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Sowing time of popcorn during the summer harvest under supplemental irrigation in Ferralic Nitisol and subtropical climate

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Abstract

The aim of this study was to investigate the effect of sowing time on the phenotypic response of popcorn grown during the summer harvest (first season), with supplemental irrigation. Experiments were performed in the 2009/2010 and 2010/2011 agricultural years in a Ferralic Nitisol, in the northwestern region of Parana State, Brazil, using a randomized complete block design with four replications. Treatments consisted of combinations of five sowing times and two commercial popcorn hybrids (IAC-112 and IAC-125) in a 5 x 2 factorial scheme. The evaluated phenotypic characteristics were as follows: plant height, leaf area index, ears per plant, thousand-grain weight, grain yield and popping expansion. The obtained data were subjected to individual variance analyses for each agricultural year. A delay in sowing time limited both the growth and vegetative development of plants, although the first sowing time of each agricultural year (Oct. 6th 2009 and Oct. 4th 2010) resulted in better phenotypic characteristics of the popcorn crop. Temperature was the environmental factor with the strongest influence on the phenology, growth and vegetative development of popcorn plants. Grain yield decreased 1.1% (46.8 kg ha^{-1} day^{-1}) for the first sowing time in 2009/2010 and 1.2% (53.2 kg ha^{-1} day^{-1}) for the first sowing time in 2010/2011. The IAC-125 hybrid surpassed the IAC-112 and produced the best results for most of the evaluated phenotypic characteristics.

Keywords: *Zea mays* L. Special Corn, Popping Expansion, Grain yield, Physiology, Physiological Plant Ecology, Temperature, Starch, Phenology.

Abbreviations: EP_ears per plant; GY_grain yield; ia_active ingredient; LAI_leaf area index; PH_plant height; PPE_popcorn popping expansion; ST_sowing time; STs_sowing times; TGW_thousand-grain weight.

Introduction

Interest in producing a commercial popcorn crop (*Zea mays* L. subsp. *everta*) in Brazil has being growing steadily, due to the potentially higher economic returns compared with common corn. However, because there is a lack of information regarding specific popcorn crop management techniques in Brazil, farmers use the same crop management techniques employed for common corn. Therefore, technological development of the management and cultivation of the popcorn crop is necessary, in particular, the determination of the proper sowing time. The sowing time (ST) affects the growth and development of plants under favorable environmental conditions, and alterations to the ST can help in escaping the climate risks (especially dry spells and frost) associated with growing corn in southern Brazil (Gonçalves et al., 2002; Forsthofer et al., 2004). The farmer's choice of a sowing time does not place a burden on production costs, but it does affect productivity, and, consequently, the net revenues of this agricultural activity (Gonçalves et al., 2002). The corn plant possesses a C$_4$ metabolism, meaning its physiology is directly affected by its environment and it responds actively to environmental stimulus, especially temperature, which is the main environmental factor influencing the growth and development of plants (Shaw, 1988; Muchow, 1990; Birch et al., 1998; Tollenaar, 1999), and the duration of phenological stages (Ritchie et al., 1993). Corn grain yield is positively impacted when the plants achieve maximum leaf area coinciding with periods of day-time temperatures between 19 °C and 35 °C and between 13 °C and 24 °C at night. These conditions also signify a greater availability of incident solar irradiance on the plant canopy under no water restrictions (Shaw, 1988; Muchow, 1990; Cirilo e Andrade, 1994a, b; Bergamaschi et al., 2006). During spring and summer in northwestern Parana, temperatures are high, commonly reaching 30 °C during the day and 25 ºC at night, a situation that favors the increase of solar irradiance beginning in mid-spring. The higher temperatures trigger the rainy season in the region, beginning in the month of September. Although the area receives over 1,400 mm of rain annually, the rainfall is poorly distributed and, prolonged dry periods commonly occur during the growing season (Caviglione et al., 2000). The aim of this study was to determine the effect of ST on the phenotypic responses of popcorn grown during the summer harvest of the 2009/2010 and 2010/2011 agricultural years, under supplemental irrigation, in a Ferralic Nitisol, in the northwestern region of Parana State, Brazil.

Results

Environmental conditions

In all Sowing times (STs) in both agricultural years, the plants received over 700 mm of water (Fig. 1), which was deemed as both sufficient or superior to the demands of most

Table 1. Sowing times (ST), seedling emergence, accumulated thermal sum, insolation and length of time until main phenological events observed in popcorn crop grown in five ST during the first season of 2009/2010 and 2010/2011, in Maringa (northwest region of Parana State, Brazil).

