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Single-row Eucalyptus plantings enhance maize productivity in a crop-forest integration system in the Cerrado of Roraima, Brazil

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Abstract

Crop–forest integration systems combine agricultural crops and forest species within the same area, promoting both productivity and sustainability. Maize is one of the most important crops in these systems due to its economic relevance; however, its productivity may be influenced by the spatial arrangement of eucalyptus trees and the cultivation distance from tree rows. Therefore, this study aimed to evaluate the productivity of maize cultivated between eucalyptus rows arranged in a single and double rows at different cultivation distances in a crop–forest integration system in the Cerrado region of Roraima, Brazil. The experiment was conducted from 2019 to 2024 at the Água Boa Experimental Field, owned by Embrapa Roraima. A randomized complete block design with a split-plot arrangement and four replications was adopted. The main plots consisted of eucalyptus arrangements in single and double rows, while the subplots comprised cultivation distances of 2.5, 5.0, 7.5, and 10.0 m from the tree rows. Data were subjected to the Shapiro–Wilk normality test, analysis of variance, and Tukey's test at the 5% probability level. No significant interaction was observed between the evaluated factors. The single-row arrangement provided higher maize yields in most of the evaluated years. Furthermore, maize productivity increased with increasing distance from the eucalyptus rows, reaching maximum values at intermediate distances, approximately between 6 and 7 m. It was concluded that the adoption of single-row eucalyptus arrangements and maize cultivation at intermediate distances from the tree rows favor productivity in crop–forest integration systems in the Cerrado of Roraima.

Introduction

Brazil has enormous agricultural potential to meet the growing global demand for food and biofuels due to its vast arable land area, favorable climate, and capacity for agricultural intensification. These factors have positioned the country among the world's leading producers and exporters of grains and agricultural commodities (Cudlínová et al. 2020; Conab 2026).

Since the mid-1970s, Brazilian agricultural frontiers, particularly in the Cerrado region, have undergone intense transformation driven by agricultural expansion and agrarian development policies aimed at increasing production (Perin 2026). These changes have promoted significant alterations in land use and land cover, consolidating the Cerrado as one of the country's principal agricultural frontiers (Colman et al. 2024).

However, part of these areas has experienced degradation processes, especially in pastures established with grasses, characterized by reduced productivity and deterioration of the physical, chemical, and biological properties of the soil (Rodrigues, Queiroz and Quartaroli 2022; Zimbres et al. 2024). In this context, there is an increasing need for production systems capable of combining high agricultural productivity with environmental conservation and the restoration of degraded lands (Carmo-Filho and Ribas 2024).

Among the available alternatives, the Crop–Livestock–Forest Integration (CLFI) system has been widely recognized as a sustainable land-use strategy, promoting synergies among agricultural, livestock, and forestry components, while contributing to the restoration of degraded areas and the enhancement of ecosystem services (Silva et al. 2021; Cunha et al. 2025). Among its various modalities, Crop–Forest Integration (CFI) stands out, characterized by the simultaneous cultivation of agricultural and forest species within the same area (Barbault et al. 2024).

One of the main crops used in CFI systems is maize (*Zea mays* L.), due to its high adaptability, economic importance, and broad utilization in human consumption, animal feed, and biofuel production (Dos Reis et al. 2025; Macalou et al. 2026). Brazil ranks among the world's largest producers of this cereal, reaching a production of more than 138 million tons in the 2025 harvest season (Usda 2024; Conab 2026).

Despite the benefits provided by integrated systems, the presence of the tree component may result in competitive interactions with agricultural crops, mainly for water, nutrients, and solar radiation. Shading caused by the tree canopy and overlap between root systems may affect the growth and productivity of intercropped crops (Majaura, Bohm and Freese 2024).

The intensity of these interactions depends on several factors, among which the spatial arrangement of trees, the forest species used, and local environmental conditions are particularly important (Mantino et al. 2023). In this regard, different forest planting configurations can alter light distribution within the environment, root occupation of the soil, and the degree of competition among system components. Therefore, the spatial arrangement of the tree component constitutes one of the main factors determining the agronomic performance of agricultural crops in integrated systems.

