the biomass, each plant structure was cut for subsequent drying until a constant weight was achieved and the dry matter (DM) was recorded, separating between aerial, root and total biomass, in order to determine the importance of each organ in the contribution to total DM during growth. Data were expressed in kg DM ha-1.

The concentration of P in the tissues was recorded by calcination of the samples that were previously ground, placing 2 g of DM of each plant organ in crucibles at 500 °C in a stove. Cooling the crucibles, the ash was boiled with 1 ml of distilled water and 10 ml of 2 N hydrochloric acid on a hot plate at 100 °C for 5 min. Subsequently, P contents were measured by the ammonium vanadomolybdate method (Gericke and Kurmies, 1952), by colorimetry in a UV visible spectrophotometer, previously calibrated with known concentrations, working with a wavelength of 440 nm. Once the P concentration was quantified (in percentage), P absorption (kg P absorbed ha-1) was determined through the biomass produced in each plant organ of D. carota.

RI was measured at solar noon, twice a week, with a 1 m long linear sensor (LI-1400, LI-COR Inc., Lincoln Nebraska, USA), two readings were taken above the canopy (Rinc) in the north and south position of each block; and three readings below the canopy (transmitted solar radiation, Rtra) in the center of the subplot, and then RI (%), RIFA (MJ m-2) and EUR (g MJ-1) were estimated. RI was calculated as the difference between Rinc minus Rtra divided by Rinc. Rinc was measured every 15 min by the weather station, located approximately 50 m from the field trial. The RIFA was established as 48% of the incident radiation (Rinc) of each day, which was multiplied by the percentage of RI and added to the accumulated photosynthetically active intercepted radiation (RIFAa) value of the previous day to determine the RIFAa at the end of the crop cycle. Finally, the EUR of each treatment was calculated as the slope of the linear regression of the accumulated aerial and total biomass as a function of RIFAa.

Analysis of variance (ANDEVA) was performed on the response variables to determine statistical differences between P levels, cultivars and factor interactions. Specific significance was also determined through Tukey's test at 95% probability, between P levels in each cultivar and experiment. The statistical programs Statgraphics plus 5.1 and GraphPad Prism v.5.04 were used for these analyses.

3. Results

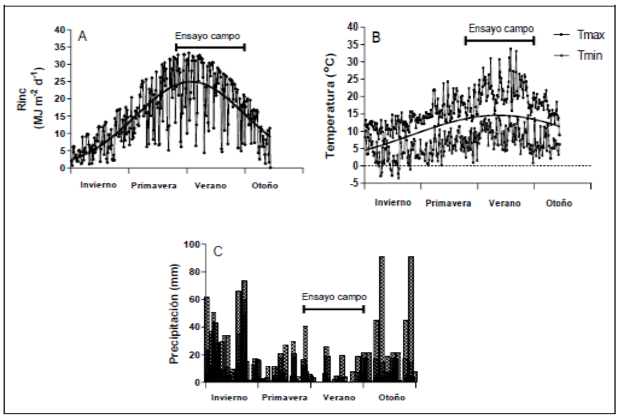
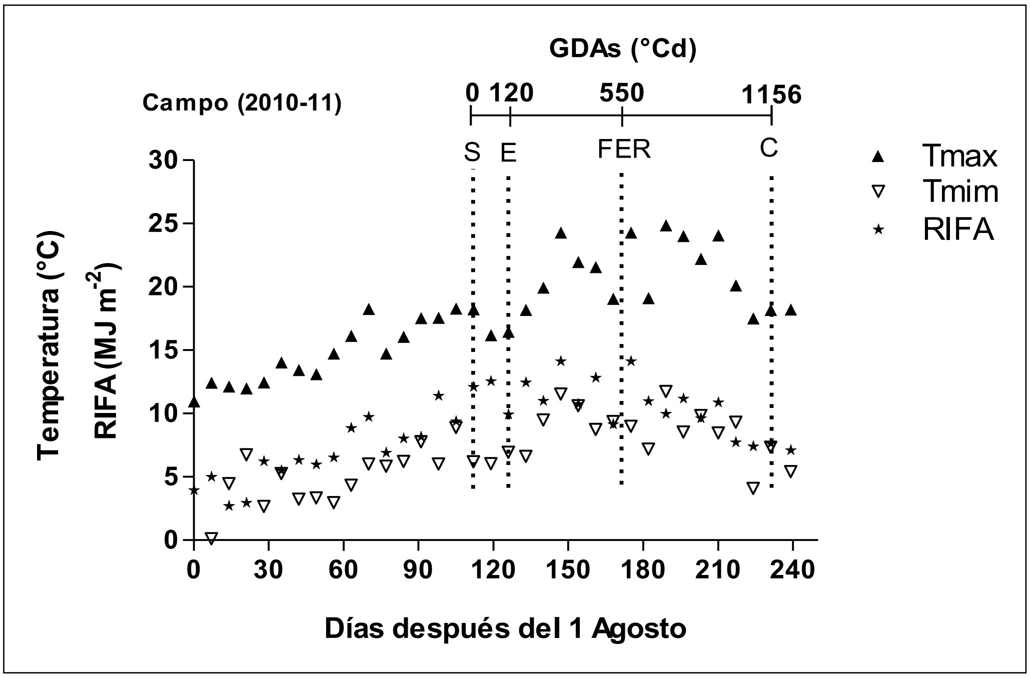


