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Combination of irrigation and fertilizer increases yield and economic profit in carrot production[1]

Combinação entre irrigação e adubação aumentam a produtividade e rentabilidade econômica do cultivo de cenoura

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HIGHLIGHTS:

The carrot yield increases due to the interaction between irrigation depth and fertilization.
The marginal cost of carrot crop yield approaches zero for irrigation depth values between 100 and 125% of ETc.
An irrigation depth unit increment may supply the need for fertilization without changing the carrot crop yield.

ABSTRACT: This study aimed to carry out an economical and productive analysis of carrot production using different irrigation depths and doses of fertilizer. A randomized block design was used arranged in a 6 × 4 factorial scheme, with three replicates. The treatments were constituted by six irrigation depths: (L_1: 210.5, L_2: 315.7, L_3: 421.0, L_4: 526.2, L_5: 631.5, and L_6: 736.7 mm) and four doses of fertilizer: (F_1: 226.9, F_2: 340.3, F_3: 453.8 and F_4: 567.2 kg ha^{-1}) applied via fertigation. At the end of the cycle, four carrot roots were collected per plot to estimate yield. The maximum estimated yield of the carrot was 95.4 t ha^{-1}, obtained using 478.1 mm of water and 538.8 kg ha^{-1} of fertilizer. The best economic return was achieved with 482.0 mm of water and 460.0 kg ha^{-1} of fertilizer, giving 95.0 t ha^{-1}. The combination of irrigation and fertilizer allows lesser amount of both to be used, giving greater response than when applied separately.

Key words: *Daucus carota*, minimum cost, production function, mineral nutrition, yield

RESUMO: O objetivo deste estudo foi realizar a análise econômica e produtiva da cenoura em função de lâminas de irrigação e doses de adubo. Adotou-se o delineamento em blocos ao acaso, num esquema fatorial 6 × 4, com três repetições. Os tratamentos foram constituídos por seis lâminas de irrigação, equivalentes a: (L_1: 210,5; L_2: 315,7; L_3: 421,0; L_4: 526,2; L_5: 631,5 e L_6: 736,7 mm) e por quatro doses de adubo, equivalentes a: (F_1: 226,9; F_2: 340,3; F_3: 453,8 e F_4: 567,2 kg ha^{-1}), aplicadas via fertirrigação. Ao final do ciclo, foram coletadas quatro raízes de cenoura por parcela, para estimar a produtividade. O rendimento máximo estimado da cenoura foi de 95,4 t ha^{-1}, obtido com o emprego de 478,1 mm e 538,8 kg ha^{-1} de adubo. O melhor retorno econômico foi obtido com 482,0 mm de água e 460,0 kg ha^{-1} de adubo, obtendo 95,0 t ha^{-1}. A combinação de irrigação com o adubo permite que seja utilizada menor quantidade de ambos, obtendo resposta superior em comparação com a aplicação isolada.

Palavras-chave: *Daucus carota*, custo mínimo, função de produção, nutrição mineral, rendimento

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Introduction

The carrot is the main vegetable in the group of tuberous roots (Resende et al., 2016). In the Agreste region of Alagoas state, Brazil, climate conditions are favorable to the production and development of the carrot; however, with the long dry season, the crop requires irrigation to achieve satisfactory yields (Carvalho et al., 2018).

The response of crops to different irrigation depths consists of the rational use of water to meet the water requirement of the plant (Yasuor et al., 2017). Since carrot is a crop with high economic value, the irrigation management schedule is designed to obtain the maximum yield (Reid & Gillespie, 2017).

Studies carried out in Brazil have shown that the decreasing order of macronutrients extracted by the carrot crop is potassium, nitrogen, calcium, and phosphorus (Bonetti et al., 2017).

Potassium contributes to water use efficiency, the opening and closing of the stomata, and the plant-water relationship (Silva et al., 2017). Nitrogen makes up many of the components of plant cells, such as amino acids, amides, proteins, nucleic acids, among others (Oliveira et al., 2014). Phosphorus is essential for their establishment and development (Pelá et al., 2018). It favors the root system, increasing the absorption of water and nutrients, resulting in increased yield (Silva et al., 2015).

