

Performance of maize hybrids as a function of spatial arrangements during second growth season under irrigation

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ABSTRACT: There is little information on how different spatial arrangements affect modern maize hybrids under irrigation in the maize second growing season in Brazil. The objectives of this study were to evaluate the performance of maize genotypes with different canopy architecture as a function of different spatial arrangements in the Southeast Brazil. Two maize hybrids with semi-erect (DKB 390) and erect (DKB 230) leaves were cultivated during the second season and evaluated for different plant densities ($4, 7$ and 10×10^4 plants·ha⁻¹) and row spacings (0.25, 0.50 and 1.00 m), under irrigation in a tropical environment. The increase in plant density increased plant height and ear insertion height, but reduced stalk diameter. The absorbed photosynthetically active radiation and the leaf area index also increased in higher plant densities, with a reduction of the SPAD index. The increase in plant density enhanced grain yield, however, there was no difference of yield between different row spacings. The hybrid DKB 230 (upright leaves) showed greater yield potential compared to DKB 390 (semi-upright leaves). The critical leaf area index was 5.2 and 4.3 for the hybrids DKB 230 and DKB 390, respectively. The estimated plant density that provides the maximum yield are 9.7×10^4 and 8.8×10^4 plants·ha⁻¹ for the hybrids DKB 230 and DKB 390, respectively.

Key words: plant density, row spacing, leaf area index, radiation use efficiency, plant arrangement.

INTRODUCTION

Maize is one of the most cultivated cereals in the world, which produced an average of 1.15 billion tons per year in the last three seasons, and Brazil is the third largest producer in the world, after the United States and China. Brazil produced, on average from 2015/2016 to 2017/2018 growing seasons, 81.5 million tons per year (CONAB 2021), equivalent to 7.1% of the world production (FAO 2020). Maize is among the main agricultural commodities produced in Brazil, only in the 2019/2020 growing season an area of 18.5 million hectares was cultivated with this crop, of this total, 74% comes from the second season (CONAB 2021).

Maize cultivated in the second cropping is usually sown between January and April, after soybean or dry beans. Cultivation in this period of the year subjects plants to different conditions of solar radiation, photoperiod, temperature and water availability when compared to maize cultivated in the main season. However, this is not always considered when positioning the recommended plant spatial arrangements for the cultivars, that is, plant density and row spacing.

The plant spatial arrangement of maize is related to sowing, which is recognized to be one of the crop management practices that most affects crop yield (Ferreira et al. 2019). As production costs have increased in recent years, it is necessary for growers to seek for a spatial arrangement, i.e., seeding rate and row spacing, that maximize yield.



Crop yield depends on the ability of the vegetation cover to intercept adequately the incident photosynthetic active radiation, which is a function of the available leaf area, the canopy architecture and the light conversion efficiency (Bhattacharya 2019). Plant arrangement can be adjusted through plant density, row spacing and plant distribution in the row, where variations in the distance between plants in the row and between rows results in different crop spatial arrangements (Almeida Júnior et al. 2018). The plant spatial arrangement aims to distribute the canopy morphological structure to increase the ability to intercept light (Baret et al. 2018; Caron et al. 2012), its photosynthetic efficiency (Evers and Bastiaans 2016) and the overall crop yield (Zhai et al. 2017). The canopy light distribution influences the energy balance, the accumulation of biomass, the growth and development of plants (Wiechers et al. 2011; Caron et al. 2012).

In the past, the ideal maize plant density ranged from 5.5 to 7.2×10^4 plants·ha⁻¹ (Fancelli and Dourado Neto 2000). Some studies suggest that high plant densities may increase the maize yield in modern cultivation, but for this a genotype with adequate plant architecture is necessary (Liu et al. 2017) and also resistant to lodging (Sher et al. 2017). With the transformations in the maize plant provided by genetic improvement in modern hybrids, it is necessary to evaluate their performance, especially for the second growing season under irrigation.

Higher maize plant densities, otherwise, can result in increased plant sterility and, therefore, lower yield. On the other hand, lower plant densities can also result in lower yield (Fawcett et al. 2017). It is necessary to look for an adequate spatial arrangement for each hybrid and each sowing season. The recommended sowing density for maize in second season is about 20% lower than that indicated for the main season, due to the greater probability of water deficit throughout the crop cycle, but in irrigated systems it is not a limitation.

In the past, the row spacing commonly used for maize was concentrated between 0.80 and 0.90 m, mainly due to fit to the mechanized harvest platform, since it was unsuitable for spacings below 0.80 m (Fancelli and Dourado Neto 2000). Meantime, this problem has been overcome and there are platforms adaptable to harvesters with spacing down to 0.45 m already. Thus, it is becoming increasingly common to use reduced spacing in maize (Cruz et al. 2009). The row spacing generally ranges from 0.45 to 0.90 m, and, in some cases, smaller row spacing can increase grain yield (Argenta et al. 2001), but it can also enhance severely foliar diseases (Fancelli and Dourado Neto 2000). Maize with upright leaves usually tolerate higher plant density when cultivated in the main season (Dourado Neto et al. 2003) and, possibly, this is also valid for the second cultivation season.

Some authors mention that the adjustment in the plant arrangement can increase maize yield by around 15%, mainly due to the better interception of photosynthetically active radiation (Kappes et al. 2011). Despite all the advances in determining the best row spacing and plant density for maize hybrids, the improvement of cultivation based on the specific characteristics of each hybrid, such as leaf area index (LAI), leaf angle (between leaf base and stalk) and optimization of light interception, are not used in practical terms for the allocation of hybrids. Those attributes should be updated for maize hybrids with high yield potential used currently, as well as how they perform in different plant arrangements. There is a lack of information on the best plant arrangement in modern maize hybrids, especially those used in Brazil in the second season and under irrigation.

The objectives of this study were to evaluate the performance of maize hybrids with different canopy architecture in function of different plant arrangements and row spacing under irrigation in the second growing season in Southeast Brazil.

MATERIAL AND METHODS

Field experiment

The field experiment was carried out in the 2018 growing season in a tropical environment located in Piracicaba, SP, Brazil (22°42'S and 47°38'W, 538 m altitude) under humid subtropical climate (Cwa, Köppen) (Alvares et al. 2013), with average annual rainfall of 1,328 mm and average annual temperature of 21.6 °C. The soil was classified as a Typic Hapludox (Soil Survey Staff 1999).

Experimental design

The experimental design consisted of randomized blocks in a $2 \times 3 \times 3$ factorial scheme, with three replicates. Two maize hybrids were chosen, DKB 230 PRO3 (upright leaf architecture) and DKB 390 PRO3 (semi-erect leaf architecture) sown in three row spacings (0.25, 0.50 and 1.00 m, RS_{25} , RS_{50} and RS_{100} , respectively) and plant densities (4 , 7 and 10×10^4 plants·ha⁻¹, D_{40} , D_{70} and D_{100} , respectively). The plot size was 24 m² (6 × 4 m), with a useful area of 8.0 m², excluding borders.

Management practices

Prior to sowing, seeds were treated with clothianidin (600 g·L⁻¹) and chlorantraniliprole (625 g·L⁻¹) at a rate of 2.5 mL per kg of seeds. After harrowing and furrowing, the maize was sown manually on January 15, 2019. When the plants presented three fully expanded leaves, thinning was performed to obtain the proper plant densities for each treatment.

The basic fertilization was 20 kg·[N]·ha⁻¹ and 100 kg·[P₂O₅]·ha⁻¹ (monoammonium phosphate). After the emergency, a topdressing application of 120 kg·[K₂O]·ha⁻¹ (KCl) was carried out. At the phenological stages V₄ and V₆ (Ritchie et al. 1966) two applications of 100 kg·[N]·ha⁻¹ (urea treated with N-(n-butyl) thiophosphoric triamide [NBPT]) were also used. Phytosanitary management was carried out properly and provided the best conditions for plant development.

