ISSN 1807-1929
Revista Brasileira de Engenharia Agrícola e Ambiental
Brazilian Journal of Agricultural and Environmental Engineering
v.28, n.5, e275518, 2024
Campina Grande, PB – http://www.agriambi.com.br – http://www.scielo.br/rbeaa

DOI: http://dx.doi.org/10.1590/1807-1929/agriambi.v28n5e275518

Original Article

Spatial analysis of irrigated carrot yield in terms of soil physical properties[1]

Análise espacial da produtividade da cenoura irrigada em função das propriedades físicas do solo

Gloria M. R. Plazas[2]*, Tayssa M. Franco[2], Felipe J. Viana[2], Job T. de Oliveira[3] & Rubens A. de Oliveira[2]

[1] Research developed at Iamaguti Farm, Campos Altos, MG, Brazil
[2] Universidade Federal de Viçosa, Viçosa, MG, Brazil
[3] Universidade Federal de Mato Grosso do Sul, Chapadão do Sul, MS, Brazil

HIGHLIGHTS:

The carrot cultivar Natuna, irrigated by center pivot, exhibits higher yield than the regional average.
Soil physical attributes, such as particle density and total water availability, showed spatial dependence.
Total water availability was the most influential factor in estimating carrot yield spatial variability.

ABSTRACT: Understanding soil, plant attributes, and carrot crop dynamics is vital for optimizing site-specific management practices and enhancing crop yield and soil quality. This study aimed to ascertain the dependence and spatial variability between irrigated carrot yield and soil physical attributes in a clayey Oxisol. The research took place during the 2021 growing season in a commercial carrot production area in Campos Altos, MG, Brazil. One hundred sampling points were established within the irrigated area, distributed across a square expanse of 40,000 m², positioned at the centers of 20 × 20 m grids. The study revealed high yield in the irrigated carrot crop (99.74 t ha^{-1}) with moderate variability. Soil attributes displayed a range of heterogeneity, ranging from low to extremely high, contingent on the variable assessed, as determined by the coefficient of variation. Among the variables exhibiting spatial dependence, particle density exhibited a minimum range of 40 m, which is recommended for further studies on irrigated carrot cultivation in a clayey Oxisol. Total soil water availability demonstrated a positive spatial correlation and proved to be the recommended variable for estimating the spatial variability of carrot crop yield.

Key words: *Daucus carota* L., precision agriculture, spatial dependence

RESUMO: Compreender o solo, os atributos das plantas e a dinâmica das culturas de cenoura é vital para otimizar praticas de manejo a sitio especifico e melhorar o rendimento das culturas e a qualidade do solo. Este estudo teve como objetivo verificar a dependência e a variabilidade espacial entre a produtividade da cenoura irrigada e os atributos físicos do solo em um Latossolo Argiloso. A pesquisa ocorreu durante a safra 2021 em uma área comercial de produção de cenoura em Campos Altos, MG, Brasil. Foram estabelecidos cem pontos amostrais dentro da área irrigada, distribuídos em uma área quadrada de 40.000 m², posicionados nos centros de grades de 20 x 20 m. O estudo revelou alta produtividade na cultura da cenoura irrigada (99,74 t ha^{-1}) com variabilidade moderada. Os atributos do solo apresentaram uma gama de heterogeneidade, variando de baixa a extremamente alta, dependendo da variável avaliada, determinada pelo coeficiente de variação. Dentre as variáveis que apresentam dependência espacial, a densidade de partículas apresentou alcance mínimo de 40 m, o que é recomendado para futuros estudos de cultivo de cenoura irrigada em Latossolo Argiloso. A disponibilidade total de água no solo demonstrou correlação espacial positiva e mostrou-se a variável recomendada para estimar a variabilidade espacial da produtividade da cultura da cenoura.

Palavras-chave: *Daucus carota* L., agricultura de precisão, dependência espacial

• Ref. 275518 – Received 13 Jun, 2023
* Corresponding author - E-mail: gloria.plazas@ufv.br
• Accepted 28 Jan, 2024 • Published 07 Feb, 2024
Editors: Toshik Iarley da Silva & Carlos Alberto Vieira de Azevedo

Introduction

Carrot (*Daucus carota* L.) is a nutritionally valuable vegetable widely cultivated in Brazil due to its popularity and nutritional benefits. The São Gotardo region in Minas Gerais is a significant carrot producer (Que et al., 2019, Carvalho et al., 2021). The growth, yield, and quality of carrot crops are influenced by numerous factors, including climate, soil, variety, and agronomic practices (Guimarães et al., 2018). Soil water availability, nutrient levels, aeration, and infiltration rates significantly affect carrot growth (D'Hooghe et al., 2018). Factors like high soil density, the presence of stones, and nutrient retention capacity can restrict root development, leading to reduced yield and quality.

Numerous studies have explored carrot responses to different management practices (Szelag-Sikora et al., 2019; Montazar et al., 2021; Silva et al., 2021). These findings highlight the importance of studying and characterizing the spatial variability of soil physicochemical attributes to assess their impact on crop responses to site-specific management practices. Given the economic significance of carrot crops, optimizing management through precision agriculture techniques is essential (Wei et al., 2020). This optimization can lead to increased yield while maintaining or enhancing soil quality.

Geostatistical analysis provides a means to characterize the spatial dependence and structure of soil physicochemical attributes and carrot crop yield. This approach facilitates the development of management strategies that maximize resource utilization without compromising yield or product quality. Hence, this study aimed to establish the dependence and spatial variability between irrigated carrot yield and soil physical attributes in a clayey Oxisol.

Material and Methods

The research was conducted in 2021 at Iamaguti Farm, owned by Iamaguti Agronegócios Ltda., located in Campos Altos, Minas Gerais state, Brazil (19° 25' 16.8" S and 46° 09' 23.2" W), at an average altitude of 1200 m (Figure 1). Carrot cultivation employed a center pivot irrigation system, with an irrigation depth of 2.99 mm per pivot turn and a theoretical Christiansen uniformity coefficient of 90%.

The region has a Cwa climate type (Köppen & Geiger, 1928), which is characterized by a humid temperate climate with distinct seasons, dry winters, and hot summers. Rainfall mainly occurs from October to March (Dezordi et al., 2015). The prevalent soils in the area are clayey Oxisols (USDA, 2014).