The economic profitability of carrot depends on the cost of production, the physical yield of the crop, and the price of the product, with the producer having the most effective control over the cost of production. As such, production functions guide farmers in making decisions regarding the amount of input to be used in the crop (Teodoro et al., 2013).

The increase in irrigation and fertilization analyzed in isolation (Silva et al., 2015; Akhmedov et al., 2018; Carvalho et al., 2018; Pelá et al., 2018) contribute to gains in the production of the carrot crop. However, there is little information about the evaluation of these factors of production in a combined way and their contributions to the increase in production in an economical way.

This study aimed to carry out an economical and productive analysis of the carrot using different irrigation depths and doses of fertilization.

Material and Methods

The experiment was conducted under field conditions at the Universidade Federal de Alagoas (UFAL), Arapiraca, AL, Brazil (9º45'09" S and 36º39'40" W and altitude of 325 m), between March and July 2016. According to Alvares et al. (2013), the climate in the region is As-type, tropical with a dry summer season, a mean annual temperature around 25 °C, and a mean annual rainfall of 854 mm. In the experiment period, the average temperature ranged from 21.38 to 30.25 ºC, and the total precipitation was 202 mm.

Soil samples were collected before installing the experiment in the 0.0 - 0.2 m layer and sent to the laboratory of UFAL-Arapiraca for chemical and physical analysis (Table 1). The predominant soil is an Oxysol of medium texture, and the relief is flat.

Soil preparation consisted of harrowing. Twenty-four seedbeds were then built, each 3 m in length, 1 m wide, 0.25 m high, and spaced 0.5 m apart. The Brasília carrot cultivar was used via direct seeding, at a spacing of 0.25 m between rows and 0.10 m between plants, equivalent to a population of 400,000 plants ha^{-1}, in a total area of 108 m^2.

A randomized block design in a 6 x 4 factorial scheme was adopted, with three replicates, giving a total of 72 experimental plots of 1.0 m², with 24 plants in three planting rows, being evaluated the four central plants. The treatments were represented by six irrigation depths based on the crop evapotranspiration (ETc), in which the water used for irrigation came from the local supply system, with electrical conductivity to 0.12 dS m^{-2}: ($L_{1(50\%\ ETc)}$: 210.5, $L_{2(75\%\ ETc)}$: 315.7, $L_{3(100\%\ ETc)}$: 421.0, $L_{4(125\%\ ETc)}$: 526.2, $L_{5(150\%\ ETc)}$: 631.5 and $L_{6(175\%\ ETc)}$: 736.7 mm) and four doses of fertilization recommendation: ($F_{1(50\%)}$: 226.9, $F_{2(75\%)}$: 340.3, $F_{3(100\%)}$: 453.8 and $F_{4(125\%)}$: 567.2 kg ha^{-1} of NPK). The recommendation was 80, 120, 90 kg ha^{-1} for nitrogen, phosphorus, and potassium, respectively.

Fertigation was carried out 30 days after sowing, based on doses of fertilization recommendation, when the plants presented four fully developed leaves, being divided during the crop cycle and applied daily through a drip irrigation system. For mixing the fertilizers, 80 L containers were used, with their injection into the main pipe through connections, registers, and a 0.5 HP motor. The sources of fertilizer were urea (45% N), MAP - mono ammonium phosphate (12% N and 60% P), and white potassium chloride (60% K_2O). The N contained in the MAP was considered for nitrogen fertilization.

According to fertilization recommendations, the carrot crop requires 80 kg ha^{-1} of nitrogen (N) during its cycle, half of which is applied as sowing fertilization and the other half as topdressing. For phosphorus (P), the recommendation is to apply 120.0 kg ha^{-1}, and for potassium (K), 90.0 kg ha^{-1}, with 60.0 kg ha^{-1} of both when sowing and the remainder as topdressing (Cavalcanti et al., 1998).

The irrigation frequency was daily, established for each treatment, and based on the crop evapotranspiration - ETc, obtained via drainage lysimeters (Silva et al., 2018).