Evaluations

The stalk diameter (SD) and plant height (PH) were evaluated based on the average of five plants per plot at stages V₁₃, V₁₇ and R₁. Stalk diameter was evaluated between the first and second knots above soil surface, while the height of the plants and ears was measured from the soil to the insertion of the tassel. The ear height (EH) was measured based on the distance from the ground to the ear insertion at the R₁ growth stage.

At stages V₈, V₁₃, R₁, R₃ and physiological maturity, light interception (LI) and LAI were evaluated with the light meter (LAI-250A, LI-COR Inc., Lincoln, Nebraska) and the plant canopy analyzer (LAI-2200, LI-COR Inc., Lincoln, Nebraska), respectively. Light interception was evaluated by the difference between the global incident photosynthetically active radiation (PAR_I) at the top of the canopy and both the reflected PAR (PAR_R) and the transmitted PAR (PAR_T). The PAR_I was evaluated at 0.3 m above the top of the canopy with the sensor horizontally facing upwards. The PAR_R was evaluated at the same position with the sensor horizontally facing downwards. The PAR_T was obtained at ground level by the average of eight evaluations measured in the longitudinal and transversal directions to the plant row. The evaluations of PAR were carried out at noon in open sky conditions, without clouds, while LAI was evaluated at dusk with diffuse light. The absorbed PAR (PAR_A) by the plant canopy was calculated by the difference according to Eq. 1:

$$PAR_A = PAR_I - PAR_R - PAR_T \quad (1)$$

or in relative terms using the subscript R, Eq. 2 was used:

$$PAR_{AR} = 1 - PAR_{RR} - PAR_{TR} \quad (2)$$

The LAI and PAR_A data were adjusted using a mathematical model to determine the critical LAI and the maximum LAI. Critical LAI was determined when the LAI intercepted 90% of PAR_A (Gifford and Jenkins 1982). Based on the derivative of the equation between LAI and PAR_{AR}, the maximum LAI was estimated.

The SPAD index of the 13th leaf was evaluated in five moments from leaf emission to senescence by the chlorophyll meter (Minolta SPAD-502 - Konica Minolta).

At the physiological maturity, the mass of one thousand grains (1,000-grain weight), rows per ear and grains per row were analyzed based on average values of five plants per plot. Grain yield and dry matter were obtained by harvesting all plants in a useful area of the plot (8 m²) and the water content of the grains was corrected to 130 g·kg⁻¹. The number of grains per area was obtained through the relationship between grain yield and the 1,000-grain weight.

Meteorological data

Average rainfall and air temperature of the experimental periods were obtained through a meteorological station located 1 km from experimental site. During the experiment, the accumulated rainfall was 412 mm, the accumulated irrigation was 336 mm (Fig. 1a) and the average temperature was 24.4 °C (Fig. 1b). The accumulated global radiation was 2144 MJ·m⁻² and the accumulated net radiation was 1124 MJ·m⁻² (Fig. 1c).

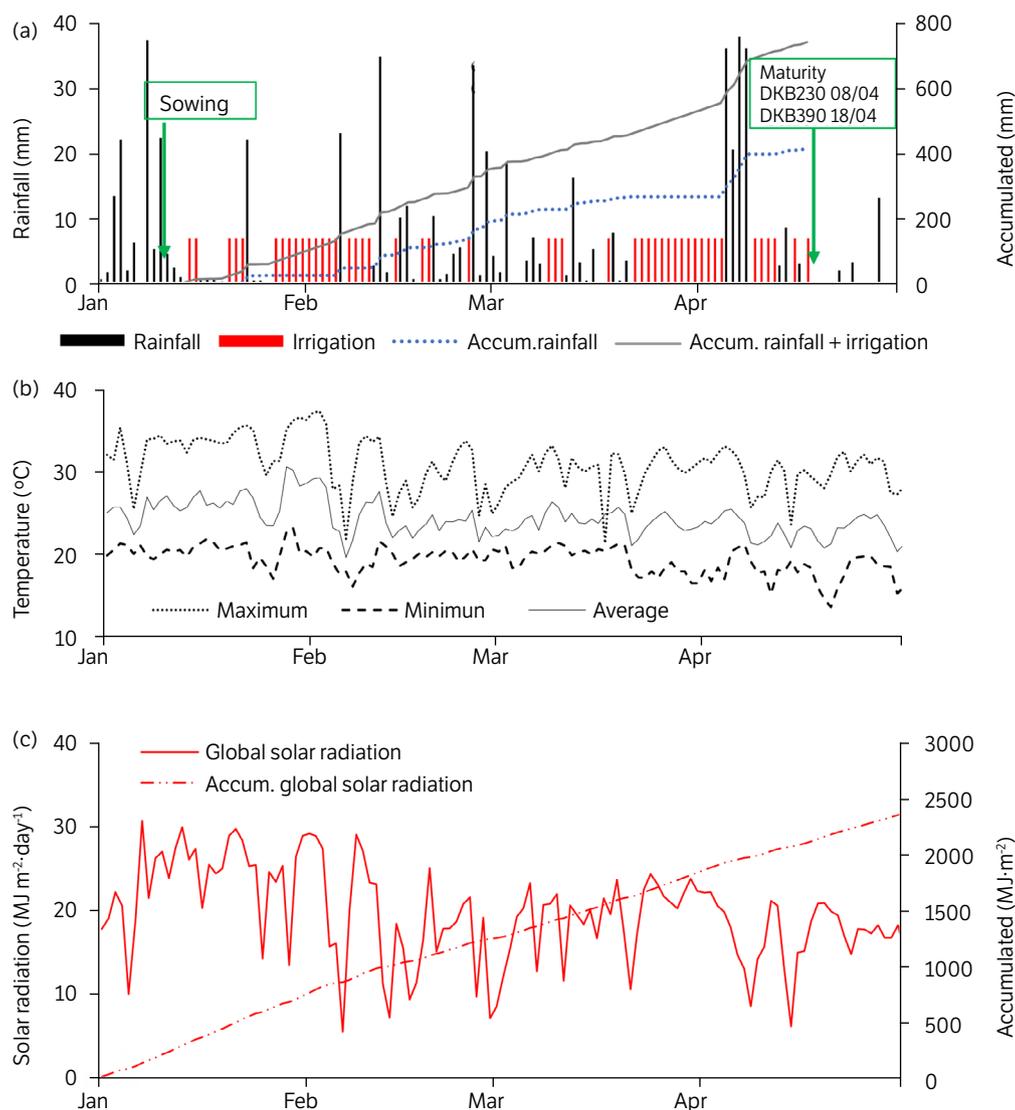


Figure 1. Meteorological data for the 2018 second maize season (from sowing until Apr. 20): daily and accumulated rainfall and irrigation (a); daily maximum, average, and minimum temperatures (b); daily and accumulated global solar radiation (c) across the crop cycle in Piracicaba, São Paulo, Brazil.

Statistics

Data were subjected to analysis of variance (ANOVA) and normality and homogeneity of residue distribution. When ANOVA indicated significant difference or interaction between the factors ($\alpha = 0.05$), the data were subjected to the Tukey's test at the level of 5% significance. From the derivatives of the regression models generated between plant density and yield, and between PAR_{AR} and LAI, the plant density that achieved de maximum yield and the LAI that intercepted the maximum PAR_{AR} were obtained, respectively. Statistical analysis was performed using the R program (Version 3.0), with the aid of the statistical packages Agricolae, ExpDes and Laercio.

RESULTS

Stalk diameter, PH and ear insertion height

At the V_{13} stage, the stalk differed between row spacing (Table 1), in which RS_{25} and RS_{50} did not differ from each other (28.7 and 28.8 mm, respectively) and had a larger diameter than plants from RS_{100} (27.5 mm) (Fig. 2a). At V_{13} , the SD also presented an interaction between hybrid and plant density (Table 1). Unfolding the plant densities for the hybrid DKB 390, the SD presented the following order: $D_{40} = D_{70} > D_{100}$, while for the hybrid DKB 230, the SD presented the following order: $D_{40} > D_{70} > D_{100}$. Unfolding the hybrids, for the D_{40} , the hybrids did not differ from each other, while for D_{70} and D_{100} the hybrid DKB 390 had a larger SD than the DKB 230 (Fig. 2a).

