Spatial Analysis and Mapping of the Effect of Irrigation and Nitrogen Application on Lateral Shoot Growing of Garlic

Job Teixeira de Oliveira, Rubens Alves de Oliveira, and Mario Puiatti
Universidade Federal de Viçosa, Avenida Peter Henry Rolfs, s/n, Campus Universitário, Viçosa, MG, Brasil, 36570-900

Paulo Teodoro
Universidade Federal do Mato Grosso do Sul, Rodovia MS 306, KM 403, Campus Chapadão do Sul, MS, Brasil, 79560-000

Rafael Montanari
Agronomy Department, State University of São Paulo (UNESP), Ilha Solteira–São Paulo, Brasil

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Abstract. The objective of this study was to evaluate whether the spatial variability of plant production components and the use of an irrigation and fertirrigation management system with controlled deficit affect the yield and incidence of garlic lateral shoot growing (LSG). An analysis of these data through statistical and geostatistical techniques made it possible to verify that the increase in yield is directly related to the height and diameter of the bulb and that the lateral shoot growing is directly related to the increase in yield. Lower water depths and lower nitrogen doses applied during clove differentiation imply a lower incidence of LSG, whereas increased irrigation and fertigation with nitrogen results in lower bulb volumes.

Garlic, although used mainly as a condiment, is recognized as an excellent source of protein and energy as well as P, Mg, and Na minerals and sulfur compounds; these attributes make it valuable as an herbal medicine and food (Brewster, 2008). Despite vernalization to enable the cultivation of noble garlic in environments where the natural conditions of the climate do not allow bulbification, this technique favors the appearance of the physiological disturbance of the lateral shoot growing (LSG) of the bulbs, especially if associated with inadequate management of irrigation and nitrogen (N) fertilization (Oliveira et al., 2018). The LSG of garlic is a genetic–physiological anomaly characterized by the atypical appearance of leaves of lateral buds before they form the normal leaves constituting bulbils (cloves). This abnormality, in addition to reducing the yield of commercial bulbs, depreciates the product, thus causing its market value to be compromised (Souza and Casali, 1986).

Garlic is a cold season vegetable; a large part of its cultivation cycle occurs in autumn and winter, which in the southeast of Brazil is characterized by a period of scarce rainfall requiring irrigation. Irrigation is a highly efficient technique used to promote increased crop productivity. Another technique that can be used to reduce water consumption in agriculture is regulated deficit irrigation (RDI). This technique consists of applying a certain level of water stress during the phenological phase of the crop with lesser susceptibility to water restriction. However, it should be emphasized that one of the assumptions of this technique is that the water stress level does not promote yield reduction when compared with full irrigation management during the whole crop cycle (Chai et al., 2016).

This work aimed to evaluate whether the spatial variability of the production components of the plant and the use of an irrigation and fertirrigation management system with controlled deficit interfere in the yield and incidence of garlic LSG.

Materials and Methods

This study was developed in the irrigation and drainage area of the Federal University of Viçosa, in Viçosa, Minas Gerais State, Brazil (23 K, 722569.09 m E; 7701897.59 m S, UTM). The climate is classified as Cwa, with an average annual temperature of 20.6 °C. The culture was installed in the field using a conventional planting system, that is, plowing, harrowing, and operation with a rototiller

for seedbed preparation. Planting fertilization consisted of the application of 20 kg·ha⁻¹ of N, 300 kg·ha⁻¹ of P₂O₅, and 200 kg·ha⁻¹ of KCl. The cultivar Ito was planted on 7 May 2018, in three double rows per seedbed, disposed of longitudinally, spaced 0.1 × 0.1 × 0.4 m (between cloves on the line, between rows, and between the double rows). In each double row of planting, 32 cloves were planted. During data collection, the two central lines were considered useful, and 0.3 m of the extremities were neglected.

The experiment consisted of three depths of irrigation (60%, 80%, and 100% of the soil field capacity) and three depths of fertirrigation with N (60%, 80%, and 100% of the recommended dose) applied during the period of clove differentiation. Topdressing was performed via fertigation at 8, 15, 22, 60, 70, 80, and 90 d after planting with 30 kg·ha⁻¹ of N and 20 kg·ha⁻¹ of K with formulated fertilizer 30–00–20. The *x* and *y* directions of the cartesian coordinate system were defined; at the end of the garlic phenological cycle (15 Sept. 2018), the experimental grid was staked in plots spaced at 1.6 m. Each experimental grid comprised three transects of 48 × 1.6 m.