Table 1. Chemical and physical characteristics of the soil in the experimental area

Chemical characteristics of the soil								
pH	OM	V	P	K	Na	Ca	Mg	H + Al
(H_2O)	(%)		(mg dm^{-3})		(cmol$_c$ kg^{-1})			
5.3	0.57	29.2	7	10	0.09	0.7	0.5	3.5

Physical characteristics of the soil							
Granulometry (%)				Textural class	Ds (g m^{-3})	FC	PWP
CS	FS	Si	Cl			(% weight)	
24.3	29.0	30.2	16.6	Sandy loam	1,48	7.8	4.05

OM - Organic matter; V - Volume; CS - Coarse sand; FS - Fine sand; Si - Silt; Cl - Clay; Ds - Bulk density; FC - Field capacity; PWP - Permanent wilting point

At the end of the crop cycle, four carrots were harvested from the center of each plot to estimate yield (kg ha^{-1}). The effects of irrigation depth and fertilizer dose were analyzed by polynomial regression. To obtain the production function, ten statistical models were tested, which, according to Aguiar (2005), satisfactorily represent a production function of the crop.

From the models tested for data regression analysis, using the package "rsm" of the R statistical software, was chosen the one that best fitted the experimental data, considering the coefficient of determination R^2, the value of the F-test in the analysis of variance, the value of the t-test for each coefficient, and the sign of each variable for the models under analysis.

The irrigation depth (D) and fertilization recommendation (F) comprised the independent variables, and the carrot crop yield (Y) the dependent variable. The production function includes some parameters that facilitate its understanding which is addressed below.

Marginal physical product: The marginal physical product (Eq. 1) is obtained from the ratio between the derivative of the function representing yield and the factor under consideration (Rocha Junior et al., 2016).

$$\mathrm{PMg}(f) = -\frac{\partial Y}{\partial f} \quad (1)$$

where:

PMg (f) - marginal physical product of the factor under consideration.

∂Y - derivative of function Y, representing yield; and.

∂f - derivative of factor f under consideration.

Marginal rate of substitution: The marginal rate of substitution was calculated from the relationship between the marginal physical product of the irrigation depths (L) and the marginal physical product of the fertilizer doses (F), as by Eq. 2. From this equation, the amount of fertilizer in kilograms was calculated to replace a gross irrigation depth of 1 mm, without altering the agricultural yield of the carrot.

$$\mathrm{MRS}_{D/F} = \frac{\mathrm{PMgD}}{\mathrm{PMgF}} \quad (2)$$

where:

$MRS_{D/F}$ - marginal rate of substitution of the factor irrigation depth (D) by the factor fertilizer (F);

PMg F - marginal product of the factor fertilizer; and,

PMg D - marginal product of the factor irrigation depth.

Determining the minimum cost: to calculate the minimum cost, combinations of the factors irrigation depth (D) and fertilizer dose (F) were made, where the minimum cost for each iso-product curve is determined by the graph method to identify the points at which the slope of the curve of the marginal rate of substitution of irrigation depth by fertilizer ($MRS_{D/F}$) equals the slope of the curve of the ratio of the cost of one millimeter of irrigation depth and the cost of one kilogram of fertilizer, C_D/C_F.

The price of a millimeter of water (energy cost with irrigation) applied was obtained based on information from carrot producers in the fruit and vegetable region of the irrigated perimeter Cinturão Verde, Arapiraca, AL, Brazil. The fertilizer cost was obtained from rural commercial companies in the Agreste region of Alagoas state, Brazil. Values of the millimeter of water and fertilizer were updated for 2020.

The value of one applied millimeter of water (10 m^3 ha^{-1}) and one applied kg of fertilizer are shown in Table 2. Based on the price of one millimeter of water (BRL 4.65/10 m^3) and one kilogram of fertilizer (BRL 3.33), the ratio of the cost for irrigation depth (C_D) to the cost for fertilizer (C_F) is 1.40.

The region of rational carrot production as a function of the total gross irrigation depth and fertilizer doses applied per hectare was determined by marking the points on the boundary lines where the slopes of the isoquants are zero or infinite.

Results and Discussion

The regression analysis of the ten models under test was significant by F-test at $p \leq 0.001$, showing that each of the models, under the conditions of this study, can represent the variation in carrot yield (Y) as a function of the irrigation depth (D) and fertilizer dose (F).

