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Scientific Paper

Do the number of bolls and the height of the first boll insertion influence the productivity of cotton lint?

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Abstract

Cotton (*Gossypium hirsutum* L.) is one of the world's most economically important crops, providing a major source of natural textile fiber, vegetable oil, and biofuel. This study aimed to map and evaluate the correlation between cotton lint productivity and the key agronomic traits, including boll number and the height of the first boll insertion, as well as other plant characteristics. Spatial variability was assessed through the interpretation of simple and cross-semivariograms, along with their respective kriging and cokriging maps. A regular geostatistical sampling grid consisting of 100 points, spaced at 9.9 m x 9.9 m, was established for data collection. The phenological indices evaluated included cotton lint productivity (PR), number of bolls per plant (NBO); height of the first boll insertion (HB); total fresh weight of the cotton plant (TF); plant height (HE); plant width (WI); number of branches per plant (NBR); and stem diameter (DS). Among these variables, most of them showed spatial dependence, except for total fresh biomass (TF) and plant height (HE), which showed a pure nugget effect, indicating the absence of spatial dependence among the sampled points. Cotton lint productivity showed a strong and positive correlation with the number of bolls per plant ($R^2=0.667$), indicating the potential of this attribute as a strong indicator of crop productivity. In contrast, the height of the first boll insertion exhibited a strong negative relationship with cotton lint productivity ($R^2=0.820$), indicating that higher boll insertion is associated with reduced crop productivity.

Keywords: Spatial correlation, geostatistics, *Gossypium hirsutum* L., sampling grid, sampling point.

Introduction

Cotton (*Gossypium hirsutum* L.) cultivation is one of the world's most important economic crops, providing natural textile fiber, vegetable oil, and biofuel (Cheng et al., 2020). Its applications are diverse, ranging from textile manufacturing to the use of its by-products, such as oil and seeds, in animal feed and other agro-industrial processes. According to Dias & Santos (2023), cotton is among the most extensively utilized plant species worldwide.

According to data from Conab (2024) for the 2023-2024 crop season, Brazil has a planted cotton area of 1,766 thousand hectares, representing an increase of 6.2% compared to the previous season. In contrast to this increased data, both productivity and total production are projected to decline by 8.0% and 2.3%, respectively. These reductions are attributed to adverse natural and climatic factors affecting crop development.

The critical period for cotton production occurs during the flowering and boll development stages, which account for approximately 58.7%–60.4% of the total cotton growth cycle (Wang et al., 2017). Investments aimed at improving floral development and reducing boll abscission are essential to ensure high yield and fiber quality, improving the economic returns of cotton production (Shui et al., 2024).

Geostatistics is a key tool in precision agriculture and, when combined with appropriate management practices, contributes significantly to the optimization of production systems (Oliveira et al., 2023). This approach enables a detailed understanding of the spatial variability of soil-plant interactions, supporting informed decision-making through the diagnosis and improvement of site-specific conditions (Montanari et al., 2015).

Understanding and analyzing plant characteristics in relation to their developmental stages generate considerable datasets throughout the crop cycle. For instance, physical and morphological attributes can provide valuable insights into crop performance, spatial variability, and yield potential.

Sousa et al. (2020) explain that the generation and dissemination of knowledge are integral components of a process that begins with producers identifying the problems to be investigated, followed by experimentation and validation of the generated technologies, and ultimately culminating in their incorporation into the production systems adopted by rural producers.

Based on precision agriculture techniques and analyses, it is possible to understand crop behavior from a multispectral perspective using geostatistical approaches. According to Montanari et al. (2015) and Oliveira et al. (2023), simple interpolation (kriging) and cross-interpolation (cokriging) between plant attributes and other correlated variables provide a robust basis for estimating the spatial variability of a given attribute using another easily measurable variable. This spatial variability may reveal significant correlations between productivity and specific phenological indices, thereby supporting more accurate yield prediction and management decisions.

Thus, the objective of this study is to map and evaluate the correlation between cotton lint productivity and the number of bolls, as well as the height of first boll insertion and other plant characteristics, through the interpretation of simple and cross semivariograms and their respective kriging and cokriging maps.