Figure 1. Climatic conditions during the experimental season. A) Incident solar radiation (Rinc); B) daily average temperature (maximum and minimum). C) precipitation, recorded from 21-06-2010 to 29-04-2011.

During the growth cycle of *D. carota* under field conditions the average RIFA was 11 MJ m-2 and the temperature was 15 °C. Figure 2 shows the average weekly RIFA and temperature recorded during crop development. The climatic data for this research came from the weather station (Davis Instruments Vantage Pro Data logger 65100, Ca, USA) installed in the experimental field.



Figur2. Weekly average of photosynthetically active intercepted radiation (PAR), temperature (maximum and minimum) and thermal time of the stages with a base temperature of 5 °C (S, sowing; E, emergence; ERF, end of root elongation; C, harvest), during the growth cycle of D. carota under field conditions.

Influence of available P-Olsen on fresh yield, cumulative biomass and P uptake in carrot.

The effect of P on the productivity of *D. carota* depended on the variations in the levels of P-Olsen availability, which were produced by the applications of different doses of P. The soils of the experiment responded positively and significantly ($p < 0.01$) in their P-Olsen levels to the increase in phosphorus fertility. The slope of the increase in P-Olsen availability was b= 0.083. These values imply that it was necessary to apply 12 kg P ha-1 to increase 1 mg P-Olsen kg-1 of soil (ppm P-Olsen).

The analysis of the physiological model, which defines yield as the product of biomass and harvest index (HI), showed variations with the availability of P-Olsen in the soil. Fresh matter (FM) yield was affected ($p < 0.01$) by the level of P-Olsen availability and cultivars presented significant differences ($p < 0.01$) in all plant parts. The interaction between both factors also showed a significant effect ($p < 0.05$), especially in the root part (Table 2).

In the field, the hybrid M, at the lowest P level (13 ppm), achieved MF productions of the aerial part, root and total plant of 27, 56 and 83 t MF ha-1 respectively, while, at the highest P level (28 ppm) these values were increased to 50% in all plant parts. The RC variety, under the same conditions generated 28, 51 and 80 t MF ha-1, with an increase of 49, 34 and 39%, respectively.

Figure 3 shows the positive trend of cumulative MF yield with respect to the level of P-Olsen availability, using a quadratic model (y=a+bx+cx2) in each structure. The accumulation root fresh yield of D.carota showed a wide range of variation depending on the cultivar, with 28 ppm, M achieved 85 t MF ha-1 and RC 68 t MF ha-1 (Figure 4).