The quadratic polynomial model with significant interaction between irrigation depth and fertilizer dose was that the best fitted the experimental data, according to the equation (Figure 1A).

Table 2. Variables used to determine the cost of one millimeter of water applied by the drip irrigation system (A) and the cost of the fertilizers (B) used in cultivating the carrot

A: Cost of one millimeter (10 m^3 ha^{-1}) of water in cultivating the carrot[1]					
BRL ha^{-1}	Fixed costs			Operational costs (BRL mm^{-1})	Total cost (BRL mm^{-1})
	Working life (years)	100% of the ETc (mm)	BRL mm^{-1}		
8,000.00	10	421	1.90	2.75	4.65

B: Cost of fertilizer in cultivating the carrot[2]			
Type of fertilizer	100% of the recommended dose (kg ha^{-1})	BRL ha^{-1} fertilizer	BRL kg^{-1} fertilizer
Urea	103.78	259.45	2.50
MAP	200.00	800.00	4.00
Potassium chloride	150.00	450.00	3.00
Total	453.78	1509.45	-------
Mean	-------	-------	3.33

[1]Source: Green Belt Technician, vegetable-producing region, Arapiraca, AL, Brazil, 2020
[2]Source: Rural Produtos Agropecuários (via Whatsapp), 2020

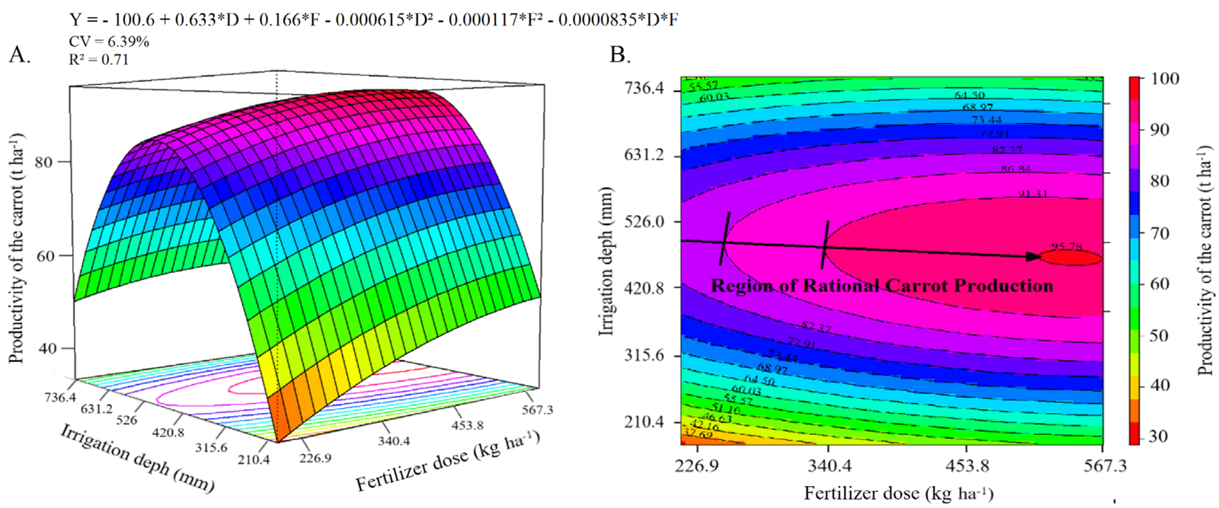

Figure 1. Response surface for carrot yield (t ha^{-1}) as a function of irrigation depth and fertilizer dose (A), and isoquants and region of rational production for yield in the carrot crop, with points at which the irrigation depth and fertilizer dose result in the minimum production cost for the respective agricultural yields (B)

From the response surface curves for each factor (Figure 1A), it can be seen that irrigation depth has the most significant effect on carrot yield. The maximum estimated yield for the carrot is 95.4 t ha^{-1}, obtained with an irrigation depth of 478.1 mm and 538.8 kg ha^{-1} of fertilizer.

The isoquants show the combinations between fertilizer dose and irrigation depth, resulting in the same yield (Figure 1B). Such combinations show that the higher the yield, the smaller the number of combinations, to the point that only one single combination is obtained, corresponding to the maximum physical yield, in this case, 95.4 t ha^{-1}.