Material and Methods

The study was conducted in a plot located within the arable area of Indaiá II Farm, situated in the municipality of Paraíso das Águas, Mato Grosso do Sul, Brazil (19°1'33" S, 53°0'37" W; altitude 608 m. The region presents average annual temperatures ranging from 14 to 31 °C, and is classified as humid tropical (Cfa) according to Köppen and Geiger climate classification. The average annual rainfall is approximately 1,303 mm. The rainfall and precipitation patterns recorded during the experimental period is presented in Figure 1.

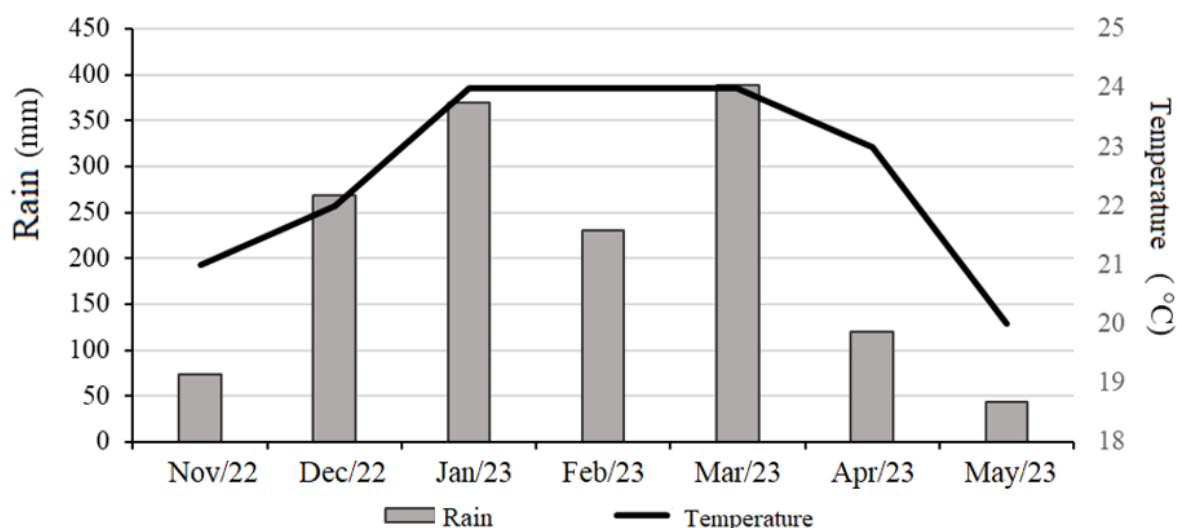


Figure 1. Average temperature and rainfall in the study area during the 2022/23 growing season.

The experiment was established in plot number 41, covering a total area of 61.22 ha. The soil exhibits a sandy texture and is classified as Quartzarenic Neosol according to the Brazilian Soil classification System (Santos et al., 2018). Detailed information on the soil's physical-hydric characteristics is presented in Table 1.

Table 1. Physical and hydrological characteristics of the soil in the experimental area.

Layer (cm)	Particle size distribution (%)			Water content (g g ⁻¹)		Density (g cm ⁻³)
	Clay	Silt	Sand	Fc	Pw	
0-20	12	5	83	0.088	0.053	1.300

Fc: Field capacity; Pw: Permanent wilting point of the plant.

A regular geostatistical grid was established within the experimental plot. Using a Cartesian coordinate system, 100 sampling points were distributed across five sections of 20 points arranged in a square grid with 9.90 m x 9.90 m. The grid covered a total area of 0.98 ha.