Table 2. *Average fresh yield and biomass in D. carota cultivars, in Miraflores (M) and Royal Chantenay (RC) plant structures, under different P-Olsen availabilities in field conditions, harvested at 1156 °Cd.*

Cv	P Olsen	Performance (t MF ha-1)			Biomass (kg DM ha-1)			IC (%)
		Aerial	Radical	Total	Air	Radical	Total	
M		27,06 d	56,66 d	83,71 d	3.517 d	4.923 c	8.440 d	58,39 a
		31,46 c	66,16 c	97,62 c	4.090 c	5.223 b	9.313 c	56,12 ab
		34,34 bc	72,04 b	106,38 b	4.464 bc	5.424 b	9.888 c	54,86 b
		37,21 b	85,63 a	122,84 a	4.837 b	6.151 a	10.988 b	55,99 b
	28	40,68 a	85,24 a	125,91 a	5.288 a	6.359 a	11.648 a	54,59 b
RC		28,81 c	51,18 c	79,99 d	3.745 c	4.733 e	8.479 e	55,88 a
		32,70 b	61,30 b	94,01 c	4.252 b	5.018 d	9.269 d	54,17 ab
		35,95 b	62,75 b	98,71 b	4.674 b	5.236 c	9.910 c	52,87 bc
		39,77 a	62,51 b	102,28 b	5.170 a	5.404 b	10.574 b	51,13 cd
	28	43,01 a	68,54 a	111,55 a	5.591 a	5.675 a	11.266 a	50,38 d
P-Olsen		**	**	**	**	**	**	**
Cv	1	*	**	**	*	**	n.s.	**

-							
OlsenxCv	n.s.	**	**	n.s.	**	n.s.	n.s.
Total							

Cv, cultivars; P-Olsen, Olsen phosphorus; P-Olsen x Cv, interaction; MF, fresh matter and DM, dry matter.

The values under the P-Olsen levels of each test correspond to the degrees of freedom of Andeva.

Data are average of three replicates, different letters between groups indicate significant difference for P-Olsen levels, analyzed by Tukey's test at 95% probability, for each plant structure, cultivar and growing conditions.

Significant probability level at 0.05

Significant Probability Level at 0.01

n.s. Level not significant

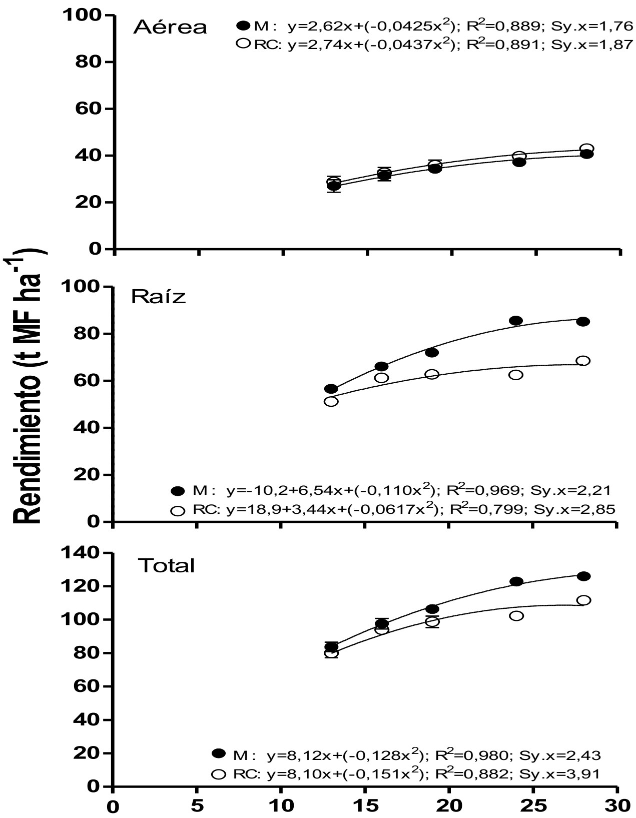


Figure 3. Relationship between fresh yield of different plant parts (aerial, root and total plant) and the level of available P-Olsen in the soil, under field conditions, in two cultivars of D. carota (Miraflores: M, black symbols; Royal Chantenay: RC, white symbols).