Carrots were planted in July using conventional methods. Beds of 2 m in width with five rows of plants per bed were established. Soil preparation involved plowing, harrowing, scarification, and mechanical bed formation. The Natuna cultivar was used with a seeding density of 681,818 seeds per hectare. No lime or organic matter was added to the soil. Sampling points were established on November 16, 2021, in a 20 × 20 m grid pattern, totaling 100 points (Figure 2).

Undisturbed soil samples were collected from the 0.00-0.30 m depth layer on November 17, 2021, using Kopecky rings.

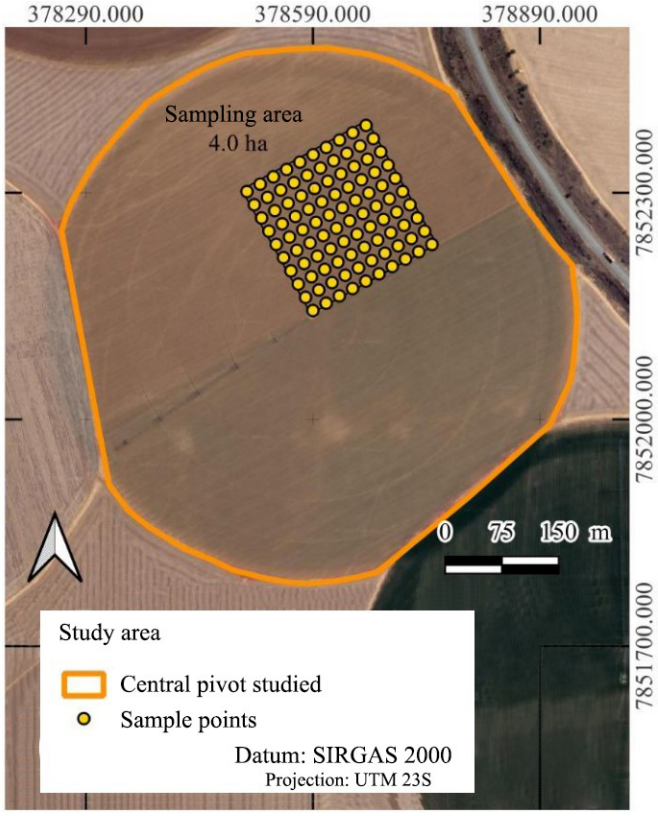

Figure 1. Study area location

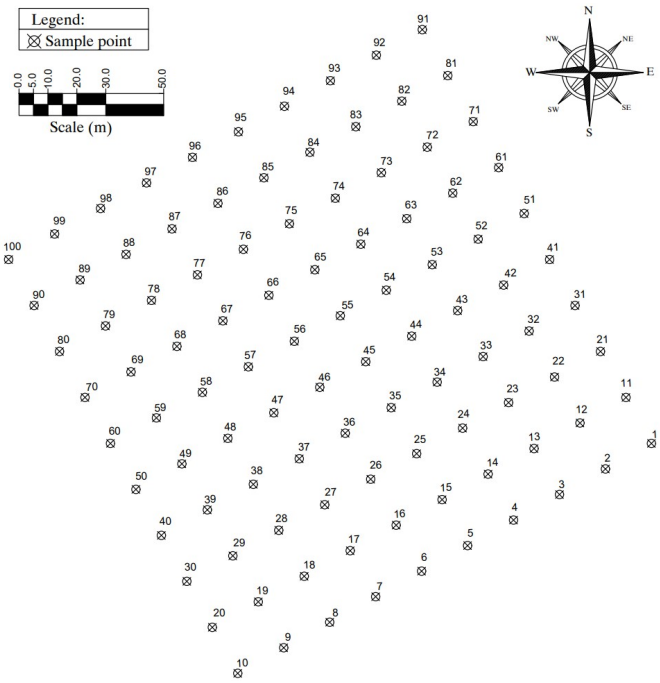

Figure 2. Sampling grid layout of the irrigated carrot field studied using a center pivot system (Campos Altos, Minas Gerais, Brazil)

Various soil properties were determined, including gravimetric moisture content at field capacity (M_{fc}), permanent wilting point (M_{PWP}), soil bulk density (Sd), particle density (Pd), total porosity (TP), and total soil water availability (TWA).

Field capacity refers to moisture retained in soil under specific conditions, -10 kPa for sandy soils and -30 kPa for clayey soils (Bernardo et al., 2019). Since the region's predominant soils are classified as considerably clayey Oxisols

(USDA, 2014), is was applied tension of 30 kPa to determine the gravimetric moisture content at field capacity. Similarly, a tension of 1500 kPa was used to establish the gravimetric moisture content at the permanent wilting point. The collected samples were then dried in an oven at 105 °C until they reached a constant weight, following the method described by Teixeira et al. (2017). The moisture content was calculated using Eq. 1:

$$M = \frac{Mms - Mds}{Mds} \quad (1)$$

where:

M - gravimetric moisture content (g g^{-1}) at field capacity (M_{fc}) and permanent wilting point (M_{PWP});

Mms - mass of soil + water in samples (g) after being subjected to the studied potential (30 kPa for M_{fc} and 1500 kPa for M_{PWP}); and

M_{ds} - mass of soil dried at 105 °C until constant weight (g).

Soil density (Sd) was determined following Teixeira et al. (2017). Undisturbed samples were collected at each sampling point using Kopecky rings with a volume of approximately 97.95 cm^3. These samples were then dried in an oven at 105 °C until a constant weight was reached to obtain the dry soil mass (Mds).

Particle density (Pd) was determined using the volumetric flask method as described by Teixeira et al. (2017). In this method, the volume of alcohol needed to fill a 50 mL volumetric flask, containing soil previously dried in an oven at 105 °C, was measured.

To calculate soil density (Sd), it was applied Eq. 2, and for particle density (Pd), it was used Eq. 3. Finally, to calculate the total soil porosity (TP) as a percentage, it was employed Eq. 4, following Teixeira et al. (2017).

$$S_d = \frac{M_{ds}}{V} \quad (2)$$

$$P_d = \frac{M_a}{V_T - V_U} \quad (3)$$

$$TP = \left(1 - \frac{S_d}{P_d}\right) \times 100 \quad (4)$$

where:

S_d - soil density (g cm^{-3});

M_{ds} - soil mass in the sampling ring dried at 105 °C (g);

V - volume of the sampling ring (cm^3);

P_d - particle density (g cm^{-3});

Ma - dry sample mass of about 20 g (g);

V_T - total volume of the flask (mL);

V_U - volume used to fulfill the flask with the sample (mL); and,

TP - total porosity (%).