Table 1. Significance (p-value) by the F test of the variables stalk diameter, plant height and ear insertion height at 13th fully expanded leaf (V_{13}), 17th fully expanded leaf (V_{17}), and/or at flowering (R_1) when subjected to different row spacings, plant densities and maize hybrids during 2018 growing season in Piracicaba, São Paulo, Brazil.

Variable	Stalk diameter			Plant height			Ear height
	V_{13}	V_{17}	R_1	V_{13}	V_{17}	R_1	R_1
Row spacing (RS)	**0.014	^{ns} 0.213	^{ns} 0.319	^{ns} 0.255	^{ns} 0.160	^{ns} 0.232	^{ns} 0.745
Plant density (D)	**0.000	**0.000	**0.000	**0.000	**0.002	**0.004	**0.000
Hybrid (H)	**0.000	**0.000	**0.001	**0.000	**0.000	^{ns} 0.190	**0.000
D × RS	^{ns} 0.063	^{ns} 0.669	^{ns} 0.639	^{ns} 0.732	^{ns} 0.667	^{ns} 0.689	^{ns} 0.567
D × H	* 0.028	^{ns} 0.307	* 0.026	^{ns} 0.888	^{ns} 0.655	^{ns} 0.750	^{ns} 0.670
RS × H	^{ns} 0.478	^{ns} 0.418	^{ns} 0.331	^{ns} 0.619	^{ns} 0.255	^{ns} 0.314	^{ns} 0.844
RS × D × H	^{ns} 0.822	^{ns} 0.871	^{ns} 0.808	^{ns} 0.980	^{ns} 0.917	^{ns} 0.552	^{ns} 0.480

^{ns}, nonsignificant; ** and * significant by F-test at 1% and 5% respectively; bold values are $p \leq 0.05$.

At the V_{17} stage, the SD presented a difference between hybrids and between plant densities, without interaction (Table 1). Among the plant densities, the diameter at the V_{17} stage presented the following order: $D_{40} > D_{70} > D_{100}$ (Fig. 2a). Among hybrids, the diameter was 11.7% larger for DKB 390 compared to DKB 230 (Fig. 2a).

At the R_1 stage, the SD showed interaction between hybrids and plant densities (Table 1). Unfolding the plant densities, for the hybrid DKB 390, the diameter presented the following order: $D_{40} = D_{70} > D_{100}$, while for the hybrid DKB 230, the following order: $D_{40} > D_{70} = D_{100}$ (Fig. 2a). Unfolding the hybrids, the SD D_{40} and D_{100} had no difference between hybrids, while for D_{70} the hybrid DKB 390 presented a larger SD than the DKB 230 (Fig. 2a).

At the V_{13} stage, the PH showed a difference between plant density and hybrids, without interaction (Table 1). Among the densities, the PH presented the following order: $D_{40} < D_{70} < D_{100}$ (Fig. 2b). Among hybrids, the PH was 8.9% lower for the DKB 390 compared to the DKB 230 (Fig. 2b).

At the V_{17} stage, the PH showed a difference between plant density and hybrids, without interaction (Table 1). Among the plant densities, the PH presented the following order: $D_{40} < D_{70} = D_{100}$ (Fig. 2b). Among the hybrids, the PH was 14.3% lower for the DKB 390 compared to the DKB 230 (Fig. 2b).

At the R_1 stage, the PH showed a difference only between plant density (Table 1). Among the plant densities, the PH presented the following order: $D_{40} < D_{70} = D_{100}$ (Fig. 2b).

The ear insertion height showed a difference between plant density and hybrids, without interaction (Table 1). Among the densities, the ear insertion height presented the following order: $D_{40} < D_{70} < D_{100}$ (Fig. 2b). Among the hybrids, the height was 15.7% higher in the DKB 390 compared to the DKB 230 (Fig. 2b).

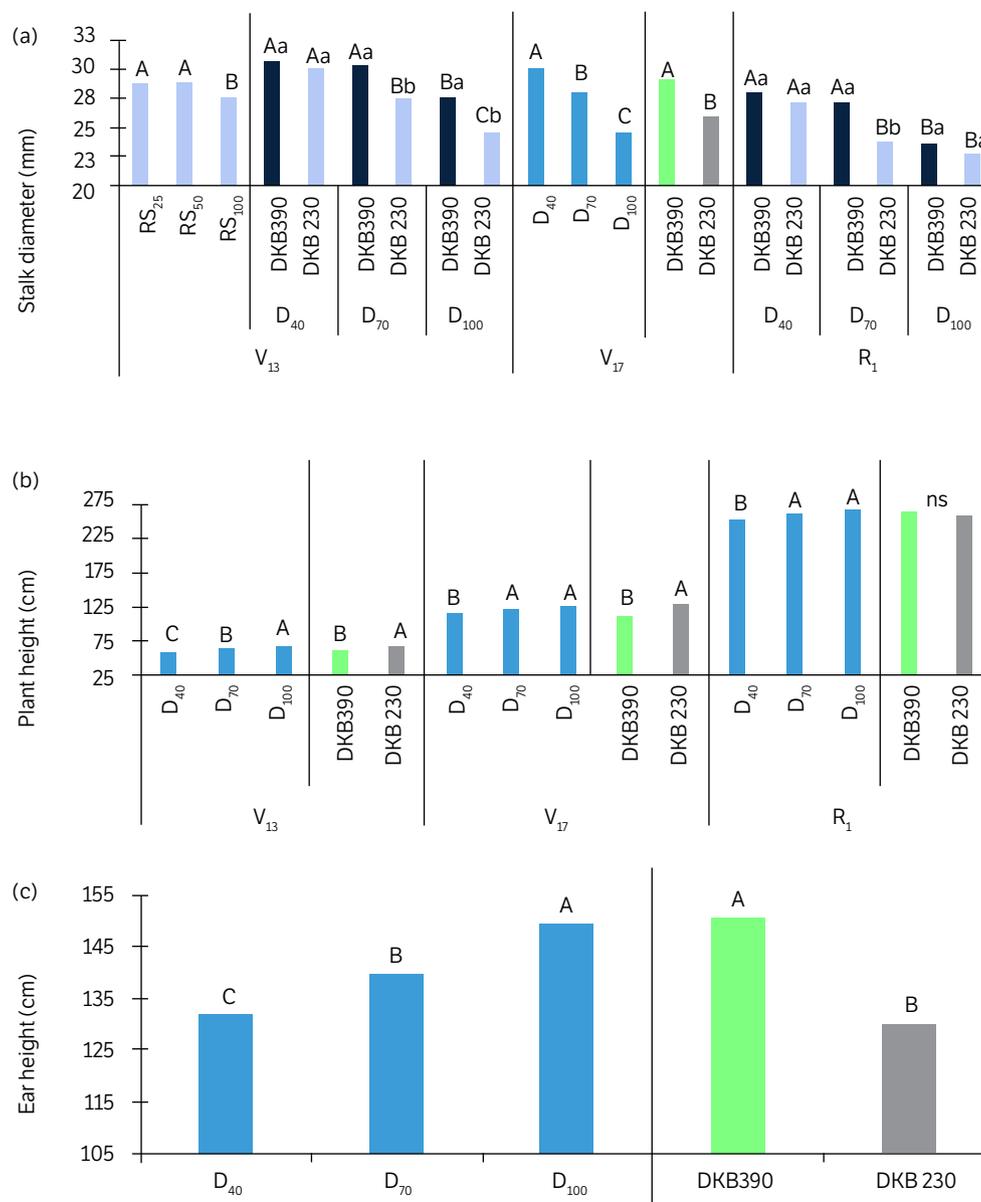


Figure 2. Stalk diameter (a), plant height (b) and ear height (c) of maize hybrids (DKB 230 and DKB 390) sown with different plant densities (plants·ha⁻¹) and row spacings (m) in 2018 growing season in Piracicaba, São Paulo, Brazil. Letters classify the averages by the Tukey's test at 5% significance. When there was interaction, lowercase letters classify hybrids, and uppercase letters classify row spacing or plant densities. D_{40} , D_{70} and D_{100} were 40, 70 and 100 x1000 plants·ha⁻¹, respectively; RS_{25} , RS_{50} and RS_{100} were row spacing 0.25, 0.50 and 1.00 m, respectively; V_{13} , 13th fully expanded leaf stage; V_{17} , 17th fully expanded leaf stage; R_1 , at flowering stage.