Vertical bars correspond to the standard error.

The fresh root yield obtained through P-Olsen availability was represented in the quadratic function fitted to zero (Figure 4). Through the derivation of the equation, the optimum level of P-Olsen availability was estimated, where the maximum root yield is achieved. In M (field) the optimum level was given at 32 ppm corresponding to 87.8 t MF ha-1; and in RC it is obtained at 25 ppm with 67.0 t MF ha-1. In summary, the optimum level of availability for the M hybrid is 32 ppm and the optimum range for the RC variety was between 25 and 32 ppm.

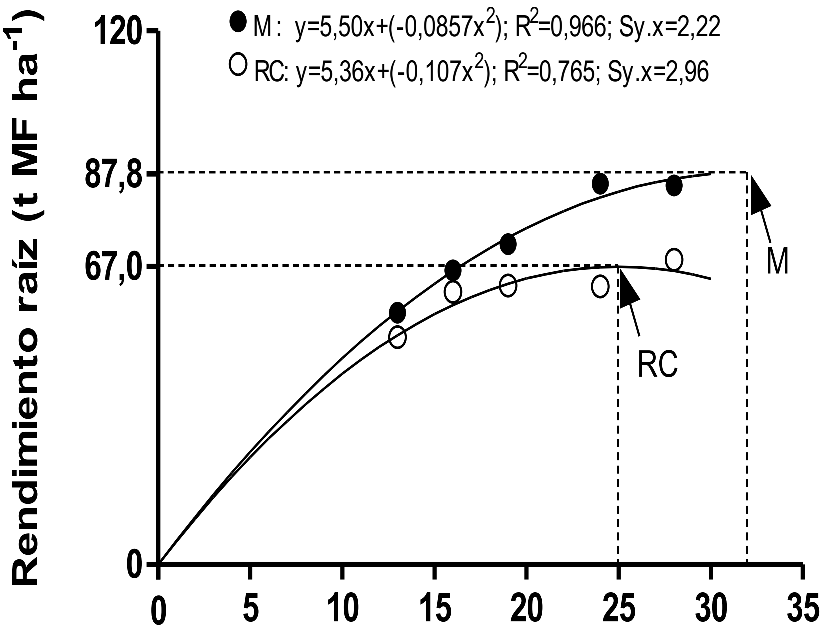


Figure 4. Effect of P-Olsen on maximum root accumulation yield in two cultivars of D. carota (Miraflores, black symbols; Royal Chantenay, white symbols) under field conditions*2*

Under deficiency conditions, crops respond to the supply of P in the soil, particularly by an increased availability of this nutrient. The results of this research show that the influence of available P-Olsen had a significant effect (p< 0.01) on biomass, increasing dry matter (DM) according to the increase of P-Olsen availability, in the plant parts of D. carota cultivars, in both growth conditions. In addition, the cultivars and the interaction of the factors showed marked differences (p< 0.01) in the root part, independent of development conditions (Table 1).

In the field trial, the accumulated biomass of the aerial, root and total plant part of hybrid M, at level 13 is 3,517, 4,923 and 8,440 kg DM ha-1 and with level 28 ppm it produced 5,591, 5,674 and 11,266 kg DM ha-1, obtaining an increase of 50, 29, 38% respectively. Under these same conditions the RC variety generated 3,745, 4,733 and 8,479 kg DM ha-1 at the lowest P level, while, at the highest level it obtained 5,591, 5,674 and 11,266 kg DM ha-1, being the increase of 49, 20 and 33% respectively.

Figure 5 shows the increasing trend between biomass and available P-Olsen, represented by a quadratic function fitted to zero, where the highest slopes of the curve are observed in the root (M= 468 and RC= 472) with respect to the aerial part (M= 341 and RC= 356), implying that there was a greater increase in root biomass, depending on the availability of P-Olsen in the soil.