In addition to spatial arrangement, the distance between tree rows and agricultural crops directly influences resource availability for plants. Studies indicate that competitive effects tend to be more intense in areas adjacent to forest rows and gradually decrease as the distance from the trees increases (Panozzo et al. 2026). Therefore, proper management of spacing between tree and crop components represents an important strategy for minimizing the negative effects of competition and maximizing system productivity (Koch et al. 2025).

However, the effects of the tree component on agricultural crops do not depend exclusively on the spatial arrangement of trees or on cultivation distance considered in isolation. The intensity of competition for light, water, and nutrients may vary according to the interaction between these factors, since different forest planting configurations modify resource distribution within the environment and the extent of tree influence on adjacent crops (Mantino et al. 2023).

Thus, cultivation distances that provide satisfactory agronomic performance under a particular spatial arrangement may not produce the same response when associated with other planting configurations. Studies in agroforestry systems have demonstrated that resource availability and crop performance vary along the distance gradient from the tree component, and this response depends on the structural characteristics of the system (Majaura, Bohm and Freese 2024).

Despite the importance of these interactions for the management of crop–forest integration systems, information regarding the combined effects of eucalyptus spatial arrangement and maize cultivation distance under the edaphoclimatic conditions of the Cerrado of Roraima remains limited. Therefore, the objective of this study was to evaluate the grain yield of maize cultivated in a crop–forest integration system under the influence of two eucalyptus spatial arrangements and four cultivation distances relative to tree rows in the Cerrado of Roraima, Brazil.

Materials and methods

The experiment was conducted at the Água Boa Experimental Field, located in the Cerrado region and belonging to Embrapa Roraima, approximately 30 km from the city of Boa Vista, the capital of the state of Roraima, Brazil. The site is situated between the geographic coordinates 02°39'00" and 02°41'10" N latitude and 60°49'40" and 60°52'20" W longitude, at an average altitude of 80 m above sea level.

According to the Köppen climate classification, the local climate is classified as Am (tropical monsoon), with a mean annual temperature of 28.2°C and an average annual rainfall of 1,761.8 mm, predominantly concentrated between April and September. The region is characterized by a distinct alternation between a rainy season, extending from April to September, and a dry season, occurring from October to March (Araújo et al. 2024). The accumulated quarterly rainfall and mean annual temperature recorded in the experimental area during the study period (2018–2024) are presented in Fig. 1.

The soil at the experimental site is classified as a medium-textured Dystrophic Yellow Oxisol (SANTOS et al. 2025). The chemical and physical properties of the soil, determined at the 0–20 cm soil layer between 2018 and 2024, are presented in Table 1.

Table 1
Physicochemical characteristics of the soil at the 0–20 cm depth in the experimental area from 2018 to 2024.

Year	pH (H_2O)	Ca	Mg	K	Al	H + Al	OM	P	SB	T	t	V	m
----	-------	..... cmolc dm^{-3}					g Kg^{-1}	g dm^{-3}	$cmol_c$ dm^{-3}	..... %			
2018	5.7	1.05	0.24	0.01	2.3	2.42	7.01	3.21	1.76	3.01	1.77	13	43
2019	5.7	1.05	0.39	0.06	0.03	1.37	9.]1	16.25	2.76	4.01	1.77	58	13
2020	5.8	1.70	0.46	0.42	0.03	1.42	15.7	32.32	2.58	4.01	2.61	65	9
2021	5.8	1.55	0.40	0.46	0.01	1.34	13.4	31.36	2.41	3.75	2.42	64	5
2022	5.9	1.20	0.23	0.10	0.28	1.42	10.3	14.18	1.53	2.95	1.81	52	15
2023	5.3	0.88	0.16	0.09	0.06	1.53	8.03	28.16	1.13	2.66	1.19	42	5
2024	5.4	0.87	0.17	0.14	0.09	1.46	11.35	27.77	1.18	3.64	1.27	32	7
Granulometria em (g Kg^{-1}): Clay = 259.7; Silt = 46.7 and Sand = 693.6													

Ca = calcium; Mg = magnesium; K = potasium; Al = aluminum; H + Al = hydrogen + Aluminum; OM = organic matter; P = phosphorus; SB = sum of the bases; T = CEC at pH 7.0; t = effective CEC; V = base saturation; and m = aluminum saturation.