Absorbed photosynthetically active radiation, LAI and SPAD index

The PAR_{AR}, LAI and SPAD index, evaluated by repeated measurements over time, showed a difference only among plant densities and between hybrids (Table 2). The PAR_{AR} presented the following order among plant densities 37 and 58 days after emergence (DAE), $D_{100} = D_{70} > D_{40}$; at 76 DAE, $D_{100} > D_{40}$, while D_{70} did not differ between both; and at 101 DAE, $D_{100} = D_{70} > D_{40}$ (Fig. 3a). The PAR_{AR} presented the following order between hybrids: at 76 DAE, DKB 390 > DKB 230, while in the other evaluations there was no difference between hybrids (Fig. 3b).

Table 2. Significance (*p*-value) of the variables photosynthetic active radiation absorbed relative (PAR_{AR}), leaf area index (LAI) and SPAD index by the F test, when subjected to different row spacings, plant densities and maize hybrids during 2018 growing season in Piracicaba, São Paulo, Brazil.

Variable	SPAD index - evaluated in days after leaf emission					
	(<i>p</i> -value)	1	16	24	33	46
Row spacing (RS)	ns0.280	ns0.719	ns0.483	ns0.5225	ns0.485	ns0.058
Plant density (D)	**0.001	*0.013	**0.000	**0.000	**0.001	**0.001
Hybrid (H)	**0.000	**0.000	**0.000	ns0.1978	**0.000	**0.001
D × RS	ns0.185	ns0.105	ns0.182	ns0.4681	ns0.144	ns0.949
D × H	ns0.127	ns0.105	ns0.299	ns0.3133	ns0.159	ns0.298
RS × H	ns0.575	ns0.144	ns0.508	ns0.0694	ns0.353	ns0.609
RS × D × H	ns0.517	ns0.585	ns0.977	ns0.423	ns0.390	ns0.422
LAI - evaluated in days after emergence						
(<i>p</i> -value)	23	28	42	59	76	108
Row spacing (RS)	*0.0298	ns0.735	ns0.240	ns0.656	ns0.235	ns0.160
Plant density (D)	**0.005	**0.000	**0.000	**0.000	**0.000	**0.001
Hybrid (H)	ns0.190	**0.000	**0.000	ns0.394	ns0.899	ns0.838
D × RS	ns0.771	ns0.601	ns0.812	ns0.561	ns0.690	ns0.245
D × H	ns0.173	ns0.117	ns0.713	ns0.626	ns0.099	ns0.121
RS × H	ns0.312	ns0.589	ns0.675	ns0.874	ns0.899	ns0.391
RS × D × H	ns0.457	ns0.845	ns0.910	ns0.637	ns0.067	ns0.919
PAR _{AR} - evaluated in days after emergence						
(<i>p</i> -value)	37	58	76	101		
Row spacing (RS)	ns0.281	ns0.081	ns0.271	ns0.056		
Plant density (D)	**0.000	**0.000	**0.000	**0.000		
Hybrid (H)	*0.018	ns0.632	**0.001	**0.003		
D × RS	ns0.544	ns0.969	ns0.405	ns0.057		
D × H	ns0.222	ns0.278	ns0.726	ns0.080		
RS × H	ns0.089	ns0.080	ns0.517	ns0.711		
RS × D × H	ns0.479	ns0.603	ns0.906	ns0.296		

ns, nonsignificant; * and ** significant by F-test at 1% and 5% respectively; bold values are $p \leq 0.05$.

Leaf area index presented the following order among plant densities: at 23 and 28 DAE, there was no difference among densities; at 42 and 59 DAE, $D_{100} > D_{70} > D_{40}$; at 76 DAE, $D_{100} = D_{70} > D_{40}$; at 108 DAE there was no difference among densities (Fig. 3c). Leaf area index presented the following order between hybrids: at 23 and 28 DAE, there was no difference between hybrids; at 42 DAE, DKB 230 > DKB 390; at 42, 59, 76 and 108 DAE, there was no difference between hybrids (Fig. 3d). The LAI showed a row spacing effect only in the first assessment, performed at 23 DAE, while in the other assessments there was no difference between row spacings (Table 2). At 23 DAE, LAI presented the following order among row spacings: $R_{25} > R_{50} > R_{100}$ (data not shown).

The SPAD index presented the following order among plant densities: at 1 and 16 days after leaf emission (DAL) there was no difference among densities; at 24, 33 and 46 DAL, $D_{100} > D_{40}$, while D_{70} did not differ from both; and at 81 DAL, there was no difference among densities (Fig. 3e). The SPAD index presented the following order for the hybrids: at 1, 16 and 24 DAL, the hybrid DKB 390 > DKB 230; at 33 DAL, there was no difference between hybrids; at 46 DAL, the hybrid DKB 390 > DKB 230; and, at 81 DAL, there was no difference between hybrids (Fig. 3f). Overall, the SPAD index was 22.4% higher for the DKB 390 hybrid compared to the DKB 230 hybrid, but the time from 13th leaf emission until leaf senescence was quite similar for both hybrids (Fig. 3f).