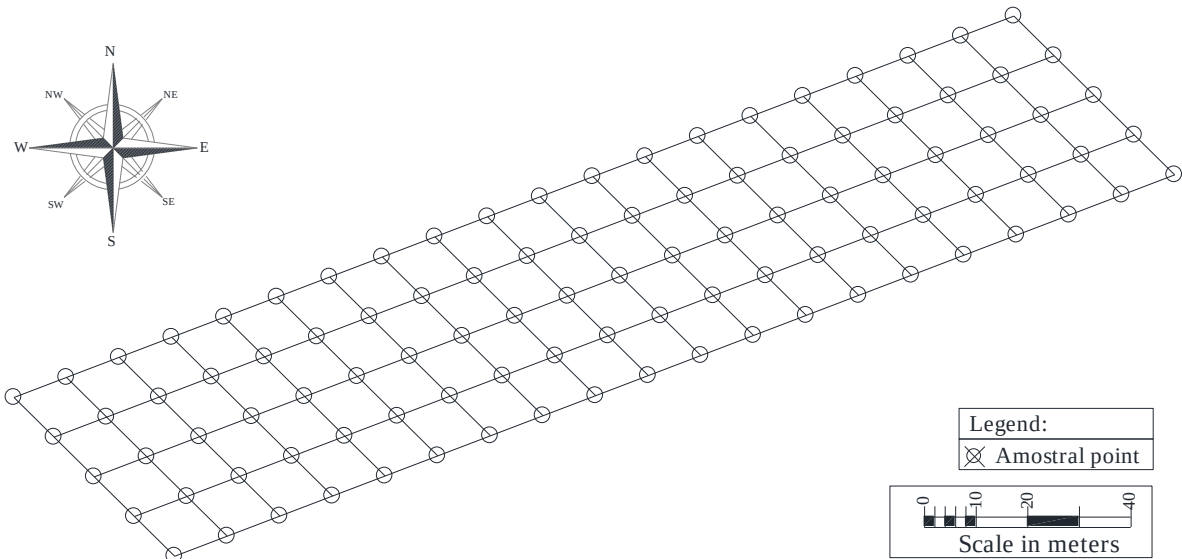


Figure 2. Sampling grid comprising 100 points in the experimental area at Indaiá II Farm, located in the municipality of Paraíso das Águas, MS, Brazil.

Sowing was performed on November 20, 2022, using a row spacing of 0.90 m, and a plant population of 95,000 plants ha⁻¹. The cotton cultivar FM 978 6LTP was used, characterized by a fiber yield of 40-43% and an average boll weight of 4.4 g, and classified as a long-cycle cultivar (Oliveira Rampazzo et al., 2024). Harvest for data collection was carried out on May 26, 2023, resulting in a total crop cycle of 187 days. At each sampling point, three plants were randomly selected, and data were collected for subsequent analyses. In addition to cotton lint productivity, seven other phenological indices were evaluated, as described below:

Cotton lint productivity (PR)

Following the random harvesting of three plants per sampling point, the harvested material was separated into lint, seeds, and foreign material. The total mass of the cleaned sample was weighed on a precision scale and subsequently converted from grams per plant to arroba (@). The values were then extrapolated to a per-hectare basis, allowing the estimation of cotton lint productivity expressed as @ ha⁻¹.

Number of bolls per cotton plant (NBO)

The number of bolls was counted on each of the three plants at every sampling point. Subsequently, the arithmetic mean was calculated to determine the average number of bolls per plant at each point. This variable is dimensionless.

Height of the first boll insertion per cotton plant (HB)

The distance from the ground level (standardized at the collection cut) to the tiller where the first boll developed was measured for each plant using a measuring tape. The arithmetic mean of the three plants sampled per point was then calculated, providing the height values in centimeters.

Total fresh weight of the cotton plant (TF)

Three plants were harvested per sampling point and weighed using a precision balance. The total fresh weigh was expressed in grams.

Height of the cotton plant (HE)

For each sampling point, three plants were measured using a measuring tape, from the base at

the harvest cut to the highest point of the plant. The arithmetic mean of the three measurement was calculated, with height expressed in centimeters, following the methodology of Plazas et al. (2024).

Width of the cotton plant (WI)

For each sampling point, the width of three collected plants was measured at their two longitudinal extremes relative to the ground. The arithmetic mean of these measurements was calculated, with the average width expressed in centimeters.

Number of branches per cotton plant (NBR)

The number of branches was counted on each of the three plants collected per sampling point. The arithmetic mean was calculated to determine the average number of branches per plant at each point. This variable is dimensionless.

