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Uneven seedling emergence affects growth and yield in corn

A emergência desuniforme de plântulas afeta o crescimento e a produtividade do milho

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Highlights

Plants whose emergence is delayed up to two days did not show a reduction in yield.
Plants delayed over two days showed an average 7.4% reduction in yield per day.
Compensatory production by plants adjacent to delayed ones is zero or insufficient.

Abstract

The timing of planting is important, as it defines the productive potential of a crop. Among planting-related factors, delayed emergence has received less attention compared with stand loss and seed spatial distribution. Some studies suggest that temporal unevenness in emergence may be more detrimental than spatial unevenness. Thus, the objective of this study was to determine the effect of delayed emergence on delayed and adjacent plants. Two experiments, arranged in randomized blocks, were conducted in a commercial area in 2018 and 2019, with one third of the plants (33%) sown with delays of 0, 2, 4, 6, 8, and 10 days. Delayed and adjacent plants were evaluated separately. In both years, delayed plants showed etiolation, characterized by increased ear insertion height and reduced stem diameter. Adjacent plants exhibited an increase in stem diameter but no change in ear insertion height. Delayed plants demonstrated a linear reduction in all yield components in both years, resulting in a 6.6% (2018) and 8.1% (2019) reduction in yield for each day of delayed emergence. Adjacent plants showed a compensatory response only in 2019, with a linear increase of 1.7% in yield for each day of delayed emergence. In both years, tolerance of up to two days of delayed emergence was observed;

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beyond this point, the reduction in average yield becomes linear, ranging from 1.6% to 2.1% for each additional day of delay.

Key words: Delayed emergence. Dominated plants. Intraspecific competition.

Resumo

O momento da implantação é importante pois definirá o potencial produtivo de uma lavoura. Considerando os aspectos de plantabilidade, o atraso da emergência é menos considerado em relação à perda de estande e à distribuição espacial das sementes. Alguns trabalhos sugerem que a desuniformidade temporal de emergência pode ser mais prejudicial que a espacial. Desta forma o objetivo do trabalho foi determinar o efeito do atraso de emergência sobre plantas atrasadas e adjacentes. Dois experimentos delineados em blocos casualizados foram implantados em área comercial nos anos de 2018 e 2019, semeando um terço das plantas (33%) com atraso de 0, 2, 4, 6, 8 e 10 dias. As plantas atrasadas e as adjacentes foram avaliadas separadamente. Em ambos os anos, as plantas atrasadas apresentaram estiolamento, caracterizado pelo aumento da altura de inserção de espiga e redução do diâmetro de colmo. Plantas adjacentes exibiram aumento no diâmetro, mas não mostraram alteração na altura de inserção de espiga. As plantas atrasadas mostraram redução linear em todos os componentes de produção em ambos os anos, resultando em 6,6% (2018) e 8,1% (2019) de redução na produção para cada dia de atraso na emergência. As plantas adjacentes apresentaram resposta compensatória somente em 2019, com aumento linear de apenas 1,7% na produção para cada dia de atraso na emergência. Para ambos os anos, uma tolerância de até 2 dias de atraso na emergência foi observada; além desse ponto, a redução na produtividade média se torna linear, variando entre 1,6% a 2,1% para cada dia de atraso.

Palavras-chave: Atraso de emergência. Competição intraespecífica. Plantas dominadas.

Introduction

Most studies on seed quality and intraspecific competition in corn focus on the spatial distribution of seeds and plants. Although some studies report increased productivity with improved spatial distribution (Sangoi et al., 2012; Silva et al., 2015; Hörbe et al., 2016; Kolling et al., 2019; Madaloz et al., 2020), many others have observed limited or no influence of this factor (Rizzardi et al., 1994; Rizzardi & Pires, 1996; Liu et al., 2004a,b; Lauer & Rankin, 2004; Shuai et al., 2019; Albarenque et al., 2023). Furthermore, part of the reported increase in productivity is explained by differences in plant population density rather than solely by variation in spatial distribution among plants (Nafziger, 1996; Hörbe et al., 2016; Madaloz et al., 2020; Albarenque et al., 2023). Temporal non-uniformity, on the other hand, has been poorly studied and is rarely considered in evaluations of sowing quality, despite strong evidence suggesting that its effects are consistent and highly damaging.

Numerous factors can lead to delayed seedling emergence under field conditions. Key factors include seed vigor (Egli & Rucker, 2012), sowing depth (Nemergut et al., 2021), seed size (Kandasamy et al., 2020), surface plant residues (Trogello et al., 2013), soil moisture and temperature (Brandelero et al., 2015), and soil-seed contact (Manohar

& Heydecker, 1964; Blunk et al., 2018). These factors may cause direct losses in delayed plants, as well as indirect damage due to reduced competitive ability relative to adjacent plants, since these conditions occur irregularly in the field.