Sowing times	Accumulated thermal sum (ATS, ºC day^{-1}) and [Days after seedling emergence (DAE)]					Insolation (h)
	V_E	V_4	V_T	R_1	R_6	V_E a R_6
IAC-112 hybrid (2009/2010)						
October, 06th	October, 11th	343.7 [24]*	703.5 [47]	747.9 [50]	1,349.1 [90]	601.5**
October, 29th	November, 03rd	338.5 [20]	704.9 [45]	754.5 [48]	1,337.6 [87]	544.7
November, 12th	November, 17th	342.3 [21]	699.3 [45]	749.9 [48]	1,339.6 [86]	562.0
November, 26th	December, 03rd	347.3 [23]	702.1 [45]	747.0 [48]	1,344.7 [86]	531.3
December, 10th	December, 16th	342.5 [21]	704.4 [44]	749.9 [47]	1,343.7 [85]	569.5
IAC-112 hybrid (2010/2011)						
October, 04th	October, 10th	355.8 [28]	705.8 [54]	748.9 [57]	1,355.6 [99]	735.1
October, 18th	October, 23th	352.9 [27]	703.4 [52]	753.0 [56]	1,360.8 [96]	678.4
November, 01st	November, 06th	358.9 [26]	704.1 [51]	749.2 [54]	1,362.8 [94]	607.6
November, 15th	November, 22th	357.5 [25]	704.0 [48]	749.2 [51]	1,358.3 [90]	542.1
November, 30th	December, 06th	359.2 [25]	702.1 [47]	752.4 [50]	1,357.5 [89]	515.5
IAC-125 hybrid (2009/2010)						
October, 06th	October, 11th	365.4 [26)	760.1 [52]	798.8 [55]	1,399.2 [97]	629.4
October, 29th	November, 03rd	361.7 [22)	760.9 [50]	787.7 [51]	1,406.3 [94]	608.4
November, 12th	November, 17th	361.7 [23)	751.5 [50]	795.6 [53]	1,392.1 [94]	591.0
November, 26th	December, 03rd	363.2 [25)	756.5 [50]	799.8 [53]	1,391.4 [93]	588.7
December, 10th	December, 16th	361.9 [22)	755.2 [48]	795.1 [50]	1,395.4 [90]	596.6
IAC-125 hybrid (2010/2011)						
October, 04th	October, 10th	371.8 [29)	760.6 [58]	803.1 [61]	1,400.2 [102]	745.2
October, 18th	October, 23th	365.0 [28)	767.7 [57]	800.2 [59]	1,407.3 [99]	690.0
November, 01st	November, 06th	373.6 [27)	762.8 [55]	792.4 [57]	1,395.2 [96]	611.3
November, 15th	November, 22th	373.4 [26)	763.7 [52]	796.0 [54]	1,394.4 [92]	560.4
November, 30th	December, 06th	373.2 [26)	758.9 [51]	805.2 [54]	1,400.4 [93]	538.0

Popcorn phenological stages: V_E = seedling emergence; V_4 = fourth leaf; V_T = tasseling; R_1 = earing; R_6 = grains physiological maturity, according to Ritchie et al. (1993). In V_E stage the ATS = zero; *First value = ATS and between brackets values = [DAE]. **Accumulated hours of sunlight in the period. Source of climatological data: Instituto Simepar and Estação Climatológica Principal de Maringá/UEM.

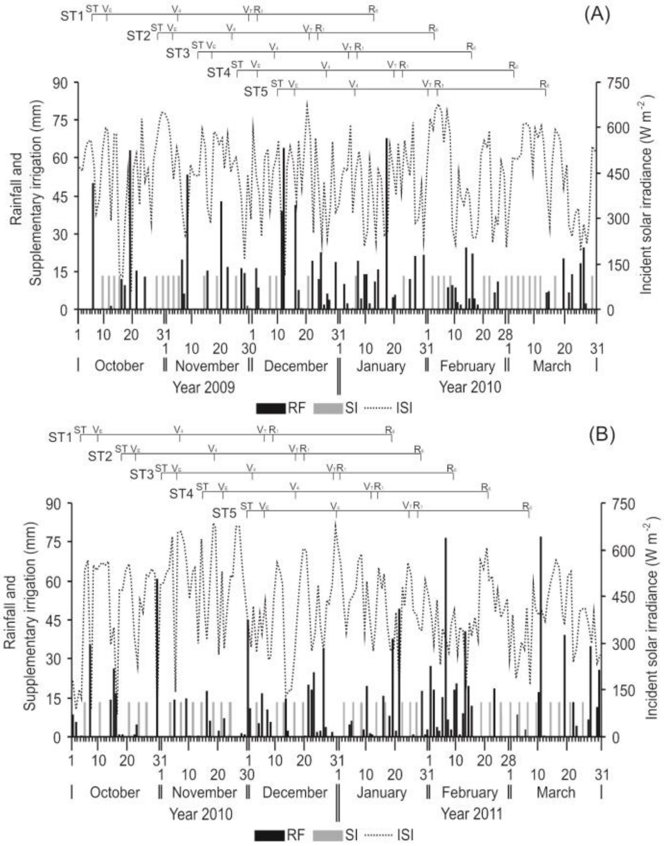

Fig 1. Daily values of rainfall (RF), supplemental irrigation (SI) and incident solar irradiance (ISI) occurring (A) between October, 1st 2009 and March, 31st 2010, and (B) between October, 1st 2010 and March, 31st 2011, during the first season, in Maringa (northwest region of Parana State, Brazil). Sowing times (ST1, ST2, ST3, ST4 and ST5). Phenological stages: V_E = seedling emergence; V_4 = four leaves completely expanded; V_T = tasseling; R_1 = earing; R_6 = grains physiological maturity, according to Ritchie et al., (1993). Source of climatological data: Instituto Simepar and Estação Climatológica Principal de Maringá/UEM.