Diameter of the cotton plant stem (DS)

For each sampling point, stem samples were collected close to the ground from the three plants. The diameter of each stem was measured using a digital caliper, and the arithmetic mean was calculated

to determine the average stem diameter per point, expressed in millimeters.

Data analysis

Class maps were generated using kriging and cokriging in GS+ software (version 7.0). Spatial correlations between variables were assessed after constructing their respective spatial patterns. The software output was used directly, preserving the spatial position of the original data.

Results and Discussion

Correlations among the evaluated attributes, as well as geostatistical analyses derived from simple and cross-semivariograms of phenological indices, are presented in Table 2. A positive correlation (indicated by the positive sign of the nugget and sill effect variables) is observed between cotton lint productivity and the number of bolls ($PR=f(NBO)$). A negative correlation (evidenced by the negative sign of the nugget and sill effect variables) is identified between cotton lint productivity and the height of the first boll insertion ($PR=f(HB)$).

Table 2. Estimated parameters for the simple and cross-semivariograms for the evaluated components in relation to the variables cotton lint productivity (PR), total fresh mass (TF), height (HE), width (WI), number of branches (NBR), stem diameter (DS), number of bolls (NBO), height of the first boll insertion (HB) in cotton plants cultivated in the municipality of Paraíso das Águas, MS, Brazil.

Attribute	LAD	Interval	Adjustment	Nugget Effect	Level	Range (m)	R ²
PR	228.0	22.8	Exp	2900	9300	38	0.592
TF	-	-	PNE	-	-	-	-
HE	-	-	PNE	-	-	-	-
WI	136.8	13.6	Exp	2200	18000	23	0.537
NBR	114.4	11.4	Exp	1000	11000	20	0.238
DS	122.4	12.2	Exp	1100	10800	27	0.299
NBO	114.4	11.4	Sph	20000	45000	33	0.577
HB	109.0	10.9	Gau	1.5	18	23	0.824
PR=f(NBO)	127.4	12.7	Sph	248	530	37	0.667
PR=f(HB)	180.0	18.0	Sph	-145	-280	150	0.820
Attribute	SDA	ASD (%)	Class	Number of neighbors	a	b	R ² (cross-validation)
PR	2911235	0.688	Moderate	64	52.670	0.79	0.123
TF	-	-	-	-	-	-	-
HE	-	-	-	-	-	-	-
WI	1140.0	0.878	Strong	64	0.257	2.58	0.141
NBR	14.7	0.909	Strong	26	0.504	8.88	0.027
DS	11.8	0.898	Strong	16	0.329	9.66	0.019
NBO	110.0	0.556	Moderate	20	0.879	2.48	0.198
HB	29.0	0.917	Strong	64	0.398	9.63	0.096
PR=f(NBO)	11716	0.532	Moderate	42	0.480	129.00	0.105
PR=f(HB)	3761	0.482	Moderate	40	0.480	129.47	0.105