Total water availability (TWA) in the soil represents the amount of water stored in the soil between field capacity and permanent wilting point. It is typically expressed in units of mm cm^{-1} (Bernardo et al., 2019). TWA is calculated using Eq. 5:

$$TWA = \frac{Mfc - Mpwp}{10} \times Sd \quad (5)$$

where:

M_{fc} - gravimetric moisture content (g g^{-1}) at field capacity;

M_{pwp} - gravimetric moisture content (g g^{-1}) at permanent wilting point; and,

Sd - soil density (g cm^{-3}).

Penetration resistance (PR) was measured in MPa at four different depth layers: 0.00-0.10 m, 0.10-0.20 m, 0.20-0.30 m, and 0.30-0.40 m. Additionally, the mean penetration resistance (MPR) for the entire depth layer of 0.00-0.40 m was determined. It was used a georeferenced electronic penetrometer (Falker model PLG 2040) to measure soil penetration resistance, with the penetrometer set to record readings at each centimeter of depth while maintaining a constant penetration speed.

Soil moisture content was simultaneously determined during sampling using the HydroFarm Falker electronic meter, equipped with a 20 cm sensor recording moisture content within a 30 cm diameter area.

An initial statistical analysis for the physical-hydraulic properties of soil was conducted using Rbio software version 17. The analysis included calculating various descriptive statistics such as mean, median, minimum, maximum values, standard deviation, coefficient of variation, kurtosis, and skewness. Additionally, a frequency distribution analysis was performed to assess data distribution. The Shapiro-Wilk test (1965) was employed at $p \leq 0.05$ to evaluate the hypothesis of normality or log-normality and determine the type of frequency distribution (Normal - NO, tending to normal - TN, or indeterminate - IN).

Spatial variability and dependence were analyzed for each variable using GS+ software. It was fitted simple and cross variograms, providing input parameters for spatial interpolation through kriging and cokriging techniques. Variogram parameters considered included the nugget effect (C_0), sill (C_1), and range (A) (Qin et al., 2020). It was assessed the spatial dependence degree (SDD) using the spatial dependence evaluator (SDE), as described in Eq. 6. SDD values less than or equal to 25% indicated weak spatial dependence, values between 25 and 75% indicated moderate spatial dependence, and values greater than or equal to 75% indicated strong spatial dependence (Rosa Filho et al., 2011).

$$SDD = SDE = \left(\frac{C_1}{C_0 + C_1}\right) \times 100 \quad (6)$$

To determine the most suitable semivariogram model for the spatial data distribution, it was considered two key criteria: the highest coefficient of determination (R2) and the highest spatial dependence evaluator (SDE). It was conducted cross-validation to validate the model that provided the best fit and to ascertain the optimal kriging mesh neighborhood size. Neighborhood size was represented by linear coefficient (a)

and angular coefficient (b), with the most suitable fits having linear coefficients close to or equal to 0 and angular coefficients close to 1 (Vieira et al., 2010).

Following the semivariogram fitting, it was employed ordinary kriging for data interpolation. This allowed to visualize spatial distribution patterns of soil physical-hydric properties within the irrigated carrot crop area through maps. Additionally, it was assessed the presence of joint spatial dependence among variables using the cross semivariogram, enabling the implementation of cokriging.

Results and Discussion

Regarding soil physical-hydric variables, such as soil density (Sd), total porosity (TP), volumetric moisture (VM), moisture at field capacity (M_{fc}), and total water availability in the soil (TWA), they conformed to a normal distribution (NO) with probabilities of 0.881, 0.730, 0.936, 0.339, and 0.267, respectively (Table 1). However, particle density (Pd), penetration resistance (PR) at depths of 0.00-0.10 m and 0.30-0.40 m, mean penetration resistance (PR1, PR4, and MPR, respectively), and moisture at wilting point (MPWP) showed a distribution tending to normal (TN) with probabilities of 0.026, 0.024, 0.014, 0.032, and 0.021, respectively. Penetration resistance at depths of 0.10-0.20 m and 0.20-0.30 m (PR2 and PR3, respectively) were classified as indeterminate (IN).

It is worth noting that Montanari et al. (2015) found a normal distribution for TP and Pd, which differs from the distribution observed in the present study for Pd. Leiva et al. (2019) reported normal and lognormal frequency distributions for penetration resistance in the 0-60 cm depth layers of an Oxisol cultivated with sugarcane. This difference can be attributed to the type of crop grown in the area. Additionally, soil preparation and agricultural practices can influence the behavior of this attribute, with such information not provided by Leiva et al. (2019).

According to Souza et al. (2020), normality is not a prerequisite for spatial dependency studies. Avoiding elongated tails in distribution curves is essential, which can be observed in the present study, as indicated by coefficients of asymmetry close to zero.

Table 1 displays descriptive statistics for this study attributes. According to Pimentel-Gomes & Garcia (2002), the coefficient of variation can be categorized (CV) as follows: low for CV < 10%, medium for 10% ≤ CV < 20%, high for 20% ≤ CV < 30%, and very high for CV ≥ 30%. Carrot cultivation, in this context, exhibited a CV of 12.77%.

Concerning soil physical attributes, Sd, Pd, TP, VM, M_{fc}, and MPWP showed low heterogeneity with CVs below 10%. PR at the 30-40 cm depth layer and mean PR (PR4 and MPR) indicated moderate heterogeneity with CVs of 17.23 and 17.44%, respectively. However, the 10-20 cm depth layer (PR2) and 30-40 cm depth layer (PR3) exhibited high heterogeneity with CVs of 25.51 and 26.57%, respectively. The CV for PR in the 0-10 cm depth layer was very high at 33.12%.

Montanari et al. (2015) found low to medium CV ranges for TP in a different soil class, suggesting little spatial variation. On the other hand, Pinto et al. (2019) noted that Pd remains stable in soil, depending on organic and mineral fractions. They also found homogeneity in Sd when no impediment layers or clay accumulation were present. This aligns with these results, showing CVs of 4.36% for Pd and 3.06% for Sd, indicating homogeneity in these attributes.