hybrid corn grown in Brazil (Embrapa, 2009). In 2009/2001, a decrease occurred in the thermal amplitude values during the plant vegetative phase, and there was also a decrease in the plant reproductive phase of the third ST, however, an increase was observed in the fourth and fifth STs (Fig. 2). In 2010/2011, there was a decrease in the values of thermal amplitude in both plant phases (vegetative and reproductive) for all STs (Fig. 3). The high rates of solar irradiance (Fig. 1) led to high temperatures (Fig. 2 and 3), which are typical characteristics observed in the spring/summer seasons at the latitude (23°20'48" S) where the experiments were located.

Duration of phenological cycle

During the first ST of 2009/2010, a delay caused a reduction in the duration of the plant vegetative phase of 3 to 4 days and 2 and 3 days for the plant reproductive phase for IAC-112 and IAC-125 hybrids, respectively, during the growing season 2009/2010 (Table 1). During 2010/2011, there was a reduction in the duration of the plant vegetative phase of 7 days, for both hybrids and a reduction in the plant reproductive phase of 3 and 2 days for the IAC-112 and IAC-125 hybrids, respectively (Table 1). For the calorific energy accumulated by the plants, there was some similarity between the values of thermal sum at each phenological stage for both hybrids (Table 1). Phenological change occurred when IAC-112 plants accumulated mean thermal sums of 349.9 ºC, 703.4 ºC, 750.2 ºC and 1,351.0 ºC in the phenological stages V_4, V_T, R_1 and R_6, respectively (Table 1). The IAC-125 hybrid showed mean accumulations of 367.1 ºC, 759.8 ºC, 797 °C and 1,398.2 ºC, showing that it received more insolation, indicating that the phenological cycle for this hybrid is slightly longer than for IAC-112 (Table 1). At the latitude 23º20’48” S where the experiment was performed, increasing elevation was followed by a reduction in photoperiod duration, which was 13.4 h on the longest day of the year (Dec. 21st). Thus, it was not possible to quantify elevation’s influence on the agronomical characteristics of the studied hybrids.

Vegetative growth

The main factor, ST, was significant ($P \leq 0.05$) for all the evaluated phenotypical characteristics (Table 2). The hybrid factor had a significant effect ($P \leq 0.05$) on the PH, EP, TGW and GY characteristics in 2009/2010. During the 2010/2011, only the EP, TGW and GY characteristics were influenced ($P \leq 0.05$) by the hybrid (Table 2). Dependency ($P \leq 0.05$) among factors was observed only for the TGW and GY characteristics in 2009/2010 (Table 2). The PH characteristic was fit to a quadratic model, in the ST function, with the hybrid mean for each agricultural year (Fig. 4a). The estimated higher responses of 2.00 m and 2.26 m were observed on Nov. 4th and Oct. 19th in 2009/2010 and 2010/2011, respectively (Fig. 4a). The IAC-112 hybrid surpassed ($P \leq 0.05$) IAC-125, for PH (mean ST), in 2009/2010, although no significant difference was observed ($P>0.05$) in 2010/2011 (Table 3). The LAI response to ST was fit to a decreasing linear model, representing this characteristic behavior in the hybrid mean for each agricultural year (Fig. 4b). No significant differences ($P>0.05$) existed among hybrids for LAI (Table 3) in either year.

Production components

The EP was fit to a decreasing linear model with ST, for the mean of the hybrids in both agricultural years (Fig. 5a). The angular coefficient of the linear equation estimated reductions of 0.004 and 0.005 EP for each day delay in ST for 2009/2010 and 2010/2011, respectively. Under these conditions, between the first and the fifth ST (65 and 57 days for 2009/2010 and 2010/2011, respectively), the reduction was approximately 17,738 and 26,139 ears ha^{-1} for 2009/2010 and 2010/2011, respectively (Fig. 5a). Using the means of EP, TGW (Fig. 5b) and the number of grains per ear (unpublished data), the estimated values represented 1,089.91 and 1,817.61 kg ha^{-1} of unproduced popcorn grains (Table 3). In both agricultural years, it was observed that the IAC-125 hybrid surpassed ($P \leq 0.05$) the IAC-112 in ear production (Table 3). When unfolding the interaction ST × hybrid, it became apparent that the TGW characteristic was fit to a linear model for the IAC-112 hybrid in 2010/2011 and 2009/2010, and for the mean of the hybrids for 2010/2011 (Fig. 5b). The means of IAC-125, in 2009/2010, fit a quadratic model, with the maximum estimated response of TGW at 142.18 g on October 16th (Fig. 5b). The IAC-125 hybrid surpassed ($P \leq 0.05$) the IAC-112 and produced heavier grains (TGW) from the second to fifth STs, but no significant difference existed ($P>0.05$) for the first ST (Table 3).