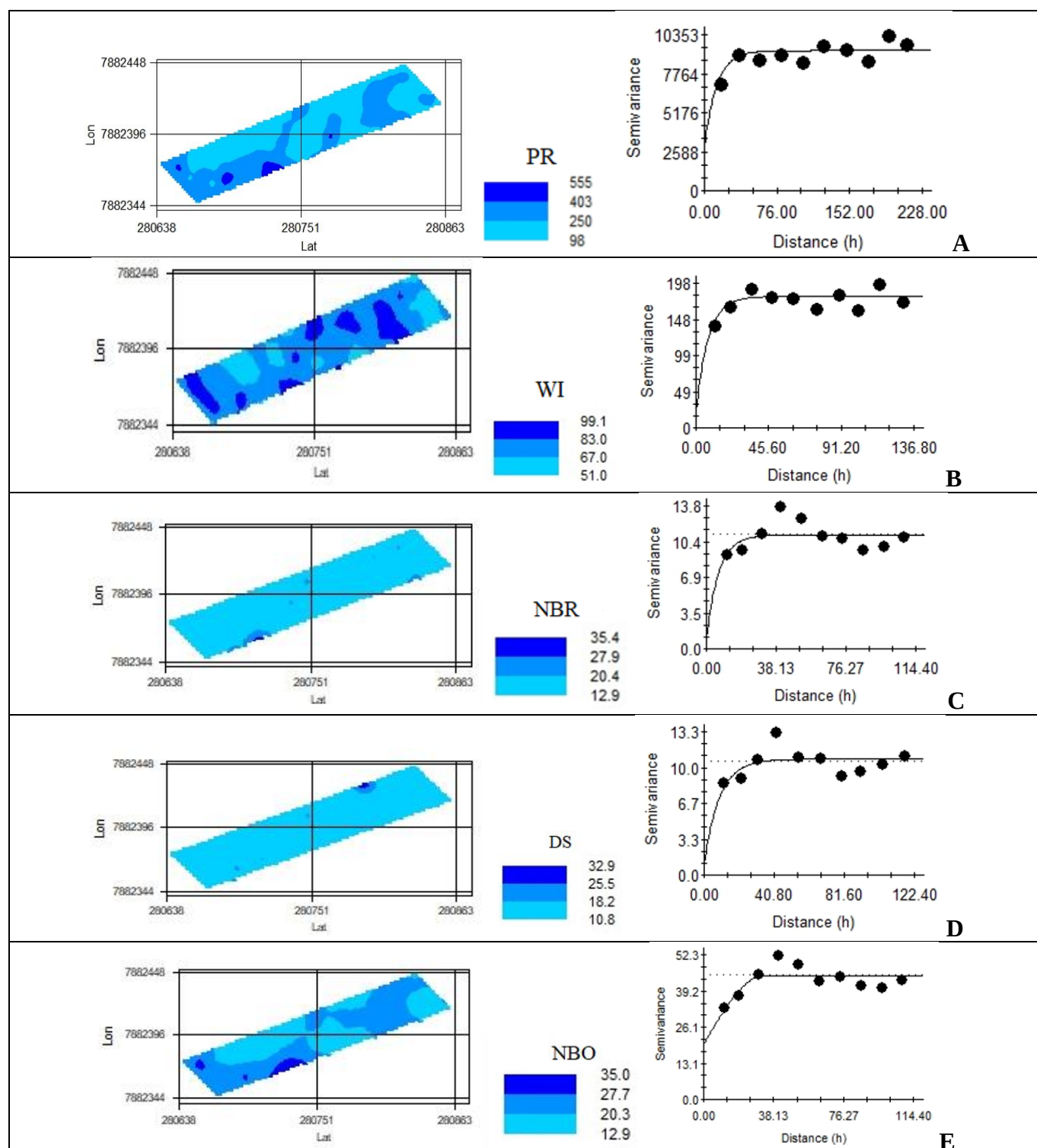
where: LAD = Leg active distance, Gau = Gaussian, Exp = Exponential, Sph = Spherical, PNE = Pure nugget effect, SQR = sum of squared residuals, SDA = spatial dependence assessment, ASD = Assessment of spatial dependence, a, b = cross-validation constants.

In Table 2, it can be observed that the phenological indices MT and ALT exhibited a pure nugget effect, indicating the absence of spatial dependence among the sampled points.

AL is a variable controlled throughout the crop cycle through the application of phytohormones, aiming to regulate plant growth and prevent excessive vegetative development. These applications are strategically managed to avoid both excessive and insufficient dosage of growth regulators (Andrea et al., 2023). Oliveira et al. (2023), when evaluating the

spatial distribution of soil physical attributes in relation to agricultural crop productivity, reported that plants with greater heights tend to exhibit higher productivity. However, in cotton cultivation, this relationship is more complex, as controlling plant height is essential to ensure efficient operation of the harvesting platform and to optimize harvesting performance.

In Figure 3, the kriging maps are shown on the left, with the amplitude zones highlighted in shades of blue, and the simple semivariograms of cotton lint productivity and the studied variables are shown on the right.