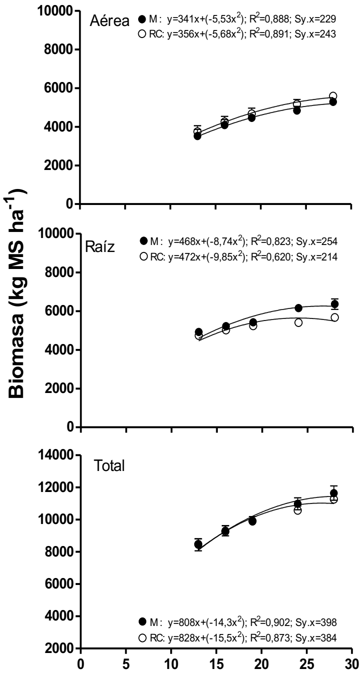


Figure 5. Relationship between the biomass of the different plant parts (aerial, root and total plant) and the level of available P-Olsen in the soil, under field conditions, in two cultivars of D. carota (Miraflores: M, black symbols; Royal Chantenay: RC, white symbols). Vertical bars correspond to the standard error.

Through the derivation of a quadratic equation between root DM and P-Olsen availability, the optimum ranges of P-Olsen were estimated, where the maximum production of root biomass is achieved. The optimum level for the hybrid M is 27 ppm corresponding to 6,258 kg DM ha-1; and for the RC variety it is 24 ppm which generates 5,644 kg DM ha-1. In summary, for maximum root biomass, the optimum range of P-Olsen availability in the M hybrid is between 27 and 32 ppm and for the RC variety it is 24 to 28 ppm.

P concentration in the biomass of D. carota cultivars was dependent on P-Olsen availability, showing significant differences ($p < 0.01$) for P-Olsen levels as well as for cultivars ($p < 0.05$), in the aerial and root parts. The interaction of the factors in general did not show differences in the plant parts of both experiments (Table 3). Root P concentrations were lower at the 13 ppm level in the hybrid M was 0.14% and for the RC variety 0.13% than those obtained with the 28 ppm level, being M 0.24 and RC 0.22%, with an increase of 65 and 68%, respectively (Figure 6).

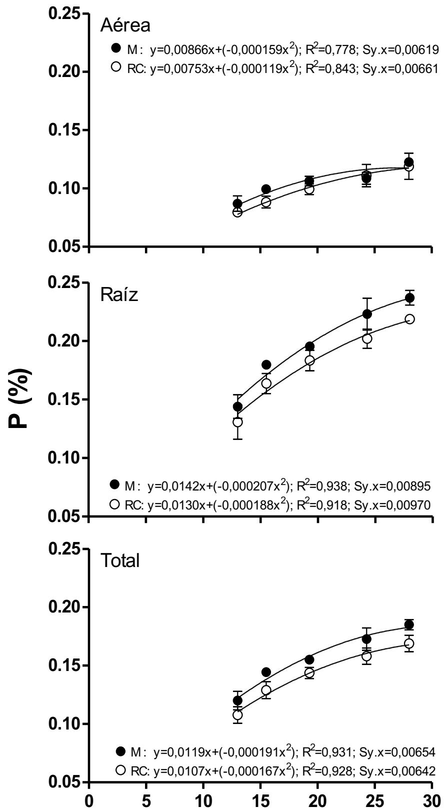


Figure 6. Relationship between P concentration in the different plant parts (aerial, root and total plant) and the level of available P-Olsen in the soil, under field conditions, in two cultivars of D. carota (Miraflores: M, black symbols; Royal Chantenay: RC, white symbols). Vertical bars correspond to the standard error.

In general, the highest values of P absorbed were registered in the root part, contrary to what was presented in the aerial part of the cultivars (Table 2). Since the availability of P-Olsen has an effect on the P absorbed in the plant tissues of the cultivars, an increasing trend was found, being described in a linear equation (Figure 7).