Previous studies have demonstrated the negative impacts of delayed emergence; however, they evaluated more severe delays, ranging from 7 to 26 days, justified by the fact that they were conducted in regions with mild climates, which result in longer crop cycles (Nafziger et al., 1991; Ford & Hicks, 1992; Merotto et al., 1999; Liu et al., 2004a). More recently, plant-by-plant evaluations conducted in commercial areas of Michigan (USA) and Paraná (Argentina) reported delays of up to 30 days, with a linear reduction in yield as a function of delayed emergence across different locations and productivity levels (Albarenque et al., 2023).

An important and underinvestigated issue in studies of intraspecific competition caused by temporal unevenness is the compensatory capacity of adjacent plants. A delayed plant may be overtaken by neighboring plants, which gain an advantage in resource acquisition, establishing a dominance relationship. However, because corn has low phenotypic plasticity, the dominant plant may not compensate, or may only partially compensate, for the loss of the delayed plant. Liu et al. (2004a), when evaluating plants with developmental delays of two ad four leaves, resulting from an approximate emergence delay of 12 and 22 days, did not observe compensation in growth or yield by plants adjacent to delayed plants, while a marked reduction was observed in the delayed plants.

Considering the limited number of publications on this topic under tropical conditions, the objective of this study was to determine how many days of delayed emergence a corn plant can tolerate without yield loss and to estimate the growth and production of delayed and adjacent plants as a function of the number of days of delay.

Material and Methods

The research was conducted in Sorriso, MT, Brazil, in a commercial production area. Two experiments were carried out in 2018 (12º 41′ 48″ S and 55º 48′ 04″ W, 355 m altitude) and 2019 (12º 41′ 55″ S and 55º 48′ 19″ W, 375 m altitude). The experimental sites were approximately 570 m apart and were established on Red-Yellow Latosol soil (Santos et al., 2025). In both growing seasons, soil samples (0-0.20 m depth) were collected from each area before sowing to determine physicochemical characteristics. The results are presented in Table 1. According to the Köppen classification, the regional climate is a hot semi-humid tropical savanna (Aw), with a well-defined dry season in fall/winter and a rainy season in spring/summer (Souza et al., 2013). Climatic data for both growing seasons are shown in Figure 1. Cumulative rainfall during the growing season was approximately 1000 mm in both years. In both seasons, the preceding crop was soybean under a no-till system. The hybrids used in 2018 and 2019 were Formula VIP2 and NK455 VIP3, respectively, both from Syngenta and classified as super-early cycle hybrids.

Table 1
Chemical and textural properties of soils from experimental areas in 2018 and 2019

Year	Clay	Silt	Sand	OM	P	pH	Al	H + Al	Ca	Mg	K	CEC	BS
	------- g kg^{-1} --------			g dm^{-3}	mg dm^{-3}	CaCl$_2$		----------- cmolc dm^{-3} -------------					%
2018	282	58	660	26	16.1	4.9	0.0	3.6	2.8	0.7	0.10	7.2	50
2019	425	117	458	31	16.2	5.1	0.0	4.3	3.8	1.0	0.12	9.2	53

Extractors: Mehlich 1: P, K. KCl: Ca, Mg, Al. Walkey Black: OM (organic matter). CEC (cation exchange capacity). BS (base saturation). $CaCl_2$ - pH.