Low to medium CV values for M_{fc}, VM, and total water availability (TWA) correlate with the homogeneity in soil density and total porosity, which are linked to soil water storage capacity (Bernardo et al., 2019; Feng et al., 2023). In terms of penetration resistance, low average values (0.10, 0.31, 0.69, and 1.54 MPa for PR1, PR2, PR3, and PR4, respectively) suggest no impediment layer at the evaluated depth, potentially affecting water storage and crop root development (D'Hooghe et al., 2018). CVs for PR in the 0-40 cm depth layers align with the findings of Feitosa et al. (2019) in a clayey Oxisol. They reported higher heterogeneity in the 0-10 cm depth layer with a CV of 26.98%, while Souza et al. (2020) found CVs ranging from 23.29 to 33.74% in the 0-40 cm depth layers, with the highest variation in the 0-10 cm depth layer.

In summary, the soil's physical properties show a range of heterogeneity from low to high within the study area. Limited

Table 1. Descriptive statistics for carrot yield, plant attributes, and physical soil properties

Attribute[a]	Average	Value		Standard deviation	Coefficient			Probability test[b]	
		Minimum	Maximum		Variation (%)	Kurtosis	Asymmetry	Pr	DF[c]
Y	99.74	71.27	129.21	12.74	12.77	-0.39	0.24	0.341	NO
Soil physical attributes									
Sd	0.86	0.78	0.91	0.03	3.06	-0.20	-0.23	0.881	NO
Pd	2.82	2.56	3.14	0.12	4.36	-0.09	0.36	0.026	TN
TP	69.56	65.33	73.34	1.62	2.33	-0.05	-0.05	0.730	NO
PR1	0.10	0.04	0.22	0.03	33.12	0.64	0.69	0.024	TN
PR2	0.31	0.17	0.80	0.08	25.51	14.31	2.69	6.12E-10	IN
PR3	0.69	0.33	1.18	0.18	26.57	-0.12	0.58	0.007	IN
PR4	1.54	1.01	2.21	0.26	17.23	-0.67	0.39	0.014	TN
MPR	0.66	0.43	0.92	0.12	17.44	-0.65	0.39	0.032	TN
VM	15.65	13.18	18.35	1.01	6.45	-0.23	0.09	0.936	NO
M_{fc}	0.30	0.28	0.32	0.01	3.00	-0.02	-0.27	0.339	NO
M_{PWP}	0.23	0.22	0.24	3.34E-03	1.46	-0.28	0.50	0.021	TN
TWA	0.61	0.44	0.79	0.08	12.54	-0.25	-0.11	0.267	NO

[a] Y - Carrot yield (t ha^{-1}); Soil physical properties: Sd - Soil density (g cm^{-3}); Pd _ Particle density (g cm^{-3}); TP - Total porosity (%); PR1, PR2, PR3, PR4, MPR - Penetration resistance at depths of 0.00-0.10 m, 0.10-0.20 m, 0.20-0.30 m, and 0.30-0.40 m, and mean penetration resistance (MPa), respectively; VM - Volumetric moisture (%); M_{fc} - Moisture content at field capacity (g g^{-1}); M_{PWP} - Moisture content at permanent wilting point (g g^{-1}); TWA - Total water availability in the soil (mm cm^{-1} soil); [b] Shapiro-Wilk test; [c] Frequency distribution; NO - normal; TN - Tending to normal; IN - Indeterminate

variation in plant attributes and crop yield can be attributed to the fact that, despite area variability, soil's physical and hydric attributes fell within ranges that did not restrict root development. However, assessing spatial variability in both plant and soil attributes remains vital to identify potential issues and improve crop development. It also enables site-specific management using precision agriculture techniques.

Table 2 and Figure 3 present simple semivariogram parameters for carrot yield and soil physical attributes. The geostatistical analysis revealed a pure nugget effect for soil TP, PR1, and Sd. On the other hand, PR3, PR4, VM, M_{fc}, and MPWP showed a trend, indicating no leveling-off of the variogram sill.

The average carrot yield reached 99.74 t ha^{-1}, surpassing the reported averages for irrigated carrots in the São Gotardo region as documented by Carvalho et al. (2021). This difference may be attributed to factors such as the specific carrot cultivar used, soil physical and chemical attributes, or the farming practices employed by the producer.

In geostatistics, the semivariogram range is a crucial parameter that indicates the maximum distance at which spatial correlation or dependence exists. Beyond the range, the variable's spatial behavior is considered entirely random (Behera et al., 2018). Concerning soil physical attributes, it was observed a range as small as 40.0 m for Pd, while the largest range was 180.0 m for TWA. These findings suggest that the recommended sampling interval should vary based on the specific attribute under study. However, for future sampling designs related to soil physical-hydric attributes in irrigated carrot cultivation in the Campos Altos region, it is advisable to keep the sampling intervals generally below the values obtained in this study, with a maximum of 40 m.

Among the various semivariogram models considered, the exponential model provided the best fit for attributes Y, PR2, and VM, with R^2 values of 0.63, 0.90, and 0.63, respectively. For the attribute MPR, the spherical model was the best fit, with a R^2 value of 0.97. Both Pd and TWA exhibited a Gaussian model fit, with R^2 values of 0.74 and 0.83, respectively.

Table 2. Parameters of simple semivariograms fitted to data on carrot yield and soil physical properties

Property[1]	Model[2]	Nugget effect (C_0)	Sill (C_1)	Range (m)	r^2	SSR[3]	SDE[4]		Cross-validation[5]		
							(%)	Class	a	b	r
Y	EXP	18.60	140.0	47	0.63	541.00	86.70	Strong	23.58	0.76	0.33
Soil physical attributes											
Sd	PNE	0.001	0.001	-	-	-	-	-	-	-	-
Pd	GAU	0.007	0.014	40	0.74	5.07E-06	50.00	Moderate	0.99	0.65	0.26
TP	PNE	3.299	3.299	-	-	-	-	-	-	-	-
PR1	PNE	0.002	0.002	-	-	-	-	-	-	-	-
PR2	EXP	0.002	0.003	90	0.90	1.11E-07	43.60	Moderate	-0.02	1.06	0.37
MPR	SPH	0.005	0.010	91	0.97	3.06E-07	52.00	Moderate	0.00	1.00	0.59
VM	EXP	0.163	1.085	72	0.63	8.68E-02	85.00	Strong	0.09	0.99	0.47
TWA	GAU	0.005	0.009	180	0.83	4.09E-06	49.40	Moderate	-0.02	1.03	0.50