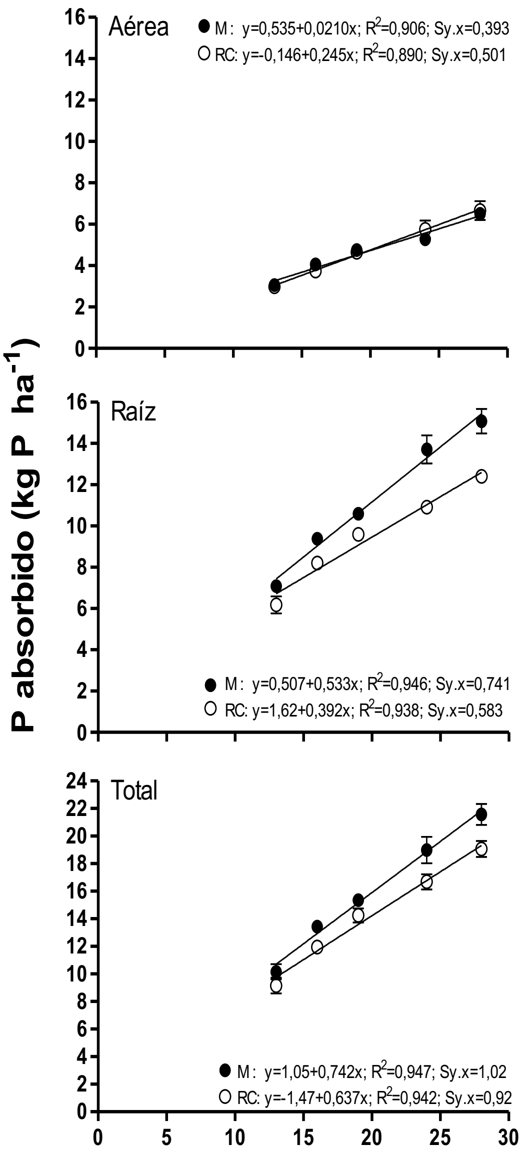


Figure 7. Relationship between P absorbed in the different plant parts (aerial, root and total plant) and the level of available P-Olsen in the soil, under field conditions, in two cultivars of D. carota (Miraflores: M, black symbols; Royal Chantenay: RC, white symbols). Vertical bars correspond to the standard error.

Effect of P on EUR in carrot crop.

Since productivity with adequate water and nutritional status (with better EUP) also depends on captured radiation, it is feasible to increase biomass by increasing radiation use efficiency (EUR). It is, therefore, important to report the behavior of the conversion of accumulated intercepted radiation into biomass production in the D. carota crop, since so far the response of EUR through P availability in this umbellifer was not known.

In this study, EUR was estimated through aerial biomass, but also through total biomass, because in this crop the agronomic product is the root, different from the analysis of grain crops, where it is estimated only through aerial biomass.

The EUR of D. carota cultivars was not influenced by the availability of P-Olsen in the soil ($p > 0.05$), while, among cultivars there were significant differences ($p < 0.01$), at medium to high levels (13 to 28 ppm of P-Olsen), under field conditions.

The highest EUR estimated through aerial dry matter, was achieved at the maximum level of P-Olsen availability, i.e., the 28 ppm level achieved 1.1 g DM MJ-1 (based on RIFA) in M and 1.5 g DM MJ-1 in RC. In addition, this variable was also estimated through total dry matter, reaching higher values (2.6 g DM MJ-1 in M and in RC 3.1 g DM MJ-1) than through aerial biomass (Figure 8).

Interestingly in this study (Figure 12), a linear association was found between EUR and aerial (M, $R2= 0.85$, $p< 0.01$; RC, $R2= 0.43$, $p< 0.01$) and total (M, $R2= 0.30$, $p< 0.05$; RC, $R2= 0.57$, $p< 0.01$) biomasses of D. carota cultivars. On the other hand, the correlation between accumulated photosynthetically active intercepted radiation (RIFAa) and biomass (aerial and total), showed a linear association (adjusted to zero) with increasing trend, showing that dry matter is more dependent on the radiation intercepted by the crop, than on the influence of P.