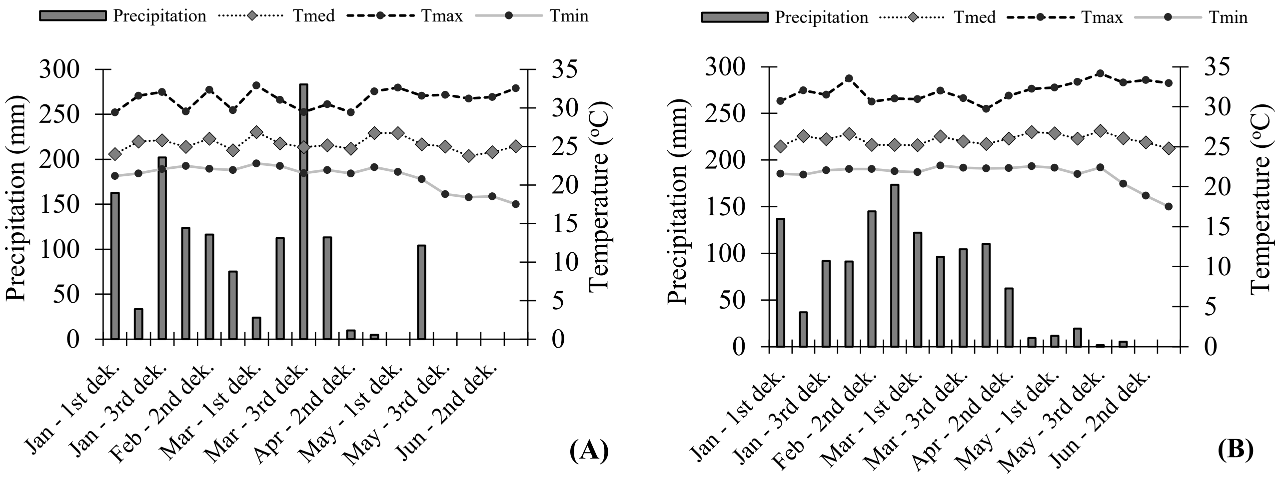

Figure 1. Precipitation (mm), minimum, mean, and maximum air temperatures (°C) recorded at the INMET (National Institute of Meteorology) weather station in Sorriso by dekad (10-day intervals) during the experimental period.
Sorriso-MT, second crop seasons of 2018 (A) and 2019 (B).

The experiment was laid out in a randomized block design with four replicates in 2018 and five replicates in 2019. Treatments were arranged in a 5 × 2 + 1 factorial arrangement. The first factor consisted of delay levels (2, 4, 6, 8, and 10 days), and the second factor comprised delayed and adjacent plants. An additional control treatment without delay between plants was also included.

Experimental units consisted of six rows spaced 0.5 m apart and 6.5 m in length. The usable area comprised the four central rows, 5.5 m long. Sowing was performed on February 8th in 2018 and January 26th in 2019. The same commercial seed lots used by the producer were adopted. Initially, sowing rows were marked by the passage of the seeder without fertilizer distribution, as fertilization was applied by broadcasting. After delimiting the experimental units, sowing was carried out manually using seed drills (SB Máquinas Agrícolas, model SB-18), adopting a population density of 60,000 plants ha^{-1} for both hybrids.

In plots with delayed emergence, the ratio of delayed to adjacent plants was 1:2, corresponding to 33% delayed plants. In the central rows of the usable area, two consecutive holes were sown, and the next hole was marked with a stake and left unsown; in the neighboring rows, sowing was staggered to prevent alignment of delayed plants. The delayed plants were then sown on February 10th, 12th, 14th, 16th, and 18th in 2018, and on January 28th, 31st, February 1st, 3rd, and 5th in 2019, corresponding to delays of 2, 4, 6, 8, and 10 days, respectively. Three seeds were placed per hole, and thinning was performed seven days after emergence, retaining the most vigorous seedling. In both years, soil moisture was adequate on all sowing dates, and seedlings emerged four days after sowing in all treatments. As soil and seed conditions were uniform across treatments, the response of delayed plants reflects only the indirect effects of delayed emergence through intraspecific competition with adjacent plants.

Base fertilization was applied after sowing at rates of 28, 98, and 56 kg ha^{-1} of N, P_2O_5, and K_2O, respectively. When plants sown on the first date reached the V4 stage, topdressing was applied at 90 kg ha^{-1} of N and 45 kg ha^{-1} of K_2O.

Thirty days after tasseling, ear insertion height and stem diameter were assessed in 10 delayed and adjacent plants per plot, evaluated separately. Ear insertion height was measured at the node where the ear was inserted. Stem diameter was determined from two measurements taken perpendicular to the ground, 10 cm above ground level, recording the smallest and largest diameters. Harvesting was carried out on June 8, 2018, and May 24, 2019. Delayed and adjacent plants were harvested and counted separately within the usable area. After this step, 10 ears from delayed and adjacent plants were randomly selected to determine the number of rows per ear and the number of kernels per row. All ears from each plot were then threshed, and grain moisture content was determined. The kernels were subsequently used to determine 100-kernel weight, production per plant, and average yield, with moisture corrected to 13%. The 100-kernel weight was determined by weighing 800 randomly selected kernels. Individual production was calculated by dividing total kernel weight by the number of plants, and average yield was determined based on total kernel weight relative to the harvested plot area, maintaining the 1:2 ratio of delayed to adjacent plants.

Data were subjected to normality analysis using the Shapiro-Wilk test and homogeneity of variances with Bartlett's test. Once assumptions were met, analysis of variance was performed using the F-test. Means for delay levels were analyzed by regression, and means of delayed and adjacent plants were compared with the control via Dunnett's test. For average plot yield, data were analyzed by regression considering one factor with five treatments (2, 4, 6, 8, and 10 days of delay) and compared to the control with Dunnett's test. All analyses were performed using R Studio software at a 5% probability level (R Core Team [R], 2023).