[1]Y - Carrot yield (t ha^{-1}); Soil physical properties: Sd - Soil density (g cm^{-3}); Pd - Particle density (g cm^{-3}); TP - Total porosity (%); PR1, PR2, MPR - Penetration resistance at depths of 0.00-0.10 m, 0.10-0.20 m, and mean penetration resistance, respectively (MPa); VM - Volumetric moisture (%); TWA - Total water availability in the soil (mm cm^{-1} soil); [2]EXP - Exponential; PNE - Pure nugget effect model; SPH - Spherical model; GAU - Gaussian model; r^2 -Coefficient of determination; [3]SSR - Sum of square residues; [4]SDE - Spatial dependence evaluator; [5]a - Linear coefficient, b - Angular coefficient, r - Correlation coefficient

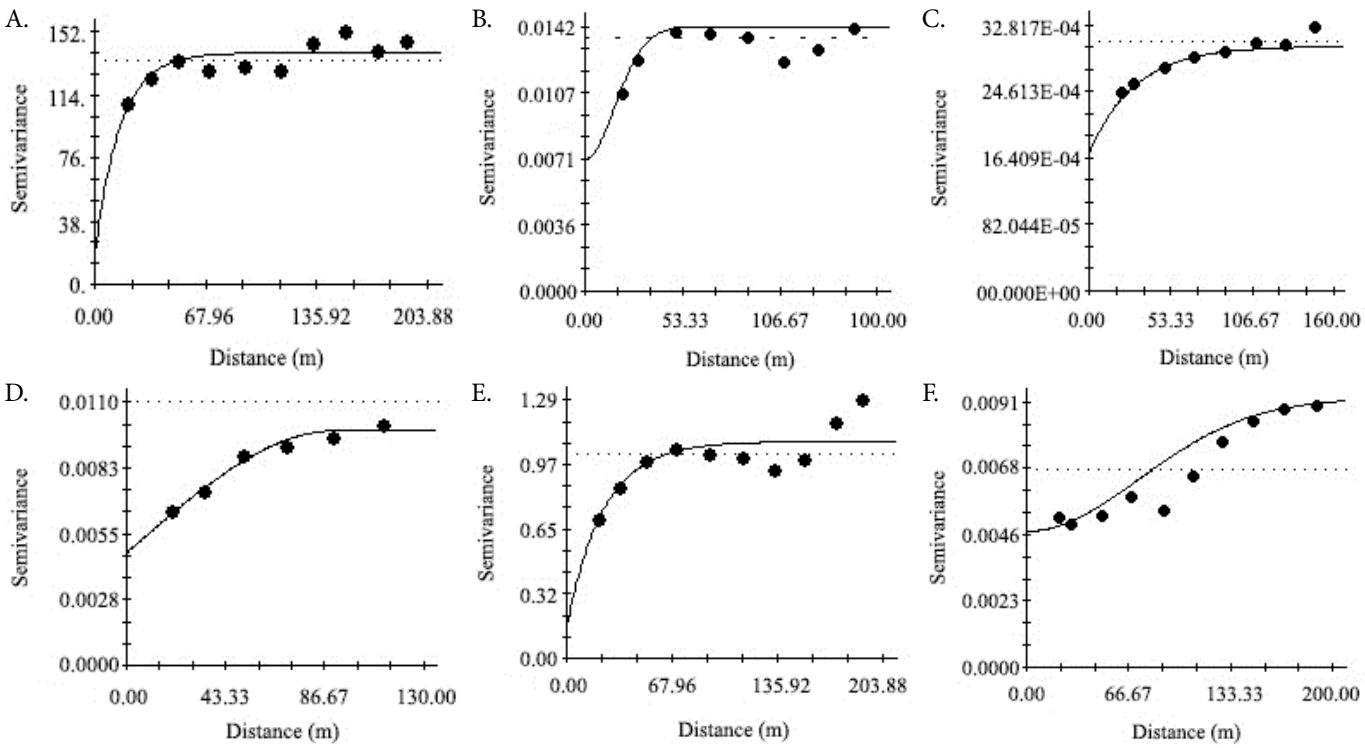

Figure 3. Semivariograms fitted to carrot yield (A), particle density (B), penetration resistance (C) at 10-20 cm depth layer, mean penetration resistance (D), volumetric moisture (E), and total water availability in the soil (F)

Spatial dependence, as classified by Cambardella et al. (1994), can be described as weak, moderate, or strong based on SDE (spatial dependence estimate) values < 25%, 25 to 75%, and >75%, respectively. In these data, strong spatial dependence was observed for Y, while moderate spatial dependence was indicated for Pd, PR2, and MPR. It is essential to note that the variables analyzed exhibited variations not only in their range values but also in the degree of spatial dependence.

Geostatistics has primarily been used for estimating and mapping properties in unsampled locations when studying soil physical attributes (Najafian et al., 2012). To visualize the spatial variability of different attributes in the area, Figures 4A to F present distribution maps generated through ordinary kriging after fitting the semivariograms.

Figure 4A illustrates the yield map that was obtained, indicating that the northern region of the field yielded the highest results. A sizable portion of the area also demonstrated average yield, surpassing the regional average reported by Carvalho et al. (2021) of 70 t ha^{-1}. This suggests that management practices such as fertilization, irrigation, and