The availability of P-Olsen on RIFAa presented significant differences ($p< 0.01$), described by a linear equation, in both cultivars, whose slopes were 54±5.3 (M) and 46±3.3 (RC). Cultivar M accumulated RIFAa values that ranged from 328 MJ m-2 at the 13 ppm level to 460 MJ m-2 at 28 ppm, while, RC registered lower values with 261 and 364 MJ m-2 respectively (Figure 11).

In addition, a close relationship was found between RIFAa and IAF in M ($R2= 0.89$, $p< 0.01$) and RC ($R2= 0.94$, $p< 0.01$) (Figure 13B). The relationship between RI as a function of P levels and IAF were represented in quadratic equations. The effect of P-Olsen availability in the soil generated an increase in RI (M, $R2= 0.97$; RC, $R2= 0.37$) (Figure 13C). Similarly, the increase of P-Olsen in the soil increased the IAF in the plant improving the RI by the foliage (M, $R2= 0.93$; RC, $R2= 0.53$).

The effect generated with the increase of P-Olsen levels in the soil on the RI produced a greater expansion of leaf area (LA), reflected in the leaf area index (LAI) (Figure 12). The influence of P-Olsen availability produced a significant increase ($p< 0.01$) in the LAI. Therefore, the greatest expansion occurred at the highest P-Olsen level, registering values of 5.8 m2 m-2 in M and 5.2 m2 m-2 for RC with 28 ppm. On the contrary, the lowest level of P-Olsen 13 ppm only generated 3.2 m2 m-2 for the hybrid M and in the RC variety it was 3 m2 m-2.

Specific leaf area (SLA) is the relationship between SLA as a function of leaf biomass (leaf only, without petiole). The SLA was positively influenced by the increase in P-Olsen, showing an acceptable linear relationship (M, $R^2 = 0.37$, $p < 0.05$; RC, $R^2 = 0.44$, $p < 0.01$), with a slope of the curve of 0.20 for M and 0.17 for RC. The increase in AFE corresponded to 28% (M) and 17% (RC).

Research conducted by Hall et al. (1995); Sinclair and Muchow (1999); Muurinen and Peltonen-Sainio (2006); Massignam et al. (2009); Lemaire and Gastal (2009), report a negative response of EUR with N deficiency in different crops, but not in the case of S deficiency (Salvagiotti and Miralles, 2008) or Al toxicity (Sierra et al., 2003; Valle et al., 2009). Regarding P, the studies carried out are more scarce and contrasting. Plénet et al., 2000b and Fletcher et al., 2008b, reported that EUR was not affected by P deficiency in Zea mays. However, Rodríguez et al. (2000), found that in Triticum aestivum it was reduced during the first 61 days after emergence and Lázaro et al. (2010), found contradictory responses during the period of ear growth under periods of P deficiency in the same species. On the other hand, Sandaña and Pinochet (2011), in full cycle Triticum aestivum did not see EUR affected by P deficiency. Recently, Sandaña et al. (2012), found similar response in the same crop and in *Pisum sativum*, under deficient and adequate P conditions.

Despite the stability of EUR, P-Olsen availabilities generated an increase in photosynthetically active radiation interception and leaf area index, confirming that crop growth is a function of leaf area development and incident radiation (Sinclair, 1994).

On the other hand, the productivity to be achieved is determined by the genetic potential that a crop can express depending on the agroecosystem in which it develops, affected by its most relevant factors, among them: photosynthetically active radiation and crop efficiency in the conversion of light energy to chemical energy (Sinclair, 1994). At the same time, it is known that crops that grow under optimal conditions (without water and nutrient limitations) basically depend on radiation, since it is the driving force for crop growth. Despite this relevance of EUR, the historical record of the study of EUR indicates that few studies have been developed and that there is a wide variation in its response, even to the same factor, depending on growth conditions, cultivars and stages of development (Rodríguez et al., 2000; Lázaro et al., 2010; Arkebauer et al., 1994; Lecoeur and Ney, 2003).