Results and Discussion

In both years, the effects of delay on delayed plants were consistent across all variables, whereas adjacent plants showed limited compensation. In both years, adjacent plants showed no variation in ear insertion height with increasing delay of neighboring plants, while delayed plants exhibited etiolation (Figure 2A and 2B). However, responses differed between years, possibly due to hybrid characteristics. In 2018, etiolation was detected within the first few days of delay (two and four days) and followed a negative linear trend. In 2019, the genotype tolerated the initial competition, differing from the control only at 10 days of delay and showing a positive linear response. Under light competition, plants may exhibit shade avoidance plasticity (Schmitt et al., 2003), promoting morphological changes such as stem elongation to position leaves more favorably for light interception (Von Arnim & Deng, 1996; Schmitt et al., 2003). However, these adjustments are known to have biological limits, beyond which they are insufficient to offset the effects of resource competition.

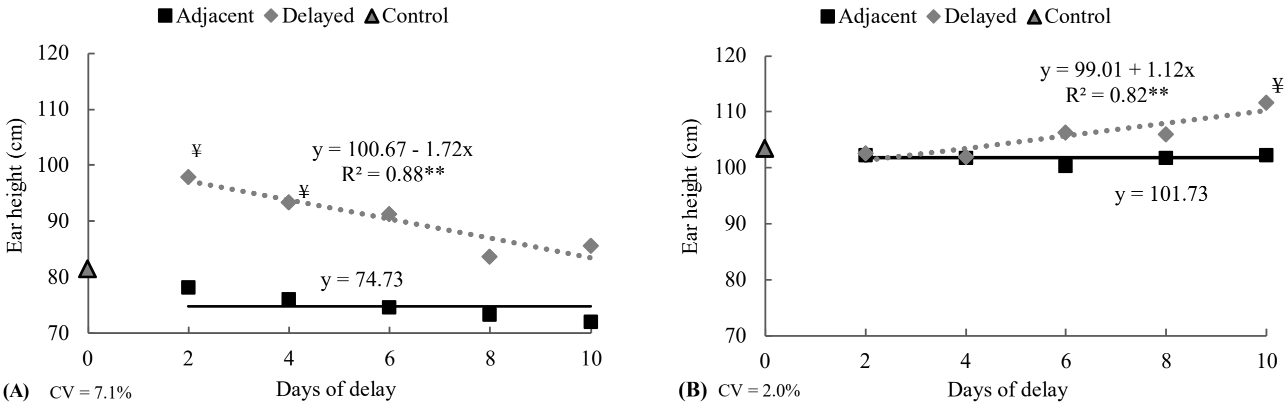

Figure 2. Ear insertion height of delayed and adjacent corn plants as a function of seedling emergence delay, Sorriso-MT.
(A) 2018, cultivar Fórmula VIP2; (B) 2019, cultivar NK455 VIP3. **: significant at 1% significance; ¥: differs from the control by Dunnett's test at 5% significance.

Increasing emergence delay caused opposite effects on stem diameter in delayed and adjacent plants. Adjacent plants showed a linear increase in stem diameter, with similar slopes in both years (b = 0.19 in 2018 and b = 0.14 in 2019), differing from the control only at eight days in 2018 and from six days in 2019 (Figure 3A and 3B). In delayed plants, a linear reduction was observed in both years, more pronounced in 2019 (b = -1.09) than in 2018 (b = -0.71). From four days onward, delayed plants differed from the control in both years.

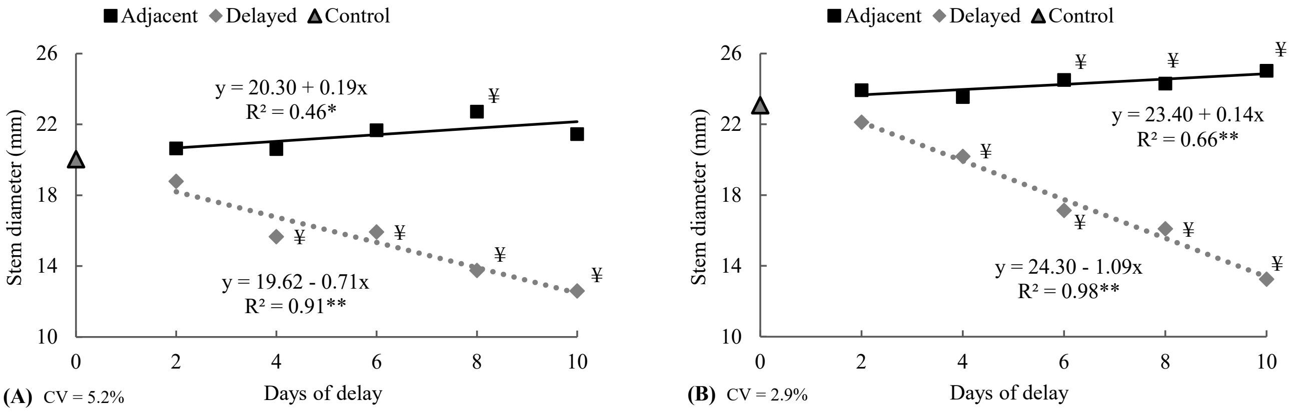

Figure 3. Stem diameter of delayed and adjacent corn plants as a function of seedling emergence delay, Sorriso-MT.
(A) 2018, cultivar Fórmula VIP2; (B) 2019, cultivar NK455 VIP3. **: significant at 1% significance; *: significant at 5% significance; ¥: differs from the control by Dunnett's test at 5% significance.