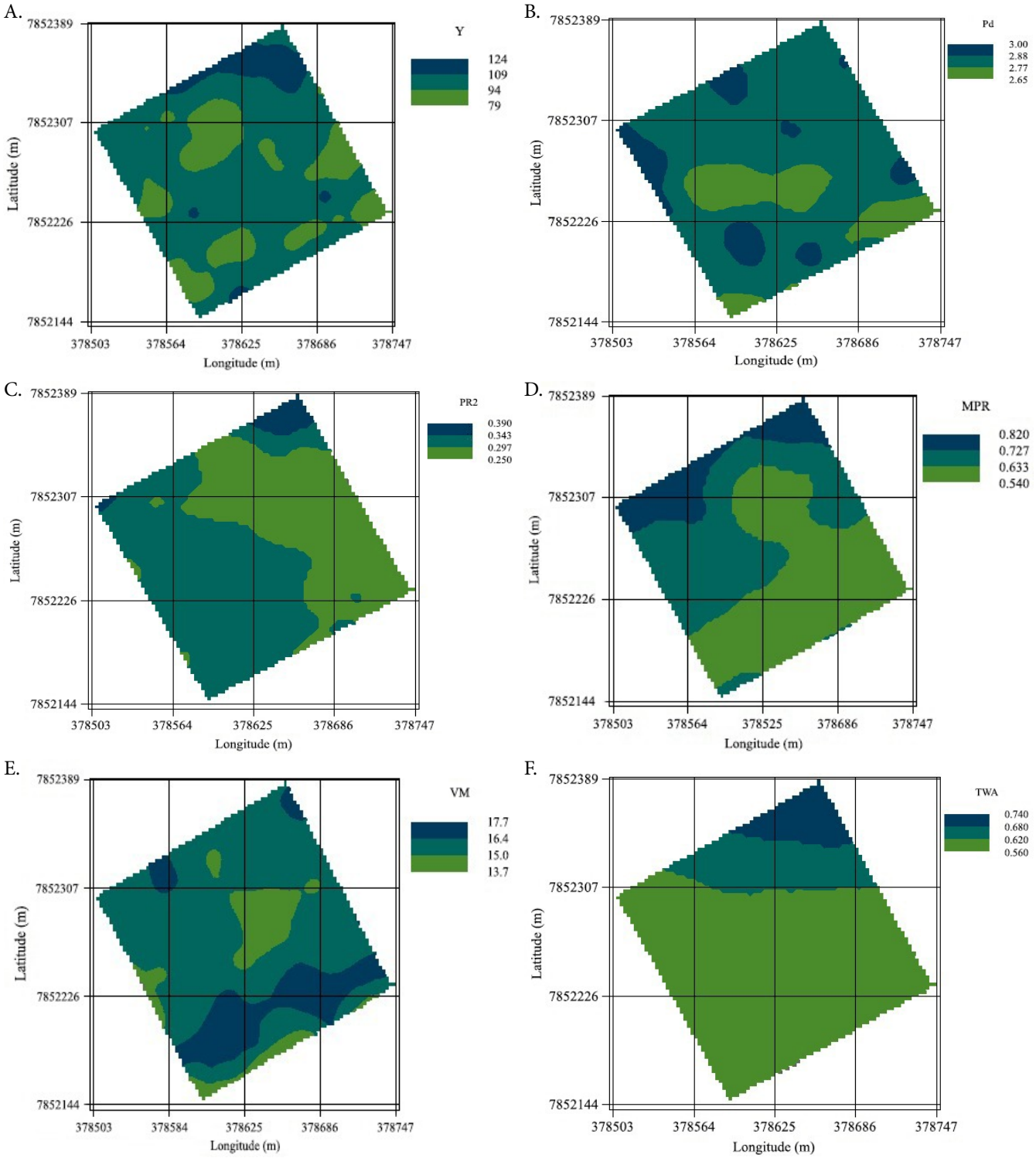

Figure 4. Simple kriging maps: A. carrot yield (t ha^{-1}), B. particle density (g cm^{-3}), C. penetration resistance at the 10-20 cm depth layer (MPa), D. mean penetration resistance (MPa), E. volumetric moisture (%), F. total water availability in the soil (mm cm^{-1} soil)

soil tillage were well-suited to meet the crop's requirements. Consequently, the analysis of yield maps alongside other data, including plant phenological indices and soil physical-hydric attributes, proves invaluable for targeted sampling and the delineation of management zones. Moreover, this information plays a crucial role in identifying potential issues during crop management, enabling producers to address them in future plantings (Oliveira et al., 2020).

Mechanical resistance poses the primary physical limitation to root growth. Severe compaction in the initial soil layers can lead to deformed roots and an increased number of conical roots, resulting in a potential yield reduction of approximately 20%. Root elongation can be significantly hindered when penetration resistance values approach 2 MPa, and total porosity falls below 50% (Hodge et al., 2009; Johansen et al., 2015). Figure 5 reveals a correlation pattern in the southern region, where larger root diameters coincide with lower average penetration resistance, ranging from 0.00 to 40.00 cm, with a variation of 0.540 to 0.820 MPa. It is important to note that the observed levels of compaction were below the maximum limits recommended for carrot crops. Therefore, while penetration resistance may have influenced crop yield, it did not pose a severe restriction.

The total water availability in the soil (TWA) ranged from 0.560 to 0.740 mm cm^{-1}, with the majority falling within the 0.560 to 0.620 mm cm^{-1} range. This limited heterogeneity in TWA can be attributed to the low variations in the parameters determining soil TWA, namely field capacity (M_{fc}), permanent wilting point (M_{PWP}), and soil density (Sd), which exhibited coefficient of variation values of 3.00, 1.46, and 3.06%, respectively. Particle density (Pd) values ranged from 2.77 to 2.88 g cm^{-3}, consistent with findings by Pinto et al. (2019) in a study on the physical properties of Oxisol under different management practices. According to the authors, particle density is a highly stable soil property, primarily influenced by the composition of solid particles, particularly the relative proportions of organic and mineral fractions, which explains the low variation observed in this attribute within the study area.

Bernardo et al. (2019) reported that TWA values in clayey textured soils typically fall within the range of 2.0 to 2.5 mm cm^{-1} soil. However, these authors mentioned that some well-structured fine-textured soils can exhibit characteristics akin to medium-coarse-textured soils, resulting in considerably lower TWA values. In this study, soil samples for physical analysis were collected from the bed at the 0-20 cm depth layer, where low penetration resistance and well-structured soil were observed due to prior bed preparation. These specific conditions may account for the low values found for soil density (Sd), with an average of 0.86 g cm^{-3}, and TWA, with an average of 0.61 mm cm^{-1} soil.

In terms of co-kriging (as presented in Table 3 and Figure 5), it was observed a significant positive spatial correlation between carrot yields and total water availability in the soil, with a spatial dependence ratio of 90.6.