Grain productivity and quality

In 2009/2010, unfolding the interaction of ST × hybrid was significant ($P \leq 0.05$) for the GY characteristic, due to ST within the hybrids (Table 2). GY means were fit to cubic and quadratic models for the IAC-112 and IAC-125 hybrids, respectively. The reduced values for the coefficients of variation and for experimental errors, as well as the elevated coefficients of determination, resulted in steadily decreasing GY values with a linear tendency (Fig. 6a). Regression has a high sensitivity for the detection of significant differences among treatments, and significant interactions among factors. For 2009/2010, we fit the main effect ST and the the means of the hybrids to a linear regression (Fig. 6a). For 2010/2011, the GY characteristic was fit to a linear model. There was an estimated decrease in GY, using the angular coefficients of linear equations, of 46.8 and 53.2 kg ha^{-1} for each day delay in ST for 2009/2010 and 2010/2011, respectively. Such values represented the loss of 72.72% and 66.99% in productivity between the first and the fifth STs, for each agricultural year (Fig. 6a). It is notable that the IAC-125 hybrid surpassed ($P \leq 0.05$) IAC-112 for GY in the first to fourth STs, while no significant difference ($P>0.05$) occurred at the fifth ST (Table 3). In relation to the PPE, the adjusted means were fit to quadratic and linear models, for 2009/2010 and 2010/2011, respectively, using the hybrid mean (Fig. 6b). The maximum estimated response was 35.8 mL g^{-1}, on Oct. 23rd for 2009/2010. In both agricultural years, no significant differences were observed ($P>0.05$) between hybrids for the PPE characteristic (Table 3).

Discussion

Temperature increases are favorable for the growth and development of popcorn plants because greater thermal amplitude values (Fig. 2 and 3) coincide with the vegetative phase (Fig. 4) and result in plants with better production capacity (Fig. 5), i.e., they yield larger and heavier grains (Fig. 6). In both agricultural years, the climatic conditions were favorable for the production of corn (Fig. 1 to 3), in Maringá (northwestern region of Paraná). Nevertheless, plants react in different ways to environmental conditions, reacting to the received stimuli by the expression of genetic and phenotypic characteristics (Shaw, 1988; Muchow, 1990;

Table 2. Summary of the individual variance analysis of popcorn phenotypic characteristics (plant height (PH), leaf area index (LAI), ears per plant (EP), thousand grain weight (TGW), grain yield (GY) and popping expansion (PPE)) during the second season of 2010 and 2011, in Maringa (northwest region of Parana State, Brazil)

Source of variation	DF	PH (m)	LAI	EP	TGW (g)	GY (Mg ha^{-1})	PPE (mL g^{-1})
Year 2009/2010							
ST (S)	4	0.078 *	0.389 *	0.073 *	2,581.261 *	11.188 *	38.588 *
Hybrid (H)	1	0.286 *	0.001^{ns}	0.178 *	2,059.369 *	2.572 *	1.879^{ns}
Blocks	3	0.012	0.200	0.004	66.030	0.037	1.416
S x H	4	0.001^{ns}	0.028^{ns}	0.011 ns	229.084 *	0.225 *	3.700^{ns}
Residue	27	0.006	0.024	0.008	31.559	0.014	3.210
VC (%)		4.24	7.29	6.74	4.60	4.51	5.30
General mean		1.89	2.13	1.33	122.24	2.66	33.81
Year 2010/2011							
ST (S)	4	0.143 *	0.511 *	0.097 *	1,259.485 *	11.447 *	12.003 *
Hybrid (H)	1	0.018^{ns}	0.056^{ns}	0.184 *	430.139 *	2.151 *	0.625^{ns}
Blocks	3	0.016	0.215	0.005	87.088	0.031	1.348
S x H	4	0.004^{ns}	0.044^{ns}	0.006 ns	31.055 ns	0.056^{ns}	1.680^{ns}
Residue	27	0.008	0.027	0.015	42.660	0.022	3.120
VC (%)		4.14	7.36	7.02	4.85	4.78	5.46
General mean		2.14	2.23	1.75	134.71	3.07	32.33

*significant and ^{ns} not significant, at the 5% probability level, by F test.

Table 3. Means of phenotypic characteristics of popcorn: plant height (PH), leaf area index (LAI), ears per plant (EP), thousand grain weight (TGW), grain yield (GY) and popcorn popping expansion (PPE), during the first season of 2009/2010 and 2010/2011, in Maringa (northwest region of Parana State, Brazil)