In March 2018, the experimental area underwent initial soil correction and land preparation, consisting of the application of 1,500 kg ha^{-1} of dolomitic limestone, 100 kg ha^{-1} of P_2O_5 as single superphosphate, and 50 kg ha^{-1} of FTE BR 12. The soil amendments and fertilizers were incorporated into the soil through two passes with a disk plow followed by two passes with a leveling harrow.

In May 2018, the experimental area was sown with soybean (*Glycine max* L.), cultivar BRS Tracajá, intercropped with *Urochloa ruziziensis*. The forage grass was sown 20 days after soybean emergence to serve as a cover crop. During the same period, 30 days after soybean emergence, the forestry component was established using seedlings produced from seeds of *Eucalyptus grandis* × *Eucalyptus urophylla* (Urograndis hybrid).

At planting, the eucalyptus seedlings received 500 g planting hole^{-1} of reactive phosphate fertilizer. The forestry component was established under two spatial arrangements, both oriented in an east-west direction: (i) single-row arrangement, with 3 m spacing between trees and 12.5 m between eucalyptus strips, resulting in a density of 266 trees ha^{-1}; and (ii) double-row arrangement, with 2 m spacing between trees, 3 m between rows, and 12.5 m between eucalyptus strips, resulting in a density of 645 trees ha^{-1}.

The experiment was conducted in a randomized complete block design with four replications using a split-plot arrangement. Treatments were distributed in a 2 × 4 factorial scheme, in which the main plots consisted of two eucalyptus spatial arrangements (single rows and double rows), while the subplots comprised four maize cultivation distances from the eucalyptus rows (2.5, 5.0, 7.5, and 10.0 m). Consequently, eight treatments were evaluated: SR2.5 (single rows × 2.5 m), SR5.0 (single rows × 5.0 m), SR7.5 (single rows × 7.5 m), SR10.0 (single rows × 10.0 m), DR2.5 (double rows × 2.5 m), DR5.0 (double rows × 5.0 m), DR7.5 (double rows × 7.5 m), and DR10.0 (double rows × 10.0 m).

The main plots covered an area of 500 m² (40 × 12.5 m) and consisted of the eucalyptus spatial arrangements. Each subplot measured 16.8 m² (7.0 × 2.40 m) and represented the different maize cultivation distances from the eucalyptus rows. The harvestable area of each subplot was 6.0 m², comprising two maize rows, each 5 m long and spaced 0.60 m apart.

Field evaluations were conducted under rainfed conditions from 2019 to 2024. A different maize cultivar was used in each growing season due to the unavailability of the same cultivar throughout the experimental period. The cultivars used were Bandeirantes, 30F53YHR, 30A91PW, LG6030, LG6036 PRO 2, and P3646 YR for the 2019, 2020, 2021, 2022, 2023, and 2024 growing seasons, respectively.

The first maize crop was sown at the beginning of the 2019 rainy season, and subsequent sowings were carried out during the same planting period in the following years. Maize was cultivated under a no-tillage system on the residue of *U. ruziziensis*. Prior to sowing, the cover vegetation was desiccated with glyphosate at a rate of 1,200 g active ingredient ha^{-1}, applied with a spray volume of 400 L ha^{-1}, 15 days before maize planting.

Ten days after maize emergence, seedlings were thinned to maintain three plants per linear meter, corresponding to a final population of approximately 50,000 plants ha^{-1}.

Fertilization was carried out according to the soil analysis results, with the application of 126 kg ha^{-1} of P_2O_5, 130 kg ha^{-1} of K_2O, 130 kg ha^{-1} of N, and 50 kg ha^{-1} of FTE BR 12. Phosphorus was applied entirely at sowing in the planting furrow, whereas nitrogen and potassium were side-dressed at 20 and 30 days after plant emergence.

Weed control was performed 15 days after maize emergence using nicosulfuron at a rate of 60 g active ingredient ha^{-1}, applied with a spray volume of 400 L ha^{-1}.

Simultaneously with the first nitrogen side-dressing, *U. ruziziensis* was sown between the maize rows using 20 kg ha^{-1} of seed with 50% cultural value and 70% germination. The forage seeds were mixed with the topdressing fertilizer and distributed in the maize interrows.

Crop management and field monitoring followed the standard agronomic practices recommended for maize cultivated under a no-tillage system. Grain harvesting and yield determination were performed mechanically approximately 100 days after sowing.