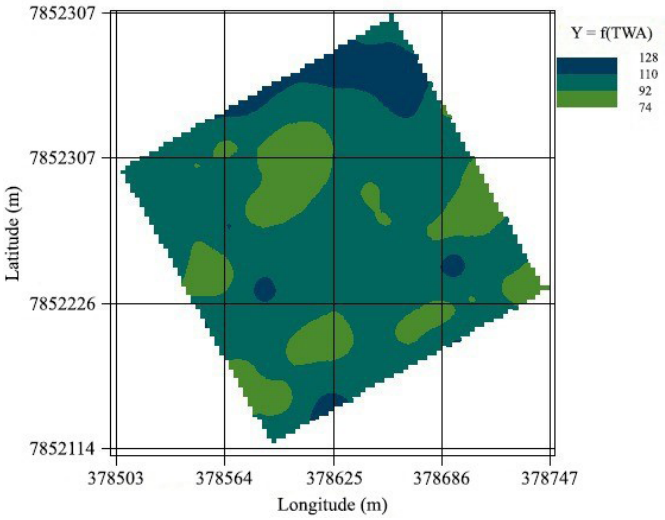

Figure 5. Cokriging Map of the carrot yield as a function of total water availability

The coefficient of determination (R^2) value for Y = f(TWA) was determined to be 0.85. These findings suggest that, within the study conditions, spatial estimation of carrot yield can be achieved with a probability exceeding 80% by employing kriging based on the soil physical attribute TWA.

In this study, the sampling point spacing was set at 20 m. Notably, some soil physical attributes, such as soil density, total porosity, and penetration resistance in the 0-10 cm depth layer, did not exhibit spatial dependence. Therefore, it is advisable to conduct further testing to determine if, at shorter distances, these variables still exhibit random behavior in irrigated carrot crops grown in clayey Oxisols. Additionally, it would be beneficial to assess spatial dependence and variability at two different depths, as this current study only evaluated depths ranging from 0 to 30 cm, except penetration resistance, which was evaluated at four different depths. This expanded analysis would provide a more comprehensive understanding of the spatial behavior of these variables.

Conclusions

1. Carrots demonstrated high yield (99.74 t ha^{-1}) with moderate variability, while soil attributes exhibited low to remarkably high heterogeneity, depending on the specific variable, as indicated by the coefficient of variation.

2. Among the dependent variables, particle density had the smallest range (40 m), suggesting that for future sampling designs in a clayey Oxisol, the recommended sampling interval should not be less than this value.

3. Several soil physical attributes, including particle density, penetration resistance at the 10-20 cm depth layer, mean penetration resistance, volumetric moisture, and total water

Table 3. Parameters of the cross-semivariograms fitted to carrot yield as a function of total water availability

Attribute [(1)]	Model [(2)]	Nugget effect (C_0)	Sill (C_1)	Range (m)	R^2	SSR [(3)]	SDE [(4)]	
							(%)	Class
Y = f(TWA)	SPH	0.042	0.45	193.0	0.85	2.80E-02	90.6	Strong

[(1)] Y - Carrot yield (t ha^{-1}); TWA - Total water availability in the soil (mm cm^{-1} soil); [(2)] SPH - Spherical model; R^2 - Coefficient of determination; [(3)] SSR - Sum of square residues; [(4)] SDE - Spatial dependence evaluator

availability in the soil, exhibited spatial dependence ranging from moderate to strong.

4. Notably, among the assessed attributes, total water availability in the soil emerged as the most reliable indicator for estimating the spatial variability of irrigated carrot yield when employing center pivot irrigation in the municipality of Campos Altos.

Literature Cited

Behera, S. K.; Mathur, R. K.; Shukla, A. K.; Suresh, K.; Prakash, C. Spatial variability of soil properties and delineation of soil management zones of oil palm plantations grown in a hot and humid tropical region of southern India. Catena, v.165, p.251-259, 2018. https://doi.org/10.1016/j.catena.2018.02.008

Bernardo, S.; Mantovani, E. C.; da Silva, D. D.; Soares, A. A. Manual de irrigação. 9. ed. Viçosa: UFV, 2019. 545p.

Cambardella, C. A.; Moorman, T. B.; Parkin, T. B.; Karlen, D. L.; Novak, J. M.; Turco, R. F.; Konopka, A. E. Field-scale variability of soil properties in central Iowa soils. Soil Science Society of America Journal, v.58, p.1501-1511, 1994. https://doi.org/10.2136/sssaj1994.03615995005800050033x

Carvalho, A. D. F. de; da Silva, G. O.; Ragassi, C. F.; Pereira, G. E.; Junior, V. L.; Lopes, C. A.; Pinheiro, J. B.; Reis, A.; Pilon, L. Sistemas de Produção - Cenoura. Brasília: Embrapa Hortaliças, 2021. 74p.

Dezordi, L. R.; de Aquino, L. A.; Novais, R. F.; de Aquino, P. M.; dos Santos, L. P. D. Nutrient recommendation model for carrot crop-Ferticalc carrot. Revista Brasileira de Ciência do Solo, v.39, p.1714-1722, 2015. https://doi.org/10.1590/01000683rbcs20150065

D'Hooghe, P.; Diaz, D.; Brunel-Muguet, S.; Davy, M.; Vial, F.; Dubois, J.; Kauffmann, F. Spatial variation of root yield within cultivated carrot fields is strongly impacted by plant spacing. Scientia Horticulturae, v.241, p.29-40, 2018. https://doi.org/10.1016/j.scienta.2018.06.072

Feitosa, I.; dos Passos, A. M. A.; Cipriani, H. N.; de Oliveira, M. S.; Marcolan, A. L.; Vasques, G. M. Spatial variability of soil physical attributes in integrated production systems in the Amazon region. Pesquisa Agropecuaria Brasileira, v.54, p.1-10, 2019. https://doi.org/10.1590/s1678-3921.pab2019.v54.00324

Feng, W.; Wang, T.; Yang, F.; Cen, R.; Liao, H.; Qu, Z. Effects of biochar on soil evaporation and moisture content and the associated mechanisms. Environmental Sciences Europe, v.35, p.1-12, 2023. https://doi.org/10.1186/s12302-023-00776-7

Guimarães, C.; Silva, F.; Xavier, W.; Costa, C.; Filho, R.; Santos, I. Moisture behavior to the spatial variability of physical attributes in different soil management. Journal of Experimental Agriculture International, v.25, p.1-8, 2018. https://doi.org/10.9734/JEAI/2018/42726

Hodge, A.; Berta, G.; Doussan, C.; Merchan, F.; Crespi, M. Plant root growth, architecture and function. Plant and Soil, v.321, p.153-187, 2009. https://doi.org/10.1007/s11104-009-9929-9

Johansen, T. J.; Thomsen, M. G.; Løes, A.-K.; Riley, H. Root development in potato and carrot crops - influences of soil compaction. Acta Agriculturae Scandinavica, Section B- Soil & Plant Science, v.65, p.182-192, 2015. https://doi.org/10.1080/09064710.2014.977942

Köppen W.; Geiger R. Klimate der Erde. Justus Perthes, Gotha, 1928.