Response variable	Hybrids (H)			
	IAC-112	IAC-125	IAC-112	IAC-125
	2009/2010		*2010/2011*	
Hybrid factor effect in the ST factor mean				
PH (m)	1.97^{a}	1.80^{b}	2.16^{a}	2.12^{a}
LAI	2.13^{a}	2.14^{a}	2.27^{a}	2.19^{a}
EP	1.26^{b}	1.39^{a}	1.68^{b}	1.81^{a}
TGW (g)	-	-	131.43^{b}	137.99^{a}
GY (Mg ha^{-1})	-	-	2.84^{b}	3.30^{a}
PPE (mL g^{-1})	34.03^{a}	33.59^{a}	32.45^{a}	32.20^{a}
Hybrid factor effect of the ST factor				
TGW - H / ST1	144.51^{a}	141.91^{a}	-	-
TGW - H / ST2	127.93^{b}	137.94^{a}	-	-
TGW - H / ST3	112.54^{b}	134.40^{a}	-	-
TGW - H / ST4	105.27^{b}	126.00^{a}	-	-
TGW - H / ST5	85.07^{b}	106.82^{a}	-	-
GY - H / ST1	3.87^{b}	4.50^{a}	-	-
GY - H / ST2	2.96^{b}	3.78^{a}	-	-
GY - H / ST3	2.36^{b}	3.01^{a}	-	-
GY - H / ST4	1.60^{b}	2.08^{a}	-	-
GY - H / ST5	1.23^{a}	1.18^{a}	-	-

For each characteristic, means followed by the same letter in the same column (in each agricultural year) are not different by F test ($p < 0.05$). ST: 2009 year – ST1 = October, 06th; ST2 = October, 29th; ST3 = November, 12th; ST4 = November, 26th; and ST5 = December, 10th; 2010 year - ST1 = October, 04th; ST2 = October, 18th; ST3 = November, 01st; ST4 = November, 15th;andST5 = November, 30th.

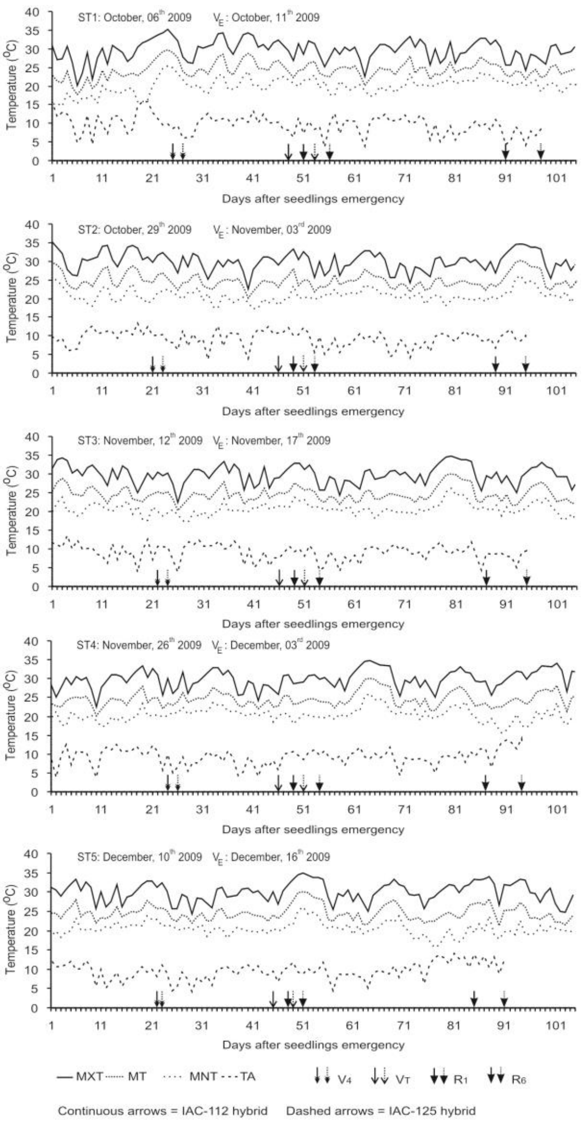

Fig 2. Daily values for maximum air temperature (MXT), minimum air temperature (MNT), mean of air temperature (MT), thermal amplitude (TA) and phenology of popcorn during first season of 2009/2010, in each sowing time (ST1, ST2, ST3, ST4 and ST5), in Maringa (northwest region of Parana State, Brazil). Phenological stages: V_E = seedling emergence; V_4 = four leaves completely expanded; V_T = tasseling; R_1 = earing; R_6 = grains physiological maturity, according to Ritchie et al., (1993). Source of climatological data: Instituto Simepar and Estação Climatológica Principal de Maringá/UEM.