There is also a gradual reduction in the iso-product curves as the yield increases. This can be explained by the smaller rises in yield as the use of production factors is increased. The highest yield found in this study (95.4 t ha^{-1}) is greater than that found by Akhmedov et al. (2018) of 81.6 t ha^{-1}. These values are considered almost four times higher than the national average (26.8 t ha^{-1}) (Léllis et al., 2017).

The values for the marginal physical products of fertilizer and irrigation depth were obtained by deriving the production function equation relative to fertilizer and water, respectively (Table 3). The marginal physical product is the additional product produced when using one additional unit of the factor under consideration, water or fertilizer.

Table 3. Marginal physical product (t ha^{-1}) of the fertilizer for different doses (upper value) and marginal physical product (t ha^{-1}) of the water for different irrigation depths (lower value) in the carrot

Irrigation depth (mm)	Fertilizer doses (kg ha^{-1})			
	226.89	340.33	453.78	567.22
210.40	0.10	0.07	0.04	0.02
	0.36	0.35	0.34	0.33
315.60	0.33	0.19	0.03	0.01
	0.23	0.22	0.21	0.20
420.79	0.32	0.18	0.03	0.00
	0.10	0.09	0.08	0.07
525.98	0.31	0.17	0.02	-0.01
	-0.03	-0.04	-0.05	-0.06
631.85	0.30	0.16	0.01	-0.02
	-0.16	-0.17	-0.18	-0.19
736.38	0.29	0.15	0.00	-0.03
	-0.29	-0.30	-0.31	-0.32

If 340.3 kg ha^{-1} of fertilizer and 315.6 mm of irrigation depth are used, the yield increases by 0.19 t ha^{-1} for each kg of fertilizer applied (NPK) and 0.22 t ha^{-1} for each millimeter water applied. This variation in the marginal products of the fertilizer as a function of applied irrigation depth is due to the interaction between the factors; the same happens with the marginal products of irrigation depth as a function of fertilizer.

The reduction in the value of the marginal product continues until it reaches zero when maximum crop yield occurs (Table 4). From the moment that the marginal products of the fertilizer and water become negative, the fall in crop yield is evident for the application of fertilizer doses and irrigation depths greater than the doses and irrigation depths that correspond to the point of maximum yield.

From this point on, it is economically unviable to apply water and fertilizer in greater quantities than the combination that provides the maximum physical yield. This would make the costs higher than necessary to obtain yields that can already be achieved with lesser combinations (Leftwich, 1976).

The values for the marginal rate of substitution (MRS) of the fertigation water are shown in Table 4 for the range covering the fertilizer doses used in this research. As can be seen, these values were obtained for pre-established production levels. It can be seen that initially, the marginal rate of substitution is negative, indicating that the substitution of water by fertilizer can be economically viable and is carried out in decreasing proportions.

From the moment that it becomes positive, this substitution becomes economically unviable, showing that the water is being replaced by fertilizer in increasing proportions. It can also be seen that the marginal rates of substitution for yield are increasing, i.e., as the yield increases, the fertilizer doses that give economic viability also increase.

It can be seen that a yield of 95.0 t ha^{-1} of carrots only achieved the marginal rates of substitution at fertilizer doses greater than or equal to 475.0 kg ha^{-1}.

For a yield of 90.0 t ha^{-1} of carrots, it can be seen that only from the dose of 325.0 kg ha^{-1} fertilizer on it is possible to achieve this level of production, when it would be necessary

Table 4. Marginal rate of substitution of water by fertilizer ($MRS_{D/F}$) and the corresponding irrigation depths (D), with fertilizer doses for predetermined levels of carrot yield