As previously discussed, etiolation in delayed plants was accompanied by reduced stem diameter. In adjacent plants, increased stem diameter suggests greater light interception and likely enhanced conversion into dry matter. According to Craine and Dybzinski (2013), increased growth in response to greater light availability is expected only when there is a positive carbon balance after meeting basal metabolic and respiratory demands. The lack of a vertical growth response (Figure 2) suggests that adjacent plants may have allocated photoassimilates to other structures, such as leaf area and stem thickening. Ford and Hicks (1992) observed increased stem diameter in adjacent plants at delay levels of 7 and 14 days across population densities of approximately 40, 60, 80, and 100 thousand plants ha^{-1}. However, in that study, delay was imposed on alternating plants (1:2; 50% of the population), meaning each normal plant was surrounded by two delayed plants, thereby enhancing the compensatory effect. In contrast, Liu et al. (2004a), imposing a delay proportion of 1:6 plants (16.7%), found no compensation by plants adjacent to those with two- and four-leaf delays in terms of total height, leaf area, or dry weight.

Delayed emergence affected the number of rows per ear more strongly in 2019 than in 2018. In 2018, adjacent plants showed no compensatory response, while delayed plants exhibited a linear reduction in rows per ear, differing from the control from eight days of delay onward (Figure 4A). In 2019, the reduction in delayed plants was more pronounced (b = -0.38), with differences from the control beginning at four days of delay (Figure 4B). Adjacent plants showed a positive but limited linear compensatory response (b = +0.09), without differing from the control. Considering the use of single-cross hybrids with high uniformity and yield potential, a limited response from adjacent plants is expected, as stand density remained unchanged and plants were already near the yield ceiling for the given environment.

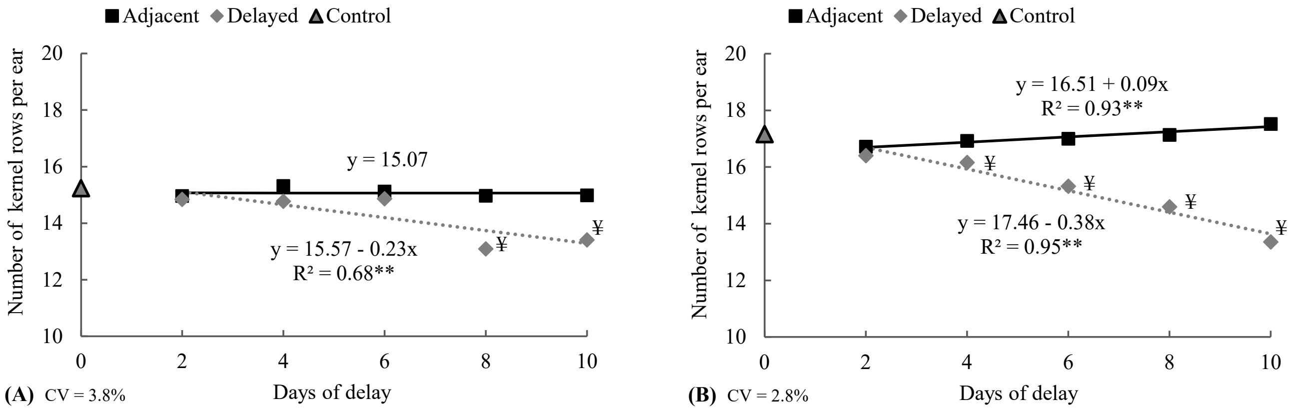

Figure 4. Number of kernels per ear of delayed and adjacent corn plants as a function of seedling emergence delay, Sorriso-MT.
(A) 2018, cultivar Fórmula VIP2; (B) 2019, cultivar NK455 VIP3. **: significant at 1% significance; ¥: differs from the control by Dunnett's test at 5% significance.

The number of kernels per row showed similar behavior in both years for delayed and adjacent plants. Adjacent plants exhibited no compensatory effect, whereas delayed plants showed a linear reduction (b = -1.95 in 2018 and -1.81 in 2019), differing from the control from six days of delay in 2018 (Figure 5A) and from four days in 2019 (Figure 5B). These results corroborate those of Albarenque et al. (2023), who observed a linear reduction in the number of kernels per ear as a function of delayed plant emergence under field conditions.