Tollenaar, 1999). This became clear for the duration of the phenological cycle of the popcorn hybrids (Ritchie et al., 1993) used in this study (Fig. 2 and 3). In Porto Alegre (Rio Grande do Sul, Brazil, 30º02’15” S and 51º13’13” W; altitude 10 m), Forsthofer et al. (2004) achieved similar results in a study with common corn and concluded that the delay in the ST promoted the shortening of the phenological cycle between the months of August and January. In a study performed in Balcarce, Argentina (37°45'00” S, 58°18'00” W, altitude 130 m), Andrade et al. (1993) also reported a reduction in the phenological cycle of common corn, due to the delay in ST between September and January. They concluded that the effect was due to temperature, especially during the plant vegetative growth phase, resulting in higher daily caloric energy accumulation. Chang (1981), Birch et al. (1998) and Tollenaar (1999), suggested that although corn blooming is not affected by the photoperiod, time of the plant exposure to the solar irradiance incidence, and consequently, air temperature, can have effects on it. This agrees with the insolation observed in both planting years and is corroborated by the similarity between the values of the thermal sum accumulated in each phenological sub-period for each ST (Table 1). The shorter plant phenological cycle (Table 1) can be attributed to the strong influence of the air temperature (Fig. 2 and 3) and solar irradiance (Fig. 1), both of which were elevated from the third 10-day period of September (beginning of spring in the southern hemisphere). Such events promoted the growth and accelerated the development of the popcorn culture, due to the resultant delay in the ST (Shaw, 1988; Muchow, 1990; Ritchie et al., 1993; Tollenaar, 1999; Streck et al., 2012). The observed ST effect on PH and LAI characteristics (Fig. 4) is consistent with the ones observed by Andrade (1995) in Balcarce, Argentina (37°45'00” S, 58°18'00” W, altitude 130 m) and by Forsthofer et al. (2004) in Porto Alegre, Brazil. They found that the common corn plants grew faster in the sowings occurring in mid-spring, and attributed that effect to temperature. A greater accumulation of dry matter in the plants, once the day-time temperatures rose and the night-time temperatures were still mild, resulted in greater photo-

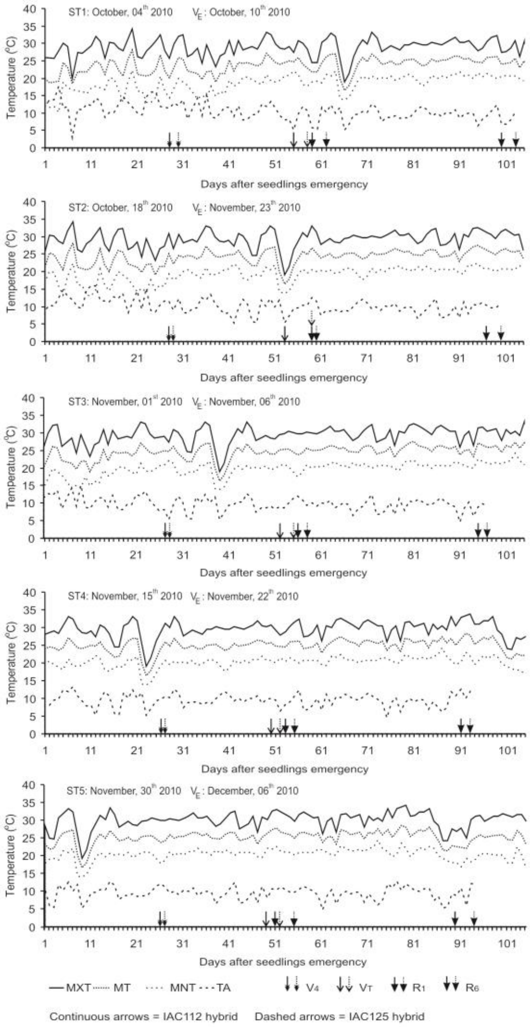

Fig 3. Daily values for maximum air temperature (MXT), minimum air temperature (MNT), mean of air temperature (MT), thermal amplitude (TA) and phenology of popcorn during the first season of 2010/2011, in each sowing time (ST1, ST2, ST3, ST4 and ST5), in Maringa (northwest region of Parana State, Brazil). Phenological stages: V_E = seedling emergence; V_4 = four leaves completely expanded; V_T = tasseling; R_1 = earing; R_6 = grains physiological maturity, according to Ritchie et al., (1993). Source of climatological data: Instituto Simepar and Estação Climatológica Principal de Maringá/UEM.