Irrigation of the garlic was performed by the drip irrigation system using a distribution line in the middle of the double row of garlic planting, with drippers spaced 0.20 m apart. Determination of the water application rate of the drippers was performed following the method described by Bernardo et al. (2006). The need for water application by the garlic culture was monitored using Irrigâmetro (UFV, Viçosa, Brazil) installed in the experiment area. The readings of the Irrigâmetro were performed daily at 8:00 AM. The water level applied during each irrigation was enough to restore the soil moisture content to the field capacity.

At 51 d after planting, the water depth applied to all seedbeds was controlled so that at the beginning of the controlled water deficit period, the water in the soil was at field capacity. At 82 d after planting, irrigation with water depth and N variation was started. A total of four irrigations with variations were performed at 82, 86, 101, and 107 d after planting.

From the total of 90 sampling points (beds), 66 of these points were irrigated with 100% of the water requirement of the crop (without water restriction), estimated by the Irrigâmetro. Of the remaining 24 sampling points, 12 points were irrigated with 80% and 12 points with 60% of the crop water requirement until the garlic harvest phase. The last irrigation was performed 15 d before harvest.

The experiment was harvested at 130 d after planting, during the senescence phase of the plants, when they had approximately six green leaves. The determined production components were individually collected in the sample area, which was composed of a double line with a length of 1.0 m, totaling 20 plants. Garlic bulb yield (BY) was determined by weighing all harvested bulbs and values were expressed in kg·ha⁻¹. Irrigation (IR) with restriction applied in the formation of the bulbs was determined by measuring the amount of water applied (mm) at all sampling points

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P.E.T. is the corresponding author. E-mail: eduteodoro@hotmail.com.

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Table 1. Estimated parameters for the simple semi-variogram of garlic crop production components.

Production component	Model	Nugget C_0	Sill C_0+C	Range A_0 (m)	r^2	SRS	SDE		Cross-validation		
							%	Class	a	b	r
BY	exp	3.86×10^6	7.72×10^6	12.6	0.71	1.63×10^{10}	50.0	Moderate	7367.8	0.60	0.35
IR	sph	2.08×10^2	5.95×10^2	14.3	0.50	5.81×10^4	65.0	Moderate	-6.74	1.04	0.67
N	sph	1.20×10^{-2}	6.30×10^{-2}	20.0	0.70	6.51×10^{-4}	81.0	Strong	-0.10	1.06	0.83
LSG	gau	5.31×10^1	1.33×10^2	36.0	0.79	4.79×10^3	60.0	Moderate	0.71	0.92	0.53
BD	exp	1.36	2.72	14.1	0.85	0.10	50.0	Moderate	30.14	0.39	0.14
BL	gau	0.95	1.50	8.5	0.80	6.70×10^{-2}	36.7	Moderate	5.38	0.86	0.35
BV	sph	3.75×10^2	6.96×10^2	9.0	0.48	3.67×10^4	46.1	Moderate	0.06	0.60	0.23
LAI	exp	8.50×10^{-3}	3.40×10^{-2}	8.5	0.43	5.60×10^{-5}	75.1	Strong	-0.08	1.12	0.45

BY = garlic bulb yield, external component interference, irrigation (IR) with restriction applied in the bulb formation (mm), and nitrogen (N); LSG = lateral shoot growing; BD = bulb diameter; BL = bulb length; BV = bulb volume; LAI = leaf area index; sph = spherical; exp = exponential, gau = Gaussian; SRS = sum of the residue square; SDE = spatial dependence evaluation.

throughout the development cycle of the crop. Nitrogen applied via fertirrigation with a restriction on bulb formation was determined by measuring the amount of nutrient applied in the topdressing (kg) at all sampling points. The LSG was obtained using the percentage of plants with secondary bulb growth at each sampling point. The bulb diameter (BD) and bulb length (BL) were measured with the aid of a caliper, and the values were expressed in mm. The leaf area index (LAI) was measured on the day of harvest using the PAR/LAI Ceptometer model CP-80 (Decagon Devices, Inc., Pullman, WA). The bulb volume (BV) was calculated as a function of BD and BL and the values were expressed in cm^3 .