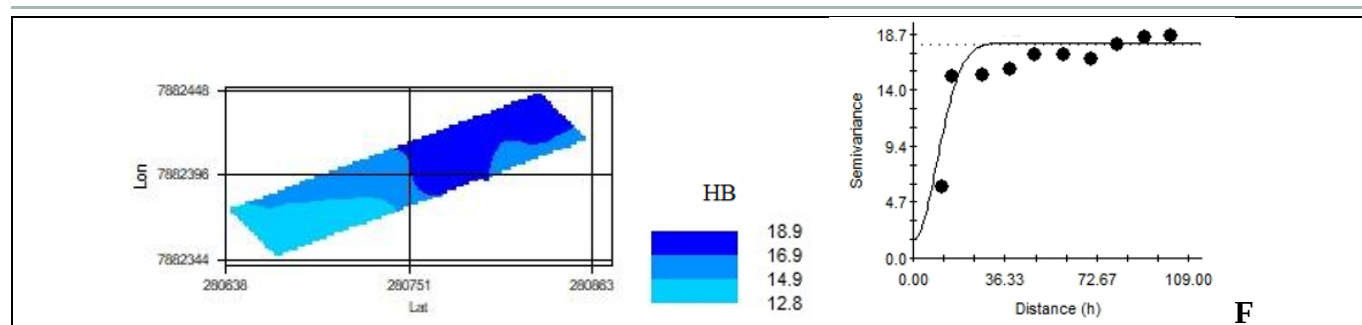


Figure 3. Kriging maps (left) and simple semivariograms (right) for cotton plants growth in the municipality of Paraíso da Águas, MS: (A) (PR) cotton lint productivity (@ ha-1), (B) (WI) plant width (cm), (C) (NBR) number of branches (dimensionless), (D) (DS) stem diameter (mm), (E) (NBO) number of bolls (dimensionless), (F) (HB) Height of first boll insertion (cm).

Precision agriculture has great potential for analyzing cotton variables, as illustrated in Figure 3, where the highest cotton lint yields were observed in the southwestern portion of the map. Mapping productive areas allows for the estimation of crop productivity based on the analysis of phenological indices (Trevisan et al., 2021). Previous studies have shown that cotton shoot and boll abscission can be triggered by environmental stressors, extreme weather events, and species-specific characteristics, resulting in significant losses in yield and fiber quality (Cheng et al., 2020). Early cotton maturation may increase both seed cotton weight and fiber per boll, but it can also reduce the rate of boll formation. Consequently, achieving a balance between cotton yield per boll and overall yield is critical (Shui et al., 2024). These authors further emphasize that, for early-maturing cotton, this balance can be optimized by increasing planting density and the number of bolls, which increases fiber productivity.

Analyzing phenological indices individually enables the identification of locations with higher or lower values. For instance, the spatial distribution of plant width (WI, Figure 3B) shows considerable dispersion throughout the map. In addition, architectural phenological indices, such as WI, are of great agronomic importance because they influence both the efficiency of harvesting and the yield potential of cotton, which is an indeterminate perennial species cultivated as an annual crop (Asiimwe et al., 2013).

Analysis of the number of branches (NBR, Figure 3C) indicates that this variable, closely related to plant architecture, exhibited low variability across the mapped area, with most plants ranging between 12.9 and 20.4 branches per cotton plant. In contrast, stem diameter (DS, Figure 3D), predominantly ranged from 10.8 to 18.2 mm. Despite this low variability, both NBR and DS are important phenological indices that influence crop development and productivity. Asiimwe et al. (2013) reported that plant architecture can

significantly affect the light distribution and penetration within the canopy and thus alter plant growth, lateral branching, biomass accumulation, boll distribution, and yield potential. In recent decades, genetic improvement has developed genotypes with enhanced traits, including higher yield, optimized plant height, and improved ease of management (Adams et al., 2019). However, in addition to the genetic material, environmental factors also influence plant development, which may help explain the observed variability in WI, NBR, and DS.