The data were initially subjected to the Shapiro–Wilk normality test at the 5% probability level. After confirming the normal distribution of residuals, the data were analyzed by analysis of variance (ANOVA), considering the individual effects of eucalyptus spatial arrangement, maize cultivation distance from the tree rows, and the interaction between these factors. Whenever a significant effect was detected by the F-test ($p \leq 0.05$), treatment means were compared using Tukey's honestly significant difference (HSD) test at the 5% significance level. Statistical analyses and graphical representations were performed using the R statistical software (R Core Team 2024).

Results and discussion

Contrary to the initial hypothesis, the results revealed no significant interaction between the row arrangement factors (single and double rows) and the distances from the tree row (2.5, 5.0, 7.5, and 10.0 m), indicating that these factors act independently in influencing maize productivity. This finding suggests that, although both factors affect crop performance, their effects are not synergistic, a pattern commonly observed in agroforestry systems, where individual components respond independently to environmental and management conditions (Ripamonti et al. 2025).

Over the six-year evaluation period, a consistent effect of the single-row arrangement was observed in five of the six years assessed (Fig. 2).

Overall, the single-row arrangement resulted in higher maize grain yield than the double-row system, with significant differences observed in most of the evaluated growing seasons. This response suggests a lower degree of competition for essential resources, particularly light, due to the greater spatial openness provided by the single-row configuration. The variability observed among growing seasons also indicates the influence of environmental and management factors, such as differences in rainfall distribution and the use of different maize cultivars throughout the experimental period, which modulated the magnitude of crop response to the evaluated treatments (Baier et al. 2023).

In agroforestry systems, the interception of photosynthetically active radiation (PAR) by trees is one of the primary factors limiting the productivity of associated intercrops, particularly in denser planting configurations such as double-row arrangements (Majaura, Bohm and Freese 2024). Therefore, the greater spatial openness provided by the single-row arrangement likely enhanced light penetration through the tree canopy, increasing the availability and utilization of solar radiation by the maize crop established within the system, thereby resulting in higher grain yield (Dlamini et al. 2026).

Maize grain yield as influenced by the distance from eucalyptus tree rows exhibited distinct response patterns across the experimental years (Fig. 3).

In the years in which distance had a significant effect, maximum maize grain yield was observed at intermediate distances, approximately 6 to 7 m from the eucalyptus tree rows. This pattern can be explained by the balance between competition and complementarity in resource use. At shorter distances (2.5 and 5.0 m), proximity to the trees intensifies competition for light, water, and nutrients due to greater root system overlap and increased shading, thereby reducing crop performance (Koch et al. 2025).

Conversely, at greater distances (approximately 10 m), the reduced interaction between the tree and crop components may limit the ecological benefits associated with agroforestry systems, resulting in less efficient complementary use of available resources. Although, this condition was not directly evaluated in the present study, previous research suggests that excessively large distances between system components may reduce the efficiency of the biological and physical interactions responsible for the productivity gains observed in integrated production systems (Dlamini et al. 2026).

This spatial productivity gradient is characteristic of alley cropping systems, in which tree influence is strongest in areas adjacent to the tree rows and gradually decreases as the distance from the rows increases (Majaura, Bohm and Freese 2024). Therefore, the experimental design adopted in this study effectively captured the spatial variability of tree–crop interactions and has been widely employed to investigate the effects of resource competition in integrated production systems (Swieter et al. 2022).

The inter-annual variability observed, particularly in the years when the effect of distance was not significant, indicates a strong influence of climatic conditions and crop management practices on maize productivity. Factors such as water availability and the use of different cultivars may alter the magnitude of interactions between system components; therefore, comparisons among growing seasons should be interpreted with caution. According to Wolde and Desalegn (2025), these interactions tend to be more pronounced under stress conditions, where competition for resources becomes more intense.

Overall, the results demonstrate that both tree row arrangement and planting distance are important factors for optimizing maize productivity in agroforestry systems. The identification of maximum grain yield at intermediate distances, approximately 6 to 7 m from the eucalyptus tree rows, in the years when distance significantly affected productivity, highlights the igmportance of appropriate spacing management as a strategy to maximize resource use efficiency and enhance the sustainability of the production system.

Conclusions

The arrangement of eucalyptus in single tree rows enhances maize productivity in crop–forest integration systems in the Cerrado of Roraima, resulting in higher grain yields in most of the growing seasons evaluated.