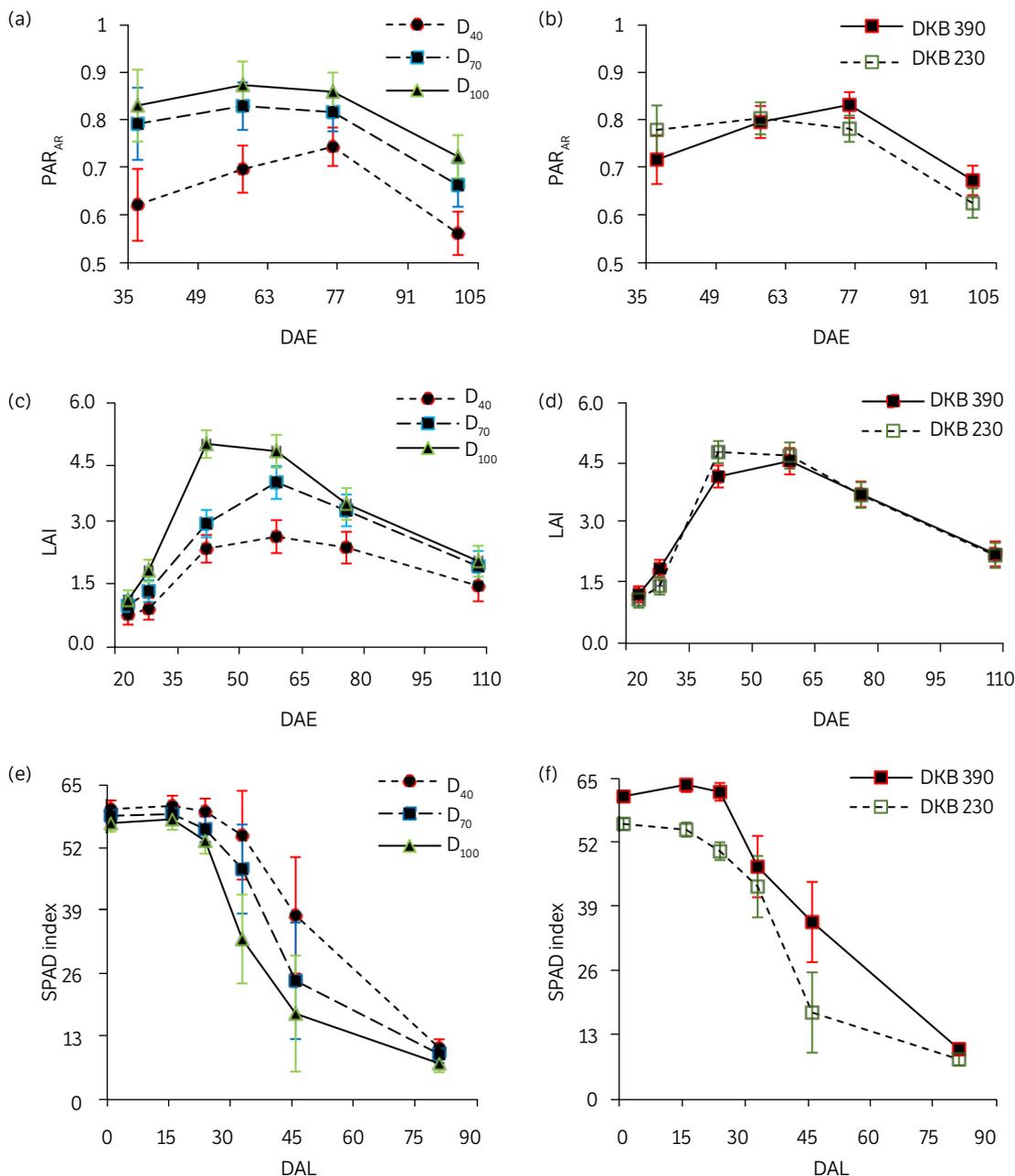


Figure 3. Temporal variation among photosynthetically active radiation absorbed relative (PAR_{AR}) (a, b), leaf area index (c, d), SPAD index (e, f) within different plant densities or hybrids (DKB 230 and DKB 390) of maize plants evaluated in 2018 growing season in Piracicaba, São Paulo, Brazil. Bars represent the mean significant difference (MSD) by the Tukey's test at the $p < 0.05$; D_{40} , D_{70} and D_{100} were 40, 70 and 100 x1000 plants·ha⁻¹, respectively; RS_{25} , RS_{50} and RS_{100} were row spacing 0.25, 0.50 and 1.00 m, respectively; DAE: days after emergence; DAL days after leaf emission.

Based on the relationship between PAR_{AR} and LAI, the critical LAI (LAIC) was determined, which is the LAI at which PAR_{AR} reaches 95% (Figs. 4a, b). For the DKB 390 and DKB 230 hybrids, the LAI_C was 4.3 and 5.2, respectively, and the maximum LAI was 4.9 and 5.3, respectively (Figs. 4c-d). For the DKB 390 hybrid, the LAI for the D₁₀₀ exceeded the LAIC for all row spacings, and for the DKB 230 hybrid, the LAI for the D₇₀ and D₁₀₀ exceeded the LAIC also for RS₅₀ and RS₁₀₀.

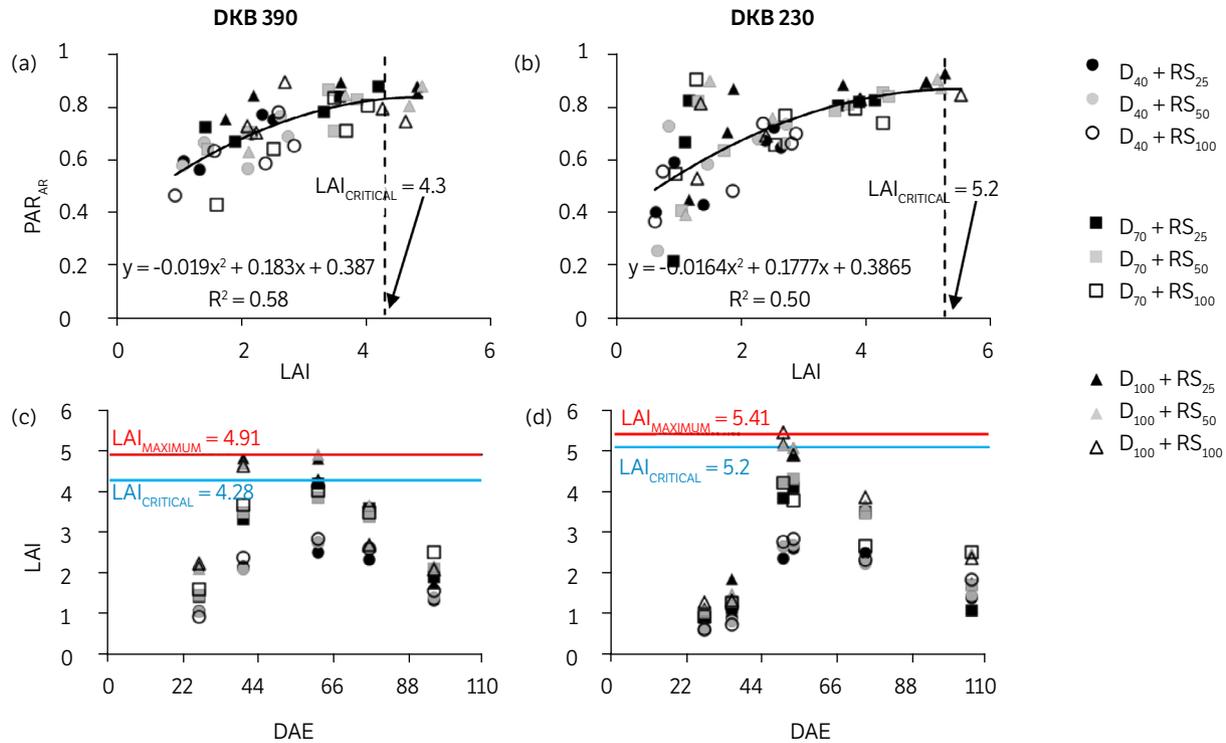


Figure 4. Relationship between photosynthetically active radiation absorbed (PARAR) and leaf area index (LAI) (a, b) and dynamics of leaf area index during the crop cycle (c, d), in two maize hybrids evaluated during 2018 growing season in Piracicaba, São Paulo, Brazil. The D₄₀, D₇₀ and D₁₀₀ were 40, 70 and 100 x1000 plants·ha⁻¹, respectively; RS₂₅, RS₅₀ and RS₁₀₀ were row spacing 0.25, 0.50 and 1.00 m, respectively; DAE: days after emergence.

Yield and yield components

Yield presented a difference between plant density and hybrids without interaction (Table 3). Among densities, yield presented the following order: D₄₀ < D₇₀ = D₁₀₀ (Fig. 5a). Among hybrids, yield was 16.1% lower for DKB 390 compared to DKB 230 (Fig. 5a).

Table 3. Significance (*p*-value) of the variables yield, mass of a thousand grains (MTG), grains per area (GA), harvest index (HI), dry matter at maturity (DM), ears per area (EA), grains per row (GR), rows per ear (RE) from two maize hybrids submitted to different row spacing and plant densities. 2018 growing season. Piracicaba, São Paulo, Brazil.