When analyzing the phenological indices individually in relation to productivity, a similarity is observed between locations on the kriging maps (Figure 3A, 3E, and 3F). The number of bolls (NBO) variable exhibits higher values in the southwestern portion of the map (Figure 3E), which correspond to areas of higher cotton lint productivity (Figure 3A). NBO showed spatial variability in the studied area, with most plants producing between 20.3 and 35 bolls. While the number of bolls is influenced by management practices and the production system, it is strongly determined by the cultivar, as even genotypes expressing their maximum genetic potential are affected by environmental conditions (Gomes et al., 2020).

Cotton is an important fiber crop, widely used in various industrial sectors due to the diversity of products and by-products it provides (Abbas et al., 2023). Cotton lint productivity is determined by several parameters, including the number of bolls (Shah et al., 2020). However, the number of bolls is influenced not only by the cultivar, but also by management practices employed during cultivation, both of which significantly affect plant growth and the final productivity achieved (Gomes et al., 2020).

The cross-semivariograms and the corresponding cokriging maps of cotton lint productivity as a function of NBO and HB are presented in Figure 4.

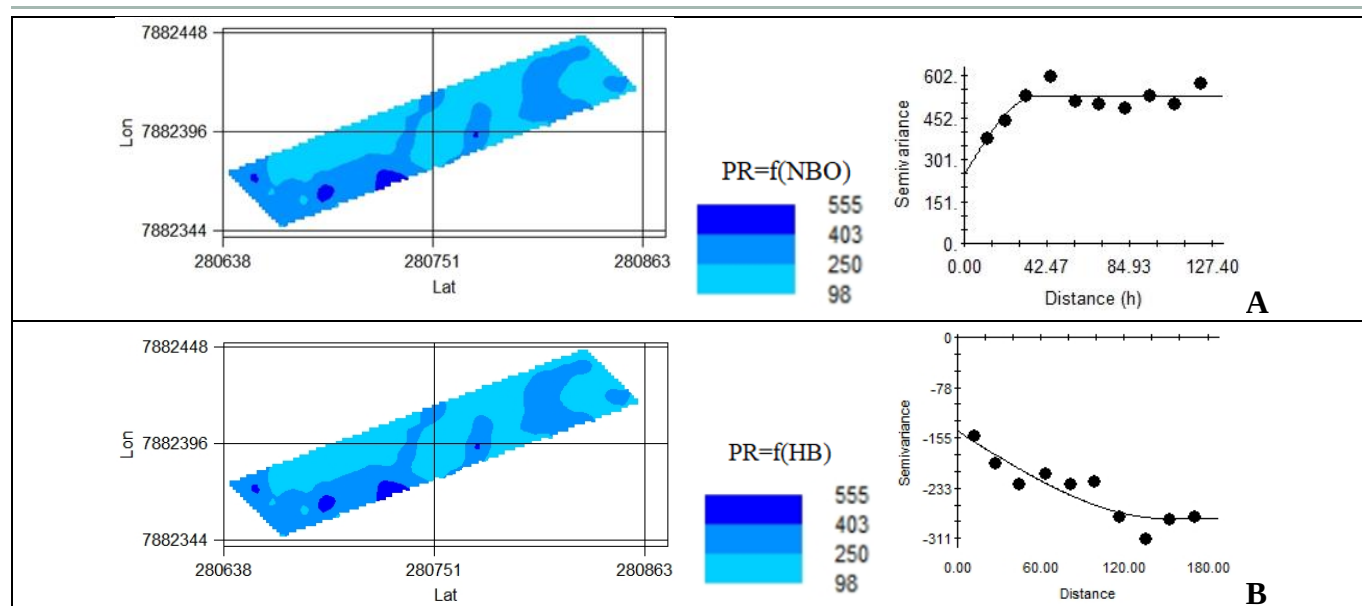


Figure 4. Cokriging maps and cross-semivariograms of cotton lint productivity (@ ha-1) as a function of (A) the number of bolls (NBO), and (B) the height of first boll insertion (HB) in plants grown in the municipality of Paraíso das Águas, MS, Brazil.

In Figures 4A and 4B is illustrated the relationship between cotton lint productivity and (A) the number of bolls ($PR=f(NBO)$) and (B) the height of the first boll insertion ($PR=f(HB)$), respectively. A positive correlation between PR and NBO is evident, as indicated by the upward curvature of the semivariogram and the positive values of the nugget and sill parameters). This correlation reflects the fact that the number of bolls is a key variable used to estimate cotton lint productivity (Shui et al., 2024).