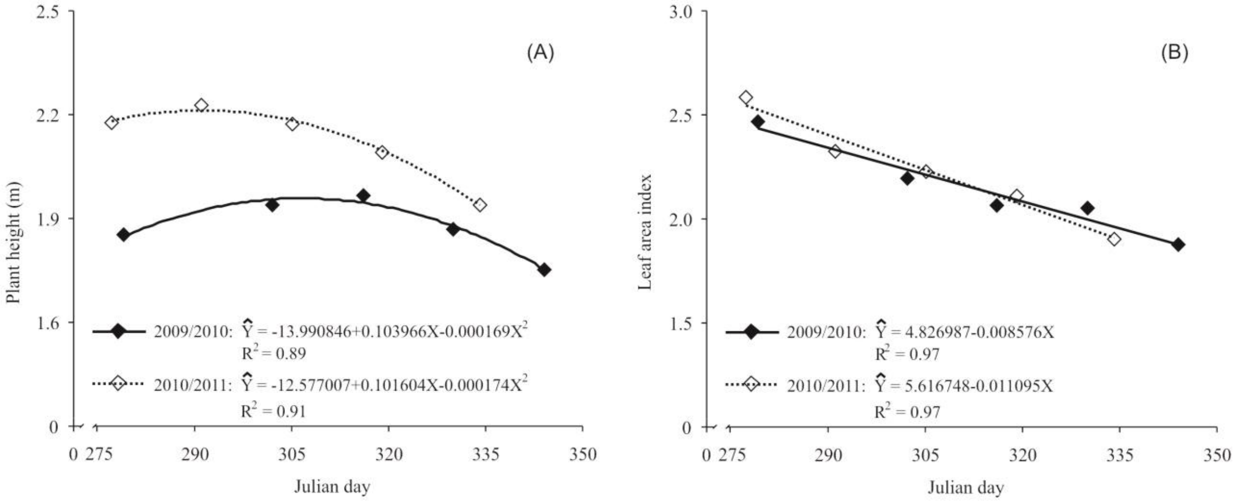

Fig 4. Mean plant height (A) and leaf area index (B) of popcorn in relation to the sowing time (ST) in the hybrids (IAC-112 and IAC-125), during the first season of 2009/2010 and 2010/2011, in Maringa (northwest region of Parana State, Brazil). ST: 2009/2010 year - ST1 = 279 (October, 06th); ST2 = 302 (October, 29th); ST3 = 316 (November, 12th); ST4 = 330 (November, 26th); and ST5 = 344 (December, 10th); 2010/2011 year - ST1 = 277 (October, 04th); ST2 = 291 (October, 18th); ST3 = 305 (November, 01st); ST4 = 319 (November, 15th); and ST5 = 334 (November, 30th).

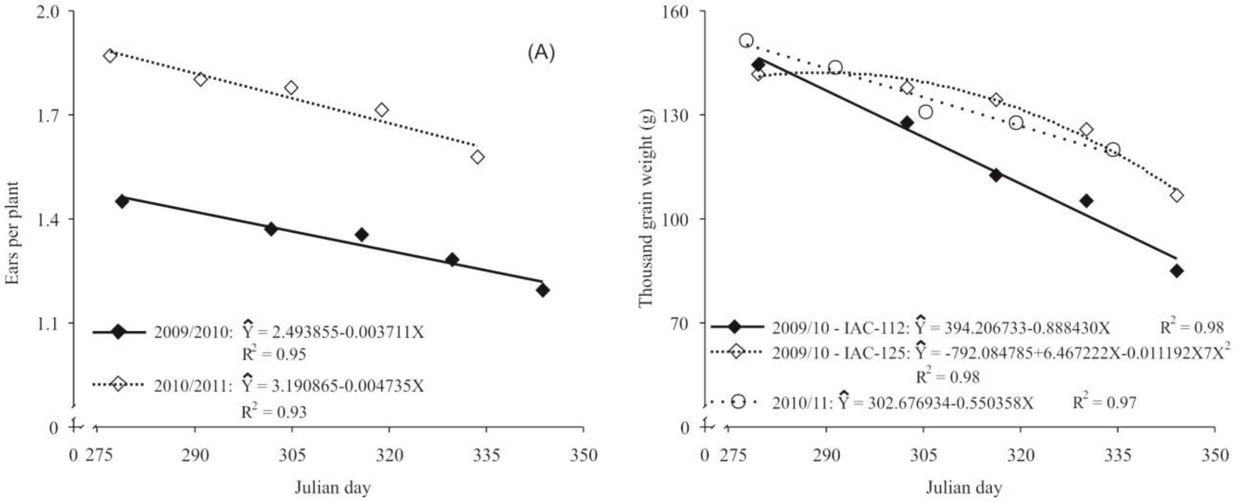

Fig 5. Mean ears per plant (A) of popcorn in relation to sowing time (ST) in the hybrids (IAC-112 and IAC-125), during the first season of 2009/2010 and 2010/2011, and thousand grain weight (B) of popcorn in relation to ST into hybrid factor in 2009/2010 and the mean of the hybrids 2010/2011, in Maringa, (northwest region of Parana State, Brazil). ST: 2009/2010 year - ST1 = 279 (October, 06th); ST2 = 302 (October, 29th); ST3 = 316 (November, 12th); ST4 = 330 (November, 26th); and ST5 = 344 (December, 10th); 2010/2011 year - ST1 = 277 (October, 04th); ST2 = 291 (October, 18th); ST3 = 305 (November, 01st); ST4 = 319 (November, 15th); and ST5 = 334 (November, 30th).