Variable	Yield	MTG	GA	HI	DM	EA	GR	RE
Row spacing (RS)	ns0.958	ns0.365	ns0.266	ns0.090	0.042	ns0.767	ns0.805	ns0.956
Plant density(D)	<.001	ns0.425	<.001	0.003	<.001	<.001	<.001	0.002
Hybrid	<.001	0.028	0.004	<.001	ns0.313	<.001	ns0.150	<.001
RS × D	ns0.838	ns0.407	ns0.740	ns0.613	ns0.735	ns0.750	ns0.784	ns0.641
RS × H	ns0.241	ns0.727	ns0.699	ns0.060	0.023	ns0.968	0.049	ns0.852
D × H	ns0.942	ns0.519	ns0.811	<.001	0.003	<.001	ns0.060	ns0.975
RS × D × H	ns0.521	ns0.617	ns0.255	ns0.262	ns0.208	ns0.375	ns0.214	ns0.764

ns, nonsignificant; * and ** significant by F-test at 1% and 5%, respectively; bold values are $p \leq 0.05$.

The relationship between yield and plant density among the hybrids presented a quadratic adjustment for the hybrid DKB 390 ($\hat{y} = -0.0013x^2 + 0.2287x$; $R^2 = 0.67$) and linear for DKB 230 ($\hat{y} = -0.0013x^2 + 0.2517x$; $R^2 = 0.66$) (Fig. 5b). Based on this adjustment, the plant density that provided the highest yield for the hybrid DKB 390 was 8.8×10^4 plants·ha⁻¹ and for the hybrid DKB 230 was 9.7×10^4 plants·ha⁻¹.

The 1,000-grain weight showed a difference between hybrids, without interaction (Table 3). Among hybrids, 1,000-grain weight was 7.5% lower for DKB 390 compared to DKB 230 (Fig. 5c). The number of grains per area showed a difference between plant density and hybrids, without interaction (Table 3). Among the densities, the number of grains per area presented the following order: $D_{40} < D_{70} = D_{100}$ (Fig. 5d). Among hybrids, the number of grains per area was 9.8% lower for DKB 390 compared to DKB 230 (Fig. 5d). The harvest index showed an interaction between plant density and hybrids (Table 3). Within the hybrids, the harvest index in the DKB 390 hybrid presented the following order: $D_{40} = D_{70} > D_{100}$, and, in the hybrid DKB 230, the harvest index did not differ between plant densities (Fig. 5e). Within densities for D_{40} , the harvest index was lower for DKB 390 compared to DKB 230, the harvest index did not differ between hybrids for D_{70} , and the harvest index was lower for DKB 390 compared to DKB 230 for D_{100} (Fig. 5e).

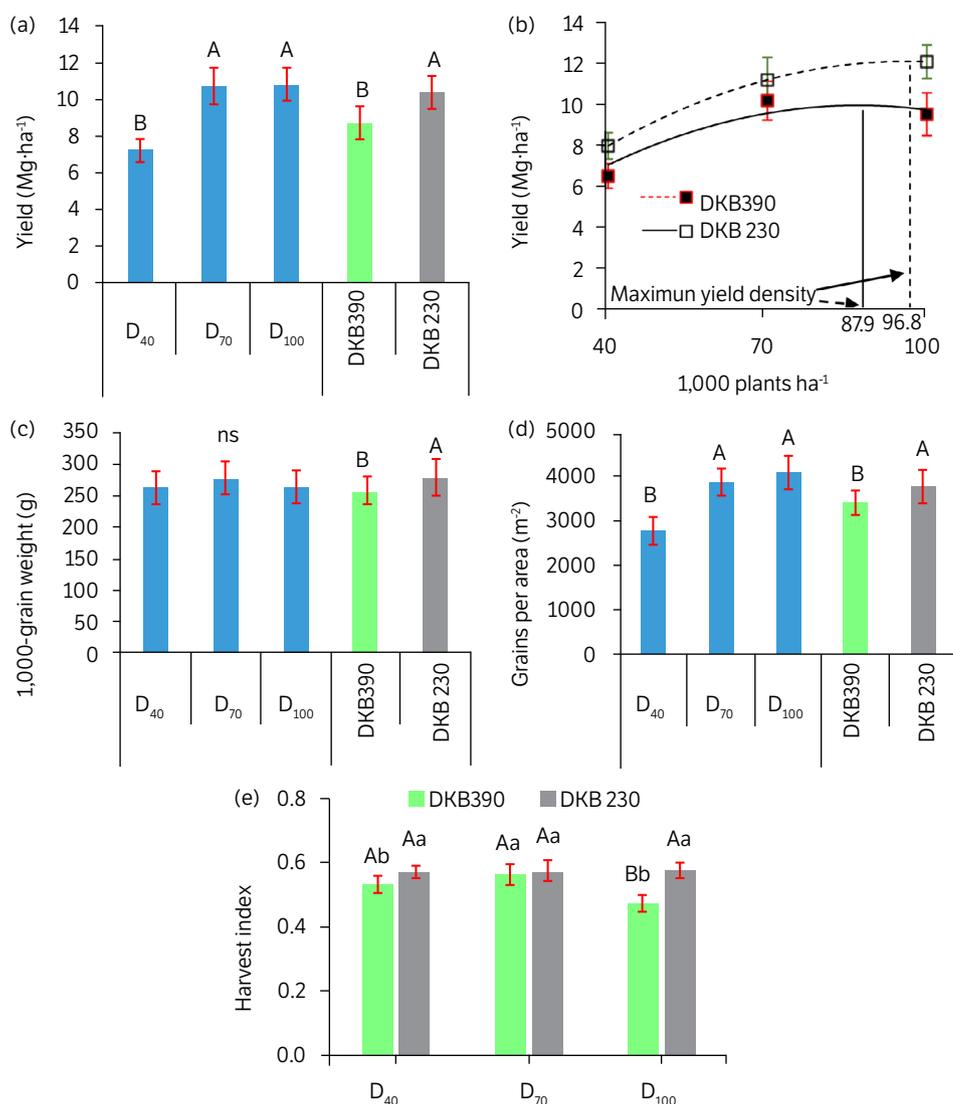


Figure 5. Yield (a), harvest index (b), 1,000-grain weight (c), grains per area (d) and dry matter (e and f) for maize hybrids under different plant density and/or row spacings in 2018 growing season in Piracicaba, São Paulo, Brazil. Letters classify the averages by the Tukey's test at 5% significance. When there was interaction, lowercase letters classify cultivars, and uppercase letters classify row spacing or plant densities. Bars mean average deviation; D_{40} , D_{70} and D_{100} were 40, 70 and 100 x1000 plants·ha⁻¹, respectively; RS_{25} , RS_{50} and RS_{100} were row spacing 0.25, 0.50 and 1.00 m, respectively; DAE: days after emergence.

The dry matter showed an interaction between row spacing and hybrids (Table 3). Within the hybrids, for the DKB 390, the dry matter presented the following order: $RS_{25} > RS_{50} = RS_{100}$, while in the hybrid DKB 230 the dry matter did not differ between the row spacings (Fig. 6a). Within the row spacings, the dry matter was higher in the hybrid DKB 390 compared to the DKB 230 for RS_{25} , while in the other row spacings there was no difference between hybrids (Fig. 6a).

The dry matter also showed an interaction between plant densities and hybrids (Table 3). Within the hybrids, for the DKB 390 hybrid, the dry matter presented the following order: $D_{40} < D_{70} < D_{100}$, whereas for the hybrid DKB 230, the dry matter presented the following order: $D_{40} < D_{70} = D_{100}$ (Fig. 6a). Within plant densities, the dry matter did not differ between hybrids for D_{40} and D_{70} , and for D_{100} the dry matter was higher for the hybrid DKB 390 compared to DKB 230 (Fig. 6a).

The number of ears per area presented an interaction between plant density and hybrids (Table 3). For both hybrids, the number of ears per area presented the following order: $D_{40} < D_{70} < D_{100}$ (Fig. 6b). Within plant densities, for D_{40} and D_{70} , the number of ears per area was lower for DKB 390 compared to DKB 230, and the number of ears per area did not differ between hybrids on D_{100} (Fig. 6b).

The number of grains per row showed an interaction between row spacing and hybrids (Table 3). Within hybrids, the number of grains per row did not differ between the spacing. Within the row spacing, in RS_{25} the number of grains per row was greater for the DKB 390 compared to the DKB 230, there was no difference between the hybrids for the other row spacings (Fig. 6c).