Fertilizer (kg ha^{-1})	Isoquants yield							
	80 (t ha^{-1})		85 (t ha^{-1})		90 (t ha^{-1})		95 (t ha^{-1})	
	L (mm)	MRS	L (mm)	MRS	L (mm)	MRS	L (mm)	MRS
225	414.92	-0.76	----	----	----	----	----	----
250	397.98	-0.61	454.68	-1.31	----	----	----	----
275	384.11	-0.51	429.52	-0.81	----	----	----	----
300	372.37	-0.43	412.07	-0.61	----	----	----	----
325	362.28	-0.38	398.39	-0.49	464.47	-1.48	----	----
350	353.53	-0.33	387.17	-0.41	439.27	-0.75	----	----
375	345.93	-0.28	377.78	-0.34	423.51	-0.54	----	----
400	339.34	-0.24	369.86	-0.29	411.76	-0.41	----	----
425	333.67	-0.21	363.19	-0.24	402.56	-0.33	----	----
450	328.83	-0.18	357.63	-0.20	395.27	-0.26	----	----
475	324.79	-0.15	353.06	-0.16	389.55	-0.20	459.12	-0.59
500	321.51	-0.12	349.44	-0.13	385.18	-0.15	448.47	-0.31
525	318.96	-0.09	346.71	-0.09	382.07	-0.10	442.83	-0.15
550	317.13	-0.06	344.85	-0.06	380.17	-0.05	440.57	-0.03
575	316.03	-0.03	343.87	-0.02	379.45	0.00	441.53	0.11

---- Region where it is not economically viable to replace water with fertilizer, or vice versa

to use 1.48 mm of water to replace one kilogram of fertilizer to have the same level of production; this means that for each kilogram of applied fertilizer, 1.48 mm of water can be saved.

The behavior of the marginal rates of substitution obtained in the present study corroborates the results obtained by Rocha Júnior et al. (2016). They found marginal rates of substitution that were initially negative and decreasing. According to Frizzone et al. (1995), substituting one factor for another only has an economic advantage if the marginal rate of substitution in absolute value is greater than the inverse relationship between the price of each factor.

Figure 1B also shows the combination of irrigation depth and fertilizer dose, which results in the lowest production costs for the respective expected agricultural yield: the point at which the cost ratio curve of the irrigation depth (C_D) divided by the cost of fertilizer (C_F) touches the isoquant for agricultural yield in the carrot.

It is possible to see these points, where they are connected by a curve that enables an estimation of the irrigation depth and fertilizer dose to be applied on any isoquant of agricultural production.

In this research, the C_D/C_F ratio was 1.40, where to produce 85.0 t ha^{-1}, the best combination is 505.0 mm of water and 237.0 kg ha^{-1} of fertilizer. The ideal is to use 496.0 and 482.0 mm of water and 321.0 and 460.0 kg ha^{-1} of fertilizer to produce 90.0 and 95.0 t ha^{-1}, respectively.

The production factors that generate the iso-product or isoquant curves are considered not substitutable at points where the slope of these curves is equal to 0.0 (zero) or infinite; the area limited by the curves that connect these points is called the region of rational production.

The concept of a region of rational production is that any combination of the production factors is economically viable within such a region. Outside the region, the inputs would be wasted. However, to optimize the net profit of the enterprise, the ratio between inputs that results in the lowest production costs should be used (Teodoro et al., 2013).

The region of rational production of the carrot crop in the district of Arapiraca, AL, Brazil (Figure 1B) is limited by the curves that start at an irrigation depth of 505.0 mm and a dose of 460.0 kg ha^{-1} of fertilizer, and that would meet in the center of the isoquant for maximum estimated yield, which would be 95.4 t ha^{-1} of carrots, obtained with an irrigation depth of 478.1 mm and 538.8 kg ha^{-1} of fertilizer.

The fact that the curve that limits the irrigation depth in the region of rational production starts at the irrigation depth of 505.0 mm shows that the carrot responds with a decline to irrigation depths greater than the maximum depth used in this research.

Based on the quantities of the inputs used in the experiment under discussion, it can be seen that the rationally recommended curve that limits irrigation depth (mm) has a negative coefficient of less than 1.0, showing that it decreases in direct relation to the increase in fertilizer (Figure 1B).

Conclusions

1. The best economic return was achieved with 482.0 mm of water and 460.0 kg ha^{-1} of fertilizer, with estimated yield of 95.0 t ha^{-1}.

2. The combination of irrigation and fertilizer allows smaller amount of both to be used achieving greater yield than when applied separately.

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