Descriptive analysis was performed. Semi-variogram adjustments and semi-variance estimation were performed to estimate the coefficients of the theoretical model for the semi-variogram called the nugget effect (C_0), sill (C_0+C), and range (A_0). The data were interpolated by kriging to allow visualization of the spatial distribution patterns of the garlic production components through maps. SE maps of kriging prediction were generated. Cross-validation is a tool used to evaluate alternative models of simple and crossed semi-variograms.

Results and Discussion

With the exception of LSG, all variables showed cv values less than 20% (Supplemental Table 1). The IR, NI, and BV components fit the spherical model, whereas the components BY, BD, and LAI fit the exponential model (Table 1). The LSG and BL components fit the Gaussian model. According to Cambardella et al. (1994), the values of the NI and LAI components presented strong spatial dependence evaluation (SDE),

whereas BY, IR, LSG, BD, BL, and BV presented moderate SDE.

The semi-variograms of garlic production components and external components are shown in Supplemental Fig. 1. The simple kriging maps of the garlic crop production components are shown in Supplemental Fig. 2. These maps allow visualization of the spatial variability of each of the components in the study area. Supplemental Table 1 shows the cross-validation parameters for garlic yield kriging and plant phenological indexes. The increasing ratio of these, as analyzed by the magnitude of the correlation coefficient (r), was as follows: BD (0.14) > BV (0.23) > BL (0.35) > BY (0.35) > LAI (0.45) > LSG (0.53) > IR (0.67) > NI (0.83).

When the cross-semi-variogram was performed between plant phenological indices, positive spatial correlations (Supplemental Table 2) for the BY = $f(\text{BL})$, BY = $f(\text{BD})$, BD = $f(\text{BL})$, LSG = $f(\text{BY})$, LSG = $f(\text{IR})$, BD = $f(\text{IR})$, LSG = $f(\text{NI})$, BD = $f(\text{NI})$ were found to have SDE values of 34.7%, 31.4%, 50.0%, 100.0%, 89.1%, 95.0%, 78.4%, and 99.9%, respectively. These results show that there is a direct relationship between the yield, height, and diameter of the bulb, and that the increase in the diameter of the bulb implies an increase in yield, and that the percentage of garlic LSG increases with the bulb yield. Another important observation was the direct relationship observed between garlic LSG and irrigation and N; the increase of irrigation depth and fertigation in the clove formation phase implies higher percentages of plants with garlic LSG.

Negative spatial correlations were obtained for BL = $f(\text{IR})$, BV = $f(\text{IR})$, BL = $f(\text{N})$, and BV = $f(\text{N})$, with SDE values of 86.7, 97.9, 80.0, and 97.1 respectively. When analyzing these indices, it was concluded that the

increase in irrigation and fertigation during the formation phase of the cloves imply lower volumes of bulbs. These results will be very useful for garlic producers because with the reduction of irrigation and fertigation during the formation phase (differentiation) of cloves, the producer will have bigger bulbs and a lower incidence of garlic.

Conclusions

Garlic yield is directly related to the height and diameter of the bulb. Garlic LSG is directly related to yield. Water depths and N doses applied during the differentiation phase of cloves are directly related to the garlic LSG. The increases in irrigation and nitrogen fertigation during the formation phase of the cloves imply lower volumes of bulbs.

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Supplemental Table 1. Descriptive statistics for garlic crop production components

Production component	Avg	Minimum	Maximum	sd	Coefficient of variation	Kurtosis	Asymmetry	Pr > F	FD
BY	10,351	8,370	12,518	840	8.12	-0.11	-0.10	0.6587	NO
IR	194.91	129.40	225.68	22.40	11.49	1.05	-1.34	1.0×10^{-8}	IN
N	1.81	1.30	2.13	0.22	12.32	-0.85	-0.72	2.0×10^{-7}	IN
LSG	9.34	0.00	46.87	9.36	100.25	3.10	1.55	3.0×10^{-8}	IN
BD	49.23	45.87	53.13	1.58	3.20	-0.47	0.03	0.9225	NO
BL	39.42	36.86	43.11	1.14	2.89	0.30	0.23	0.8713	NO
BV	32.10	26.45	38.28	25.14	7.83	-0.21	0.03	0.4613	NO
LAI	0.84	0.25	0.91	0.18	26.74	-1.03	-0.37	2.0×10^{-4}	IN