The results of this investigation showed that the availability of P-Olsen did not generate a significant effect (p>0.05) on EUR. This confirms the conservative nature of EUR (Gallagher and Biscoe, 1978; Sinclair, 1986), even in a harvestable crop in vegetative stage. This is reinforced with other research, where similar EUR stability responses were found, facing the same variability factor (P) or other soil constraints (Valle et al., 2009, Salvagiotti and Miralles, 2008; Plénet et al., 2000b; Fletcher et al., 2008b and Sandaña et al., 2012), although this work is the first report of its constancy in Daucus carota. Because of this, comparisons were made with other species where EUR has been studied. According to the results of this work, D. carota presented a higher average EUR through aerial biomass (1.23 g MJ-1 based on RIFA) compared to legumes such as Pisum sativum (1.13 g MJ-1) and lower values than cereals such as in Triticum aestivum (1.63 g MJ-1) (Sandaña et al., 2012). These differences could be attributed to differences in the energy cost of biomass synthesis (Sinclair and Muchow, 1999).

On the other hand, given that the organ of agronomic interest of D. carota is the root, it is important to report that the average EUR based on total biomass is 2.86 g MJ-1, being 1.3 times higher than the EUR of aerial biomass, probably due to a larger destination size (root accumulation) of the assimilates.

Our biomass values had a better association with RIFAa than with EUR. These results are similar to what was found in crops such as Triticum aestivum (Sandaña and Pinochet, 2011; Rodríguez et al., 2000; Lázaro et al., 2009), Zea mays (Pellerin et al., 2000; Colomb et al., 2000; Fletcher et al., 2008b) and Helianthus annuus (Rodríguez et al., 1998a). Considering the linear associations shown between RIFAa with the level of soil P availability reflect that the pattern described in other species was maintained in both cultivars of D. carota.

Many crop models assume EUR as a constant (Sinclair, 1986), but other studies reported that it varies widely depending on plant phenology (Garcia et al., 1988 and Arkebauer et al., 1994). In this regard, Lecoeur and Ney (2003) reported a change in EUR during the development of the Pisum sativum crop, and in particular a decrease was observed during the vegetative phase; and Werker and Jaggard (1998) found that sugar beet had a decrease in EUR at the end of the crop cycle, under rainfed conditions. EUR can also vary with crop species (Valle et al., 2009), environmental conditions, management factors such as water supply, disease and nutritional status (Monteith, 1994).

The variability of EUR also depends on the extent to which the canopy absorbs the available radiation, i.e. the leaf area index (LAI), where characteristics such as leaf angle, canopy architecture (Russell et al., 1989; Guiducci et al., 1992), photosynthetic rates, photorespiration and respiration, or a limitation of sink demand, are of differential importance. Particularly, the species D. carota (C3), presents a less efficient photosynthetic process compared to Brassica oleracea var. capitata, Allium cepa and Beta vulgaris, due to the horizontal cover of the leaves that intercepts high levels of radiation in the upper leaves, making the area illuminated by the sun smaller compared to the total leaves (Jovanovic et al., 1999).

Additionally, several pot experiments have shown that leaf photosynthetic rate was negatively affected by P supply in Helianthus annuus (Plesnicar et al., 1994; Rodriguez et al., 1998a), Triticum aestivum (Rodriguez et al., 1998b), Nicotiana tabacum (Pieters et al., 2001) and other species, including C3 and C4 metabolism (Halsted and Lynch, 1996). In Zea mays, under controlled conditions, EUR was slightly affected by P deficiency (Mollier and Pellerin, 1999). Therefore, lower photosynthetic efficiency of carrot and reduced photosynthetic rate with lower P supplies could influence the decrease in EUR in this Umbelliferae.

4. Conclusions

Radiation use efficiency was not affected by the levels of P-Olsen used in this study for both cultivars, although photosynthetically active radiation, leaf area index and specific leaf area showed a positive effect of increased P-Olsen in D. carota. The increased availability of P-Olsen in the soil had a positive effect on the P content absorbed in plant tissues, fresh yield and biomass due to the higher uptake of assimilates in D. carota.

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