Maize grain yield is influenced by the distance from eucalyptus tree rows, with the highest productivity observed at intermediate distances, approximately 6 to 7 m from the tree rows.

Therefore, the adoption of single tree rows combined with maize cultivation at intermediate distances from the eucalyptus rows represents a promising strategy for optimizing the performance of integrated crop–forest systems.

Long-term studies are needed to evaluate the dynamics of interactions between the tree and crop components as eucalyptus trees continue to grow and the system matures.

Declarations

Conflict of interest

The authors declare no conflicts of interest.

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Author Contribution

Aldelonio Alves da Silva: Experiment execution, data collection, manuscript writing, statistical analysis and final adjustments; Marcos Evangelista da Silva: Experiment execution and Data collection; Anderson Carlos de Melo Gonçalves: Statistical analysis; Felipe Fernandes Dias, José de Anchieta Alves de Albuquerque and Kedma da Silva Matos: Review and final adjustments; Musibau Oyeleke Azeez: Final adjustments, translation, formatting; Roberto Dantas de Medeiros: Supervision, statistical analysis, review.

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Data availability

The datasets generated during and analyzed during the current study are available from the corresponding author on reasonable request.

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Figures

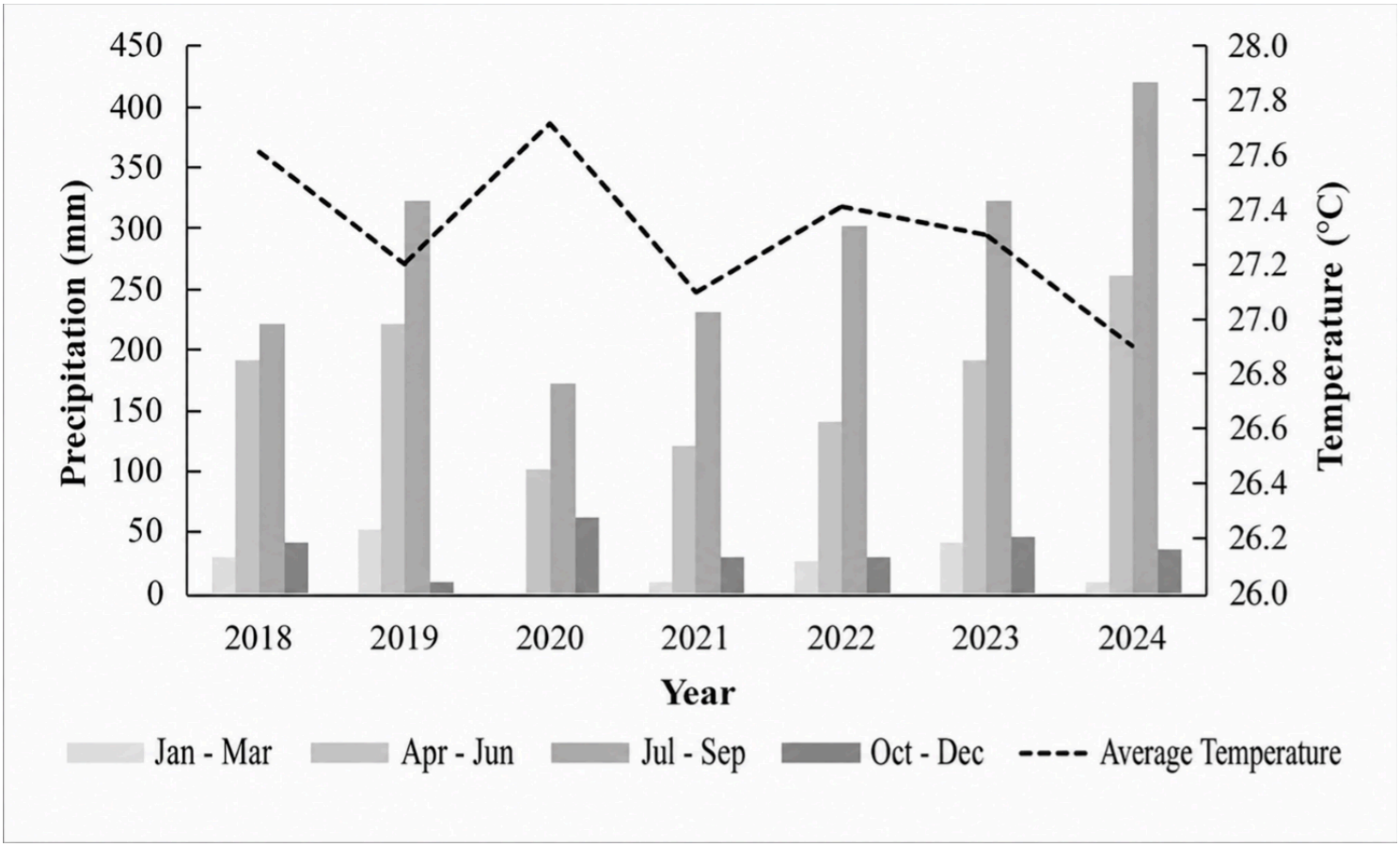


Figure 1

Quarterly cumulative rainfall and annual mean temperature recorded at the experimental site during the experimental period (2018–2024).

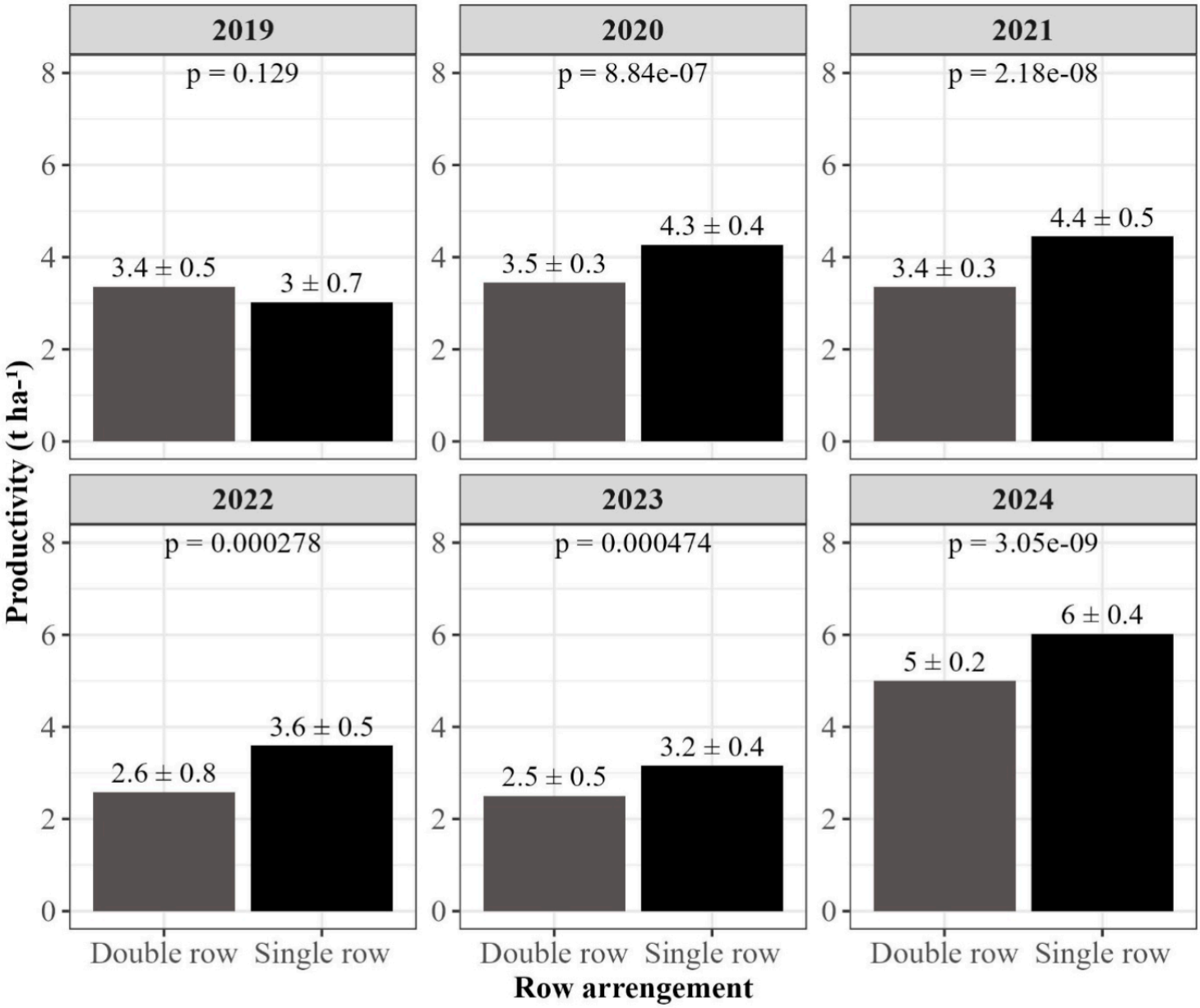


Figure 2

Maize grain yield as affected by eucalyptus spatial arrangement (single and double rows) over six growing seasons (2019–2024).