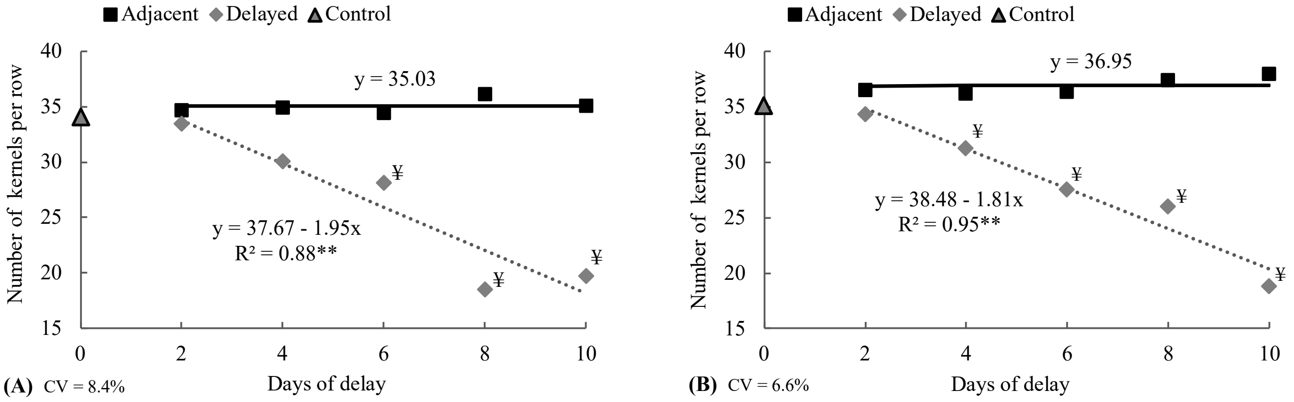

Figure 5. Number of kernels per row of delayed and adjacent corn plants as a function of seedling emergence delay Sorriso-MT.
(A) 2018, cultivar Fórmula VIP2; (B) 2019, cultivar NK455 VIP3. **: significant at 1% significance; ¥: differs from the control by Dunnett's test at 5% significance.

Similar responses in adjacent plants were reported by Merotto et al. (1999), who evaluated delays of 12 and 19 days imposed on 50% of the plants. The authors observed no compensation in the number of kernels per ear by plants adjacent to delayed plants at all population densities (40, 60, 80, and 100 thousand plants per hectare), whereas delayed plants exhibited fewer kernels per ear. They suggested that intraspecific competition among delayed plants was intensified at higher population densities, possibly increasing the interval between tasseling and silking and thereby impairing pollination. According to Pagano et al. (2007), dominated plants, although presenting a similar number of developed flowers per ear as dominant plants, form fewer kernels per ear. This outcome may be attributed to flower abortion and reduced pollination, associated with an increased interval between tasseling and silking. Thus, the reduction in kernels per row observed in the present study may be explained by lower pollination efficiency or greater abortion of fertilized flowers in delayed plants.

The 100-kernel weight was affected by increasing delay levels but did not differ from the control, except for plants delayed by two days in 2019 (Figure 6B). In both years, delayed plants showed a linear reduction in 100-kernel weight as delay increased (Figure 6), whereas compensation by normally emerging plants occurred only in the second year. The impact of delayed emergence on 100-kernel weight was less pronounced than on other yield components. With a 10-day delay, the average reduction relative to the control was 7.8%, compared with 17.1% for the number of rows per ear and 44.3% for the number of kernels per row (Figures 4 and 5). Merotto et al. (1999) also observed lower 100-kernel weight in delayed plants, with more drastic effects when intraspecific competition was intensified by higher population density, reaching a 55% reduction at 19 days of delay and at the highest population density (100,000 plants ha^{-1}). In contrast, Albarenque et al. (2023) did not observe changes in individual kernel weight in plants delayed by up to 30 days in commercial crops.