Leiva, J. O. R.; Silva, R. A.; Buss, R. N.; França, V. L.; Souza, A. A.; Siqueira, G. M. Multifractal analysis of soil penetration resistance under sugarcane cultivation. Revista Brasileira de Engenharia Agricola e Ambiental, v.23, p.538-544, 2019. https://doi.org/10.1590/1807-1929/agriambi.v23n7p538-544

Montanari, R.; Panachuki, E.; Henrique Lovera, L.; Correa, A. R.; Oliveira, I. S.; Queiroz, H. A.; Tomaz, P. K. Variabilidade Espacial da Produtividade de Sorgo e de Atributos do Solo na Região do Ecótono Cerrado -Pantanal, MS. Revista Brasileira de Ciência do Solo, v.39, p.385-396, 2015. https://doi.org/10.1590/01000683rbcs20140215

Montazar, A.; Geisseler, D.; Cahn, M. Spatial variability of nitrogen uptake and net removal and actual evapotranspiration in the California desert carrot production system. Agriculture, v.11, p.1-22, 2021. https://doi.org/10.3390/agriculture11080752

Najafian, A.; Dayani, M.; Motaghian, H. R.; Nadian, H. Geostatistical assessment of the spatial distribution of some chemical properties in calcareous soils. Journal of Integrative Agriculture, v.11, p.1729-1737, 2012. https://doi.org/10.1016/S2095-3119(12)60177-4

Oliveira, J. T.; Oliveira, R. A.; Oliveira, L. A. A.; Teodoro, P.; Montanari, R. Spatial variability of irrigated garlic (*Allium sativum* L.) production components. HortScience, v.55, p.300-303, 2020. https://doi.org/10.21273/HORTSCI14409-19

Pimentel-Gomes, F.; Garcia, C. H. Estatística aplicada a experimentos agronômicos e florestais: exposição com exemplos e orientações para uso de aplicativos. 1.ed. Piracicaba: FEALQ, 2002. 309p.

Pinto, L. C.; Chagas, W. F. T.; Amaral, F. H. C. Physical attributes of a Dystroferric Red Latosol (Oxisol) under different management systems. Revista Agrogeoambiental, v.11, p.111-119, 2019. https://doi.org/10.18406/2316-1817v11n120191198

Qin, Q.; Wang, H.; Lei, X.; Li, X.; Xie, Y.; Zheng, Y. Spatial variability in the amount of forest litter at the local scale in northeastern China: Kriging and cokriging approaches to interpolation. Ecology and Evolution, v.10, p.778-790, 2020. https://doi.org/10.1002/ece3.5934

Que, F.; Hou, X. L.; Wang, G. L.; Xu, Z. S.; Tan, G. F.; Li, T.; Wang, Y. H.; Khadr, A.; Xiong, A. S. Advances in research on the carrot, an important root vegetable in the Apiaceae family. Horticulture Research. v.6, p.1-15, 2019. https://doi.org/10.1038/s41438-019-0150-6

Rosa Filho, G. R.; Carvalho, M. D. P. E.; Montanari, R.; da Silva, M. J.; Siqueira, M. G.; Zambianco, C. Spatial variability of dendrometric properties of eucalyptus and physical attributes of a Rhodic Eutrudox. Bragantia, v.70, p.439-446, 2011. https://doi.org/10.1590/S0006-87052011000200027

Shapiro, S.; Wilk, M. B. An analysis of variance test for normality: Complete samples. Biometrika, v.52, p.591-611, 1965. https://doi.org/10.1093/biomet/52.3-4.591

Silva, J. C.; Costa, L. F. F.; Santos, D. P.; Santos, L. J. S.; Silva, C. B.; Santos, M. A. L. Combination of irrigation and fertilizer increases yield and economic profit in carrot production. Revista Brasileira de Engenharia Agrícola e Ambiental, v.25, p.807-812, 2021. https://doi.org/10.1590/1807-1929/agriambi.v25n12p807-812

Souza, M. D. C.; de Oliveira, F. P.; Silva, J. R.; Martins, A. F.; da Silva, P. L. F. Spatial variability of resistance to penetration in soil under sugarcane crops with different harvest methods. Revista Caatinga, v.33, p.480-489, 2020. https://doi.org/10.1590/1983-21252020v33n220rc

Szelag-Sikora, A.; Sikora, J.; Niemiec, M.; Gródek-Szostak, Z.; Kapusta-Duch, J.; Kuboń, M.; Komorowska, M.; Karcz, J. Impact of integrated and conventional plant production on selected soil parameters in carrot production. Sustainability, v.1, p.1-13, 2019. https://doi.org/10.3390/su11205612

Teixeira, G. K.; Donagemma, A.; Fontana, W. G. Teixeira. Manual de métodos de análise de solo. Brasília: EMBRAPA, 2017. 574p.

USDA - Soil Survey Staff. Keys to Soil Taxonomy (12th ed.) USDA NRCS, 2014. Available on: <https://www.nrcs.usda.gov/resources/data-and-reports/web-soil-survey>. Accessed on: Nov. 2020.

Vieira, S. R.; de Carvalho, J. R. P.; González, A. P. Jack knifing for semivariogram validation. Bragantia, v.69, p.97-105, 2010. https://doi.org/10.1590/S0006-87052010000500011

Wei, M. C. F.; Maldaner, L. F.; Ottoni, P. M. N.; Molin, J. P. Carrot Yield Mapping: A precision agriculture approach based on machine learning. AI, v.1, p.229-241, 2020. https://doi.org/10.3390/ai1020015