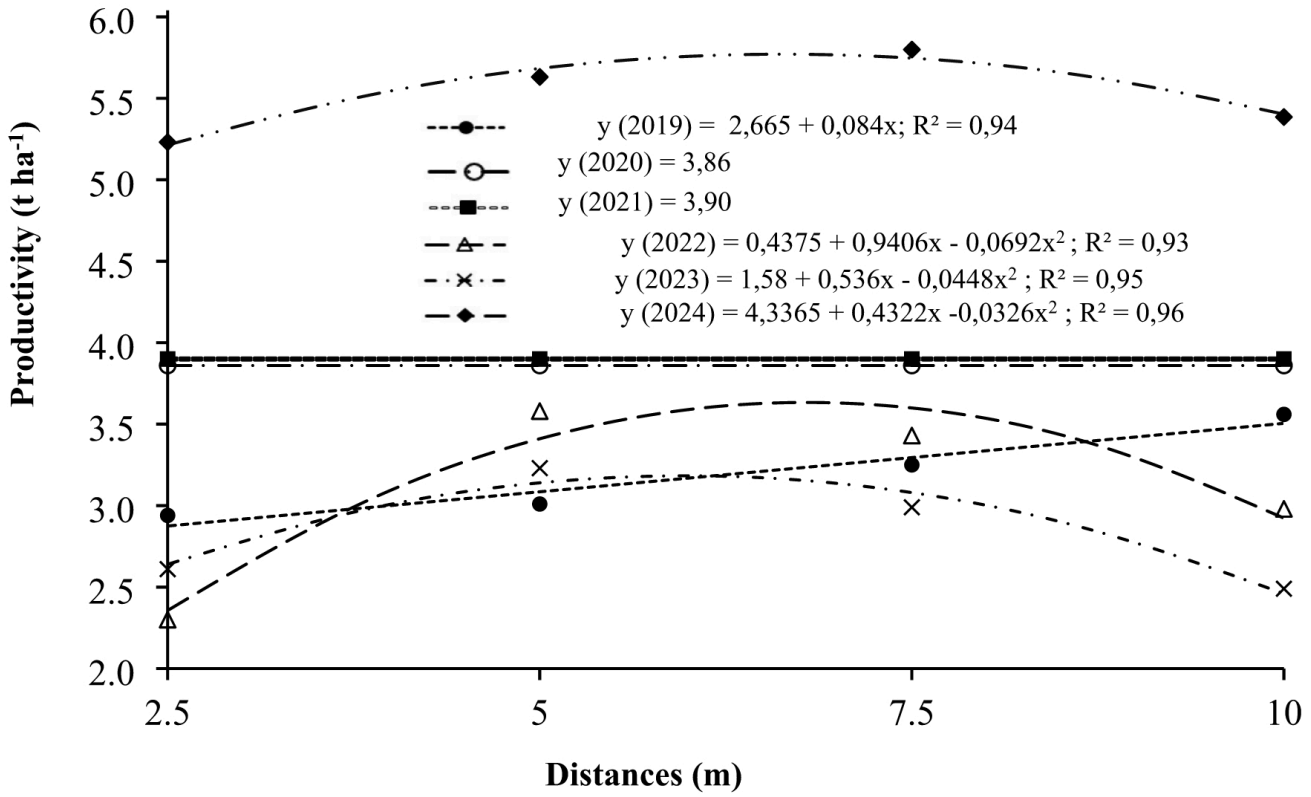


Figure 3

Average maize grain yield as a function of distance from eucalyptus tree rows during the 2019–2024 growing seasons. Symbols represent the observed means, and the lines represent the regression models fitted for each growing season, considering the absence of a significant interaction between the factors *distance* and *row arrangement*.