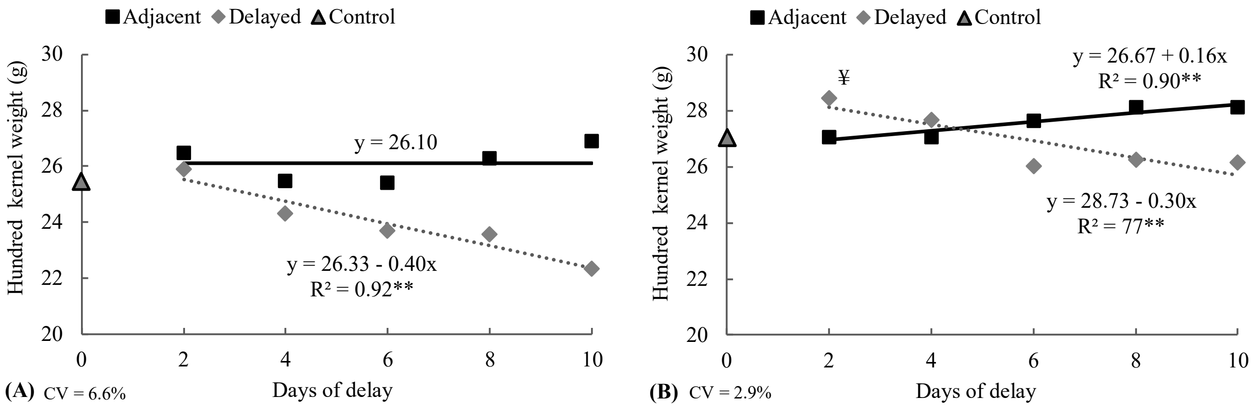

Figure 6. 100-kernel weight of delayed and adjacent corn plants as a function of seedling emergence delay, Sorriso-MT.
(A) 2018, cultivar Formula VIP2; (B) 2019, cultivar NK455 VIP3. **: significant at 1% significance; ¥: differs from the control by Dunnett's test at 5% significance.

Production per plant differed between years for adjacent plants. In the first year, no compensatory effect was observed, whereas in the second year production increased linearly by 1.7% relative to the control for each day of delay (Figure 7). In 2019, only the normally emerging plants adjacent to a 10-day delay differed from the control, with 14.6% higher production. In 2018, none of the yield components showed compensation (Figures 4A, 5A, and 6A), whereas in 2019 the increase in production per plant was associated with increases in the number of rows per ear and 100-kernel weight (Figures 4B and 6B). Nafziger et al. (1991) and Ford and Hicks (1992) reported increased production in adjacent plants only at the highest delay level of 14 days, with increases of 15.6% and 9.2% relative to the control, respectively. In both studies, the treatments with the shortest delay (7 to 10 days) did not result in substantial increases in plant production. Liu et al. (2004a) observed a 6.5% increase in relative production of plants adjacent to those delayed by 22 days; however, the difference was not statistically significant.

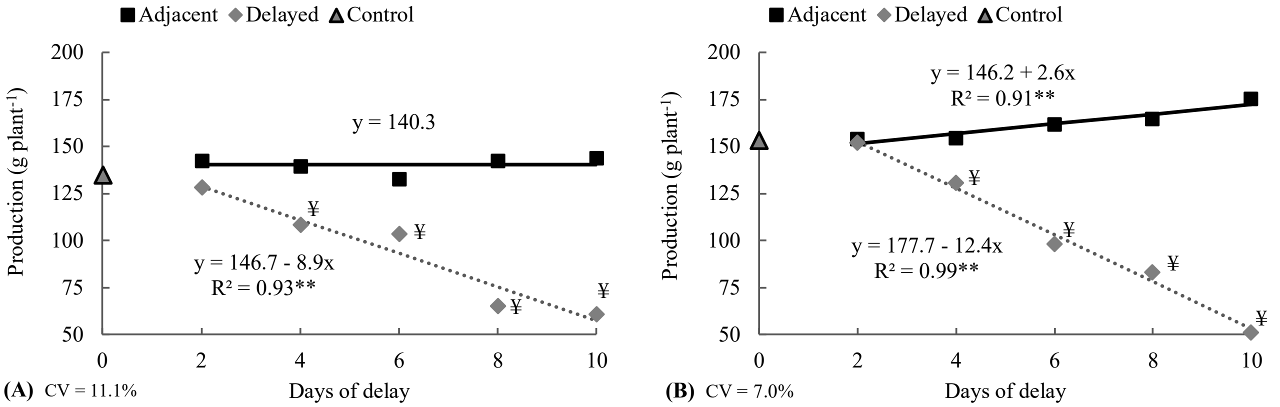

Figure 7. Grain production of delayed and adjacent corn plants as a function of seedling emergence delay, Sorriso-MT.
(A) 2018, cultivar Formula VIP2; (B) 2019, cultivar NK455 VIP3. **: significant at 1% significance; ¥: differs from the control by Dunnett's test at 5% significance.