BY = garlic bulb yield ($\text{kg} \cdot \text{ha}^{-1}$), external component interference, irrigation (IR) with restriction applied in the bulb formation (mm), and nitrogen (N) (kg); LSG = lateral shoot growing (%); BD = bulb diameter (mm); BL = bulb length (mm); BV = bulb volume (cm^3); LAI = leaf area index (%); FD = frequency distribution; NO = normal type; IN = indeterminate.

Supplemental Fig. 1. Semi-variograms of the garlic production components: (A) garlic bulb yield (BY) in $\text{kg} \cdot \text{ha}^{-1}$; (B) irrigation (IR) with restriction applied in the bulb formation (mm); (C) nitrogen (N) (kg); (D) lateral shoot growing (LSG) (%); (E) bulb diameter (BD) (mm); (F) bulb length (BL) (mm); (G) bulb volume (BV) (cm^3); and (H) leaf area index (LAI) (%).

Supplemental Table 2. Estimated parameters for the cross-semi-variogram of the garlic crop production components

Production component	Model	Nugget C_0	Sill C_0+C	Range A_0 (m)	r^2	SRS	SDE	
							%	Class
BY = f(BL)	gau	4.59×10^2	7.03×10^2	11.4	0.781	1.48×10^4	34.7	Moderate
BY = f(BD)	gau	9.78×10^2	1.43×10^3	17.0	0.896	3.42×10^4	31.4	Moderate
BD = f(BL)	sph	0.55	1.10	16.3	0.777	6.00×10^{-2}	50.0	Moderate
LSG = f(BY)	gau	1.00	2.35×10^3	32.0	0.874	3.19×10^6	100.0	Strong
LSG = f(IR)	exp	5.00	4.59×10^1	4.6	0.833	5.21×10^1	89.1	Strong
BL = f(IR)	gau	-0.91	-6.85	11.6	0.885	5.03×10^0	86.7	Strong
BD = f(IR)	gau	1.00	1.90×10^1	37.0	0.706	3.12×10^2	95.0	Strong
BV = f(IR)	gau	-0.09	-8.50	11.6	0.794	3.73×10^1	97.9	Strong
LSG = f(N)	exp	0.08	0.37	13.0	0.855	5.36×10^{-3}	78.4	Strong
BL = f(N)	gau	-0.02	8.50×10^{-2}	16.0	0.943	3.97×10^{-4}	80.0	Strong
BD = f(N)	gau	1.0×10^{-4}	0.16	37.0	0.700	2.43×10^{-2}	99.9	Strong
BV = f(N)	sph	4.0×10^{-3}	-0.14	20.3	0.868	2.90×10^{-3}	97.0	Strong

BY = garlic bulb yield, in function of f(BL) = bulb length, and f(BD) = bulb diameter; BD = bulb diameter, in function f(BL) = bulb length, f(IR) = irrigation, and f(N): nitrogen; LSG = lateral shoot growing, in function f(BY) = bulb yield, f(IR) = irrigation, and f(N) = nitrogen; BL = bulb length, in function f(IR) = irrigation, and f(N) = nitrogen; BV = bulb volume, in function (IR) = irrigation, and f(N) = nitrogen; sph = spherical, exp = exponential, and gau = Gaussian; SRS = sum of the residue square; SDE = spatial dependence evaluation.

Supplemental Fig. 2. Simple kriging maps of the garlic production components: (A) garlic bulb yield (BY) in $\text{kg} \cdot \text{ha}^{-1}$; (B) irrigation (IR) with restriction applied in the bulb formation (mm); (C) nitrogen (N) ($\text{kg} \cdot \text{ha}^{-1}$); (D) lateral shoot growing (LSG) (%); (E) bulb diameter (BD) (mm); (F) bulb length (BL) (mm); (G) bulb volume (BV) (cm^3); and (H) leaf area index (LAI) (%).