The number of rows per ear showed a difference between plant density and hybrids, without interaction (Table 3). Among the densities, the number of rows per ear presented the following order: $D_{40} = D_{70} < D_{100}$ (Fig. 6d). Among hybrids, the number of rows per ear was 13.3% higher in DKB 390 compared to DKB 230 (Fig. 6d).

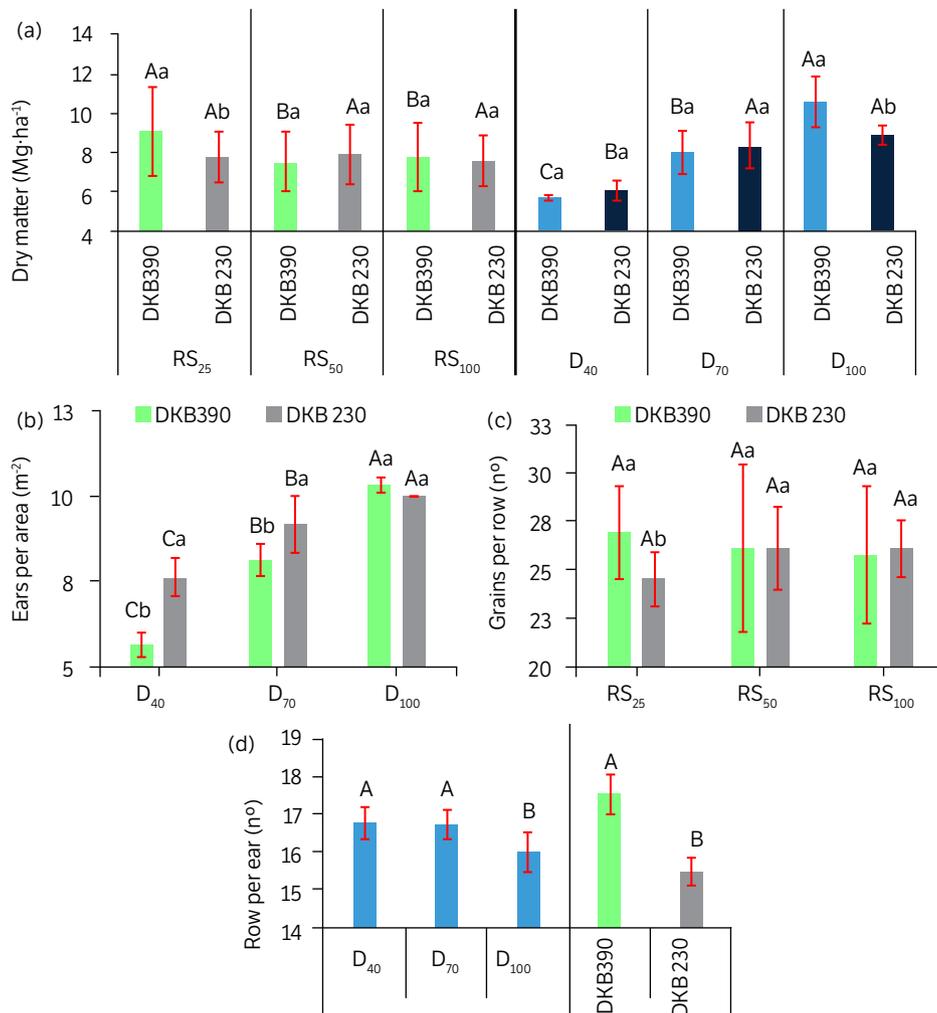


Figure 6. Dry matter at maturity (a), ears per area (b), grains per row (c) and rows per ear (d) for maize hybrids DKB 390 and DKB 230 grown in the 2018 growing season in Piracicaba, São Paulo, Brazil. Letters classify the averages by Tukey's test at 5% significance. When there was interaction, lowercase letters classify cultivars and uppercase letters classify plant spacing/densities; Bars mean average deviation; D_{40} , D_{70} and D_{100} were 40, 70 and 100 x1000 plants·ha⁻¹, respectively; RS_{25} , RS_{50} and RS_{100} were row spacing 0.25, 0.50 and 1.00 m, respectively; DAE: days after emergence.

DISCUSSION

Stalk diameter, PH and ear insertion height

From D_{40} to D_{100} for both DKB 390 and DKB 230 hybrids, the PH and ear insertion height increased; however, it reduced the SD of the plants (Fig. 2). These results corroborate with other authors, who mention that the SD is inversely influenced by plant density (Almeida Júnior et al. 2018; Demétrio et al. 2008; Stacciarini et al. 2010; Sangoi et al. 2002; Brachtvogel et al. 2012). For the hybrid DKB 390 grown in a tropical environment, increasing the plant density from 5×10^4 to 8×10^4 plants·ha⁻¹ reduced the SD in a linear fit (Santos et al. 2018).

The low interference of row spacing in the analyzed variables agrees with Skonieski et al. (2014), who evaluated row spacing of 0.40, 0.60 and 0.80 m and, similarly, did not observe differences in PH, ear insertion height and SD. This information also corroborates Pereira et al. (2017) and Afférri et al. (2008).

Higher plant densities tend to increase PH (Calonego et al. 2011). The increase in plant density can cause greater intraspecific competition for light, which results in greater height growth at the expense of radial stalk growth (Stacciarini et al. 2010; Calonego et al. 2011).

Changes in PH, ear and SD are direct physiological responses of plants to the environment to which they are submitted. Plants that are in higher plant densities are under greater intraspecific competition, perceived by the leaves since the first phenological stages by the proportion of red and distant red (Taiz and Zeiger 2013). They can also alter metabolism and promote height growth to increase light uptake (Taiz and Zeiger 2013).

Absorbed photosynthetically active radiation, LAI and SPAD index

Higher densities of maize plants increased the LAI and absorption of PAR_{AR} in the canopy of the plants, as well as reduced the SPAD index (Fig. 3a, c). Likewise, greater LAI and greater absorption of PAR_A was observed at the bolting stage (R_1 phenological stage) when the plants had a larger number of leaves, still counting on the leaves of the lower part of the canopy. Row spacing did not consistently affect LAI in this study across the crop cycle. In another study, a similar result was observed using spacings ranging from 0.5 to 0.76 m (Westgate et al. 1997).

Sangoi et al. (2005) verified a linear increase in the LAI with the increase in the plant density of maize. With the higher LAI, a plant tends to have more interference or intraspecific competition in addition to providing higher maintenance costs (Loomis and Connors 1992).

According to Gardner et al. (1985), the maize crop needs LAI oscillating between 4 and 5 to optimize the use of solar radiation under favorable water and soil conditions. Other authors mention that the 95% light interception in maize occurs with LAI of 4.9, this being the maximum value that the plants should reach in the field (Maddonni et al. 2001; Westgate et al. 1997). Higher LAI does not always mean greater PAR_{AR} , as it depends on the efficiency of light energy conversion of the plant canopy.

The period of greatest radiation interception must occur between pollination to milky grain, which must result from the best combination between LAI and PAR_{AR} (Vieira et al. 2016). The interception efficiency of solar radiation in the maize crop is practically 100% when the crop is in the reproductive stage with a LAI greater than 5 (Müller and Bergamaschi 2005).

The interception of PAR_{AR} and LAI in the canopy decreases after the bolting, after this stage most of the photoassimilates are destined to produce grain, which explains the beginning of senescence of the leaves of the bottom part of the canopy (Fig. 4a, b). Some hybrids differ in leaf senescence (Pereira et al. 2017; Sangoi et al. 2013) due to the intrinsic characteristics of each genetic material.