Delayed plants exhibited a linear reduction in production in both years (Figure 7). In 2018, production decreased by 6.6% per day of delay relative to the control, whereas in 2019 the reduction was 8.1% per day. After 10 days of delay, cumulative losses relative to the control reached 57% and 65% in 2018 and 2019, respectively. Compared with the control, differences were detected from four days onward, indicating a tolerance of up to two days of delay. Nafziger et al. (1991), Ford and Hicks (1992), and Merotto et al. (1999) also reported lower production in delayed plants, without identifying a tolerance threshold, likely due to the more severe delay levels imposed (10 to 14 days; 7 and 14 days;

and 12 and 19 days, respectively). Nafziger et al. (1991) reported per-plant losses of 14.6% and 40.3% at delays of 10 and 14 days, respectively, while Ford and Hicks (1992) observed reductions of 16.8% and 38.2% at delays of 7 and 14 days, respectively. Liu et al. (2004a) reported reductions of 35% and 72% in the relative production of plants delayed by 12 and 22 days, respectively.

Regarding average plot yield, a linear trend was observed in both years, with reductions of 2.1% and 1.6% relative to the control for each day of delay in 2018 and 2019, respectively (Figure 8). Compared with the control, significantly lower productivity in 2019 was detected only from six days of delay onward. Merotto et al. (1999) reported an approximately 20% reduction in average yield when 50% of the plants were delayed by 12 or 19 days. Liu et al. (2004a) did not observe a reduction in average yield with a 12-day delay, which was attributed to the lower proportion of delayed plants (16.7%); however, a 22-day delay resulted in a 9% decrease in average yield. Albarenque et al. (2023) reported more pronounced effects of delayed emergence, with yield reductions of 3%, 7%, and 5% per day of delay in Springport (USA), Portland (USA), and Paraná (Argentina), respectively. It is important to note that the study by Albarenque et al. (2023) was conducted under commercial field conditions, where delays likely resulted from factors such as seed vigor, soil moisture and temperature, soil-seed contact, sowing depth, or excess crop residue. In the present study, delays were artificially imposed; therefore, late-emerging seedlings originated from seeds with the same vigor and were grown under the same soil conditions. Under actual field conditions, delayed seedlings are therefore expected to exhibit even lower growth and yield potential than observed in this study and in the other cited works.

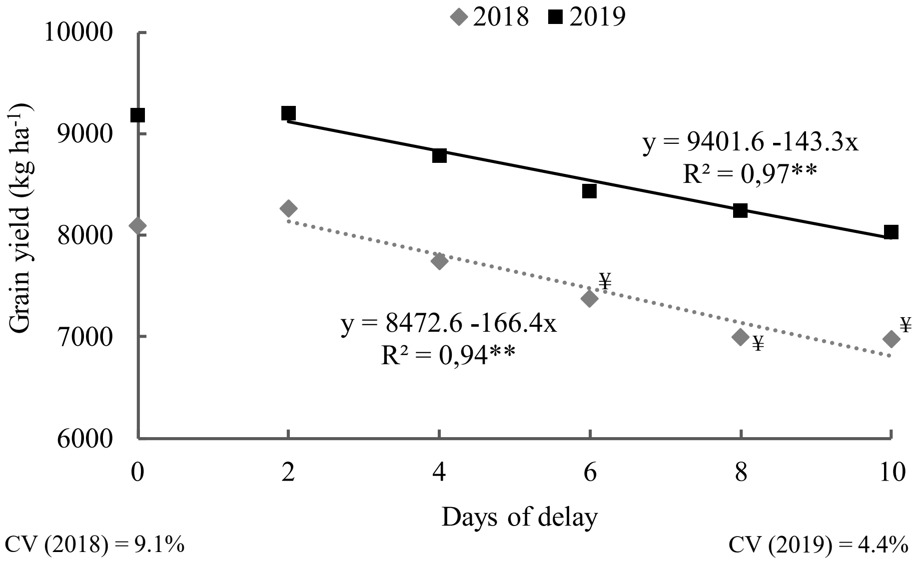

Figure 8. Average corn grain yield as a function of seedling emergence delay, Sorriso-MT. Yield based on a plot with a 1:2 delayed-to-adjacent plant ratio. Cultivar in 2018: Formula VIP2; Cultivar in 2019: NK455 VIP3. **: significant at 1% significance; ¥: differs from the control by Dunnett's test at 5% significance.

Conclusions

In general, maize plants tolerate emergence delays of up to two days. Beyond this threshold, delayed plants exhibit etiolation and reduced productivity due to increased intraspecific competition. Delayed plants consistently showed reductions in stem diameter, number of rows per ear, kernels per row, and 100-kernel weight in both years. Production of plants adjacent to delayed plants showed compensation of 1.7% per day in only one of the evaluated years, associated with increases in the number of rows per ear and 100-kernel weight. Production of delayed plants declined due to reductions in all yield components, resulting in losses of 6.6% to 8.1% per day of delay. Considering a 1:2 ratio of delayed to adjacent plants, the reduction in average crop yield ranged from 1.6% to 2.1% per day of delay.

Acknowledgments

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