The relationship between PA and AI is negative, as indicated by the downward curvature of the semivariogram and the negative values of the nugget and sill parameters. The height of first boll insertion (HB) is closely related to boll production and is commonly used to estimate crop productivity. Specifically, higher HB values are associated with lower expected productivity, as shown in Figures 3F and 3A. This inverse relationship occurs due to the decrease in the number of bolls on the plant, reducing yield and productivity (Abbas et al., 2023). Theoretically, a higher first boll insertion results in a reduced productive height of the cotton plant.

The height of the first boll insertion in cotton plants also influences agronomic management and mechanization. Low first-boll insertion can reduce productivity because harvesting machines are unable to collect bolls positioned too close to the ground. It is also important to emphasize that bolls close to the ground are more susceptible to contamination with dust, pebbles, and dirt, which increases the leaf grade (L.G.) and the number of surface impurity particles (Count - Cnt), two indices used to assess cotton fiber quality (a test performed with Uster High Volume Instruments)) (MAPA, 2016). A high impurity index negatively impacts the market value of cotton lint.

Field-stage operations require careful management during mechanized harvesting (Embrapa, 2005). Modern harvesters are capable of harvesting, storing, pressing, baling, and wrapping the fibers in a polyethylene film, protecting the seed

cotton, which can weigh up to 2,500 kg. Cylindrical roller baling technology enables continuous harvesting without interruptions for unloading, while maintaining minimal contamination and minimal impurities (De-Carli & Oliveira, 2021).

When the height of the first boll insertion in cotton plants is higher than optimal, the number of bolls per plant tend to decrease, resulting in reduced productivity and economic losses. The use of agricultural machinery improves operational efficiency and land productivity, facilitating timely crop management practices such as sowing, planting, irrigation, fertilization, and harvesting (Zhou et al., 2024). Consequently, mechanization plays a crucial role in mitigating the impacts of adverse weather conditions and contributes to increased crop productivity (Guo et al., 2022; Zhi et al., 2022).

Understanding the relationship among variables supports informed decision-making regarding possible alternatives to enhance crop productivity. The application of area mapping techniques and phenological index analysis allows for efficient and accurate data evaluation (Andrea et al., 2023). Furthermore, the use of precision agriculture tools, such as kriging maps, allows for the site-specific application of growth regulators, optimizing the use of products while reducing costs and improving efficiency in crop growth management.

The results of this study demonstrate a clear relationship between cotton productivity and both the number of bolls and the height of first boll insertion. The use of spatial maps enables the identification of areas with higher productivity, as well as the evaluation of multiple variables associated with cotton cultivation. Future research should focus on expanding analyses to other production areas and refining additional variables that may enhance the prediction of cotton productivity. These efforts will contribute to the integration of technology into agriculture practices, ultimately improving efficiency and profitability for producers.

Conclusions

Cotton lint productivity is positively and directly associated with the number of bolls, indicating that this attribute is a strong predictor of crop productivity.

The height of the first boll insertion exhibits a negative relationship with cotton lint productivity; that is, higher the first boll is associated with lower crop productivity.

The generation of kriging and cokriging maps has proven to be an effective approach for estimating cotton lint productivity based on the spatial variability of plant attributes. The spatial visualization of these relationships enables the identification of specific management zones within the field, where cultivation practices can be strategically adjusted to optimize productivity. Thus, the applied geostatistical methodology represents a promising tool for precision agriculture in cotton cultivation, enabling reliable productivity estimates based on attributes that are easily and efficiently measured in the field.

Data Availability Statement

The data supporting the conclusions of this study will be available upon request to the corresponding author, Prof. Dr. Job Teixeira de Oliveira, via email: job.oliveira@ufms.br.

The datasets generated and/or analyzed during the research will be provided in an appropriate format, ensuring the transparency and reproducibility of the results, whenever compatible with the privacy and intellectual property rights involved.

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