Conversely to LAI, the SPAD index decreased with increasing plant density and this reduction was different between hybrids. The hybrid DKB 390 showed a higher SPAD index than the hybrid DKB 230, and this study hypothesizes that this can be justified by the fact that the first is less efficient in translocating nutrients from the leaves to the ear, so the leaf senescence was slower when compared to the second hybrid.

The inversion of these parameters with the increase in plant density is related to the lack of radiation intercepted by the bottom part of the canopy, therefore the higher the LAI, the less radiation will reach the bottom part of the canopy, which decreased the photosynthesis and maintenance of metabolism. Likewise, hybrids that have a higher LAI have a higher energy expenditure for maintaining respiration and photorespiration.

Increasing plant density increases LAI and PAR_{AR} . The associations of these parameters increase the conversion efficiency in these plant spatial arrangements. Diffuse radiation, as it is multidirectional, is more efficient in penetrating the plant canopy when compared to direct radiation, and thus reaches the bottom part of the canopy (Buriol et al. 1995).

For the soybean crop, there is a higher conversion efficiency with a greater number of plants per area, which presented a higher leaf area index and possibly greater interception of diffuse radiation, thus increasing the conversion efficiency and soybean yield (Caron et al. 2019). Solar radiation is the main source of energy for the biological activity of plants. The way the plant can intercept and absorb PAR will determine its yield, since they are linked to the ability to perform photosynthesis (Kunz et al. 2007).

Yield and yield components

In this study, the best plant density with higher yield was for the hybrid DKB 390, with 8.8×10^4 plants·ha⁻¹ (Fig. 5b), corroborating with Sangoi et al. (2005). The hybrid DKB 230 showed higher yield for the plant density of 9.6×10^4 plants·ha⁻¹. The difference between higher yield between different plant densities of maize plants is mainly related to the increase in the number of grains per area (Santos et al. 2018). In high yield environments, where no water or nutritional stress occurred, yield was higher in higher plant densities compared to medium yield environments (Cruz et al. 2009). This information corroborates with the data obtained in this study with maize cultivated in the second season under irrigation.

Sangoi et al. (2013), by testing a hybrid, also showed a quadratic response regarding grain yield at densities of 2.5, 5.0, 7.5, 10 and 12.5×10^4 plants·ha⁻¹. The greatest production obtained by the authors was 12,663 kg·ha⁻¹, with a density of 7.5×10^4 plants·ha⁻¹; however, the optimal density calculated by the adjusted equation was 8.7×10^4 plants·ha⁻¹. Another study reported the highest yield with the plant density of 8.25×10^4 plants·ha⁻¹ (Pereira et al. 2017). Thus, greater grain yield with changes in plant arrangement, through the reduction of row spacing and plant density, have been strategies frequently reported in the literature (Calonego et al. 2011; Stacciarini et al. 2010; Takasu et al. 2014). The higher plant density is a strategy to increase the interception of solar radiation incident by the maize plant community, enhancing its use and, consequently, grain yield (Demétrio et al. 2008).

The increase in grain yield is related to how much the plant was able to assimilate and export its photoassimilates to the grains, and, in this way, it was possible to observe that the hybrid of upright leaf angulation, DKB 230, had higher yield when compared to DKB 390, of semi-upright leaves. The upright leaf angulation allowed greater light interception in the lower leaves and less shading, which made them remain viable as sources, rather than drains. In addition, upright leaves reduce self-shading and, therefore, possibly contribute to the higher yield of the DKB 230 hybrid. Maize plants also obtain photoassimilates from the stalk, so a larger stalk diameter may represent a greater redistribution of photoassimilates to the grains in the DKB 230 hybrid.

However, semi-upright angulations allow for a greater number of leaves between the lines and, consequently, greater self-shading. When the canopy presents greater self-shading, early senescence of the leaves is induced, which reduces source photoassimilated leaves, reduces the final yield, which may have occurred with the DKB 390 hybrid.

The evaluated plant densities did not influence the 1,000-grain weight; however, the DKB 230 hybrids presented higher 1,000-grain weight when compared to the DKB 390. The fact that the DKB 230 hybrid has a lower number of rows per ear is offset by the increase in 1,000-grain weight, which justifies its higher yield.

What may have favored the 1,000-grain weight to have the same potential in all densities was because the plants were irrigated and were not subjected to water deficit. In another study without irrigation, a reduction in 1,000-grain weight was observed with the increase in plant density (Demétrio et al. 2008), which may be linked to the water stress factor. In another study, the highest grain weight per ear and 1,000-grain weight were observed at the density of 5×10^4 plants·ha⁻¹ and decreased at higher plant densities (Santos et al. 2018). These authors mention that the lower plant density reduced

the competition between plants for water and nutrients, in addition to less shading, which allocates more photoassimilates to grain filling.

Higher plant density is reported to decrease number of grains per ear (Sangoi et al. 2005). Plant density above the value considered optimal can, sometimes, cause ear sterility due to the mismatch in the differentiation of the ear in relation to the differentiation of the tassel (Sangoi et al. 2000).

There was no effect of row spacing on yield components in this study, and, in the past, it was already reported that row spacing has less influence on yield components when compared to plant density (Afféri et al. 2008; Demétrio et al. 2008; Kappes et al. 2011).

In crops with a higher density of plants and under good growing conditions, the additional ears result in greater grain yield by increasing the number of grains per area. However, this compensation occurs until the largest number of ears per area is no longer sufficient to compensate for the reduction in the number and mass of grains (Dourado Neto et al. 2003).

Despite all the advances in determining the best plant spacing and density for maize hybrids over time, the improvement of cultivation based on the specific characteristics of each hybrid, such as LAI and optimization of PAR_A , are not used in practical terms for the positioning of genotypes of maize. In this study, it was observed that for the conditions of irrigated maize in second growing season, plant density is the factor that presented the greatest effect in PAR_A throughout the crop cycle, as well as in yield, while row spacing presents greater plasticity in the evaluated hybrids. Small row spacings could even slightly increase dry matter, but it was not enough to increase grain yield in the conditions of this study.

CONCLUSION

In second maize season under irrigation in Southeast Brazil, the increase in plant density from 4×10^4 to 10×10^4 plants·ha⁻¹ increased grain yield, while row spacing from 0.25 to 1 m had no effect, regardless of the hybrid evaluated. The increase in plant density increased yield mainly due to the increase in the number of grains per area, the greater dry biomass and the greater number of ears per area. Along the growth cycle, the increase in plant density also increased PH, ear insertion height, PAR_A and the LAI, but reduced SD and the SPAD index.

The hybrid DKB 230 (upright leaves) had 16% higher grain yield potential when compared to DKB 390 (semi-upright leaves) considering the average of plant densities and row spacings evaluated. This, in part, can be attributed to a 21% higher critical LAI, consequently, a higher response to the increase in plant density compared to DKB 390. The DKB 230 compared to DKB 390 also had 9% higher harvest index, an 8% higher 1,000-grain weight and a 10% higher number of grains per area. The estimated plant density that provided the maximum yield was 9.7×10^4 and 8.8×10^4 plants·ha⁻¹ for hybrids DKB 230 and DKB 390, respectively.

AUTHORS' CONTRIBUTION

Conceptualization: Graffitti M. S., Umburanas R. C., Dourado Neto D. and Pilau F. G.; **Methodology:** Graffitti M. S., Umburanas R. C., Dourado Neto D. and Pilau F. G.; **Investigation:** Graffitti M. S. and Fontana, D. C.; **Writing – Original Draft:** Graffitti M. S., Umburanas R. C., Fontana D. C., Reichardt K. and Dourado Neto D.; **Writing – Review and Editing:** Umburanas R. C. and Fontana D. C.; **Funding Acquisition:** Graffitti M. S. and Dourado Neto D.; **Resources:** Graffitti M. S., Umburanas R. C. and Fontana, D. C.; **Supervision:** Umburanas R. C., Reichardt K., Dourado Neto D. and Pilau F. G.

DATA AVAILABILITY STATEMENT

Data will be available upon request.

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