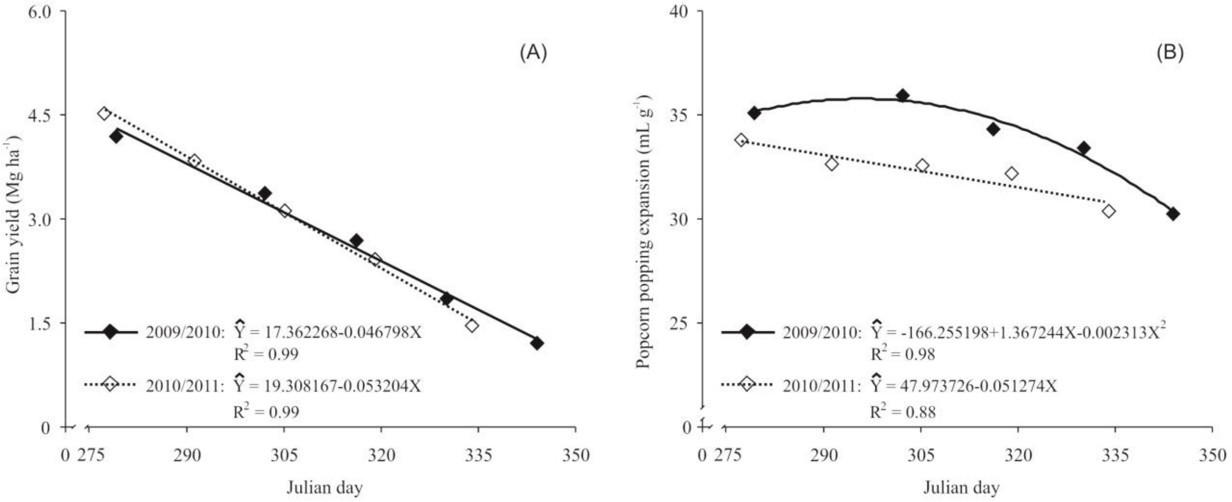

Fig 6. Mean grain yield (A) and popcorn popping expansion (B) in relation to sowing time (ST) in the hybrids (IAC-112 and IAC-125), during the first season of 2009/2010 and 2010/2011, in Maringa (northwest region of Parana State, Brazil). ST: 2009/2010 year - ST1 = 279 (October, 06th); ST2 = 302 (October, 29th); ST3 = 316 (November, 12th); ST4 = 330 (November, 26th); and ST5 = 344 (December, 10th); 2010/2011 year - ST1 = 277 (October, 04th); ST2 = 291 (October, 18th); ST3 = 305 (November, 01st); ST4 = 319 (November, 15th); and ST5 = 334 (November, 30th).

synthesis in the plants (Shaw, 1988; Muchow, 1990; Birch et al., 1998; Tollenaar, 1999). In contrast, Andrade (1995) and Forsthofer et al. (2004) also found that both the foliar expansion and the foliar formation rates were lower in the plants sown during high temperature periods (during the final third of spring) and those characteristics are directly related to the efficiency of solar irradiance utilization (Tollenaar, 1999). Broadly speaking, the greater thermal amplitude observed in the initial STs favored the growth and the development of the plants during the vegetative phase because the highest and lowest temperatures described (Fig. 2 and 3) were within the range considered optimum (day-time: >19˚C and <35 ºC; night-time: >13˚C and <24 ºC) for corn culture (Duncan and Hesketh, 1968; Shaw, 1988; Muchow, 1990). The reduction in the thermal amplitude from the first ST (Oct. 6th, 2009 and Oct. 4th, 2010), due to elevation of night-time temperatures (Fig. 2 and 3), could favor the increase in cellular respiration in plants (Muchow, 1990; Cantarero et al., 1999; Edreira and Otegui, 2012). Consequently, there is a chance that a reduction might have occurred in the photo-assimilates accumulated in the vegetative tissues, which was evidenced by the smaller phenotypic responses of PH and LAI (Fig. 4) observed in this study (Muchow, 1990; Cirilo and Andrade, 1994a; Edreira and Otegui, 2012). It can also be emphasized that the use of carbon composts by the plants' respiration process increases under higher night-time temperatures, resulting in less photosynthesis (Krömer, 1995; Vedel et al., 1999). This phenomenon can affect both the growth and the development (vegetative and reproductive) of the plant (Muchow, 1990; Cantarero et al., 1999; Edreira and Otegui, 2012) and has an origin in the large amount of substratum and energy used in the plant growth and development stage that are received from respiratory routes (Krömer, 1995; Hoefnagel et al., 1998; Vedel et al., 1999). Cirilo and Andrade (1994a, b), in Balcarce, Argentina (37°45'00” S, 58°18'00” W; altitude 130 m), Didonet et al. (2001) in Coxilha, Rio Grande do Sul, Brazil (28º15’00” S, 52º24’00” W; altitude de 687 m) and Forsthofer et al. (2004) in Porto Alegre, Brazil, also observed a reduction in EP in studies performed with ST of common corn in the first season, between August and December. They attributed the lower ear production to the limited sources of photo-assimilation represented by the reduction in the foliar area (Tollenaar and Bruulsema, 1988), which was also observed in this study (Fig. 4b). According to Cirilo and Andrade (1994b), the decrease in EP is not related to a shorter vegetative growth prior to anthesis in late sowings, but, rather to the translocation of the necessary photo-assimilates for vegetative structural growth. That is, the photo-assimilates are consumed by respiration for maintenance of the plants, and temperature elevation results in an alteration of the source-drainage relationship (Krömer, 1995; Vedel et al., 1999). The characteristic EP reduction (Fig. 5a) in late sowings can be related to the high rate of sterile ears as occurs in common corn plants under the same circumstances as those in this study (Williams et al., 1968; Prine, 1971). Several studies show that the corn production components are affected by vegetative growth prior to anthesis, specially related to the active foliar area which directly influences the interception ability of solar irradiance by plants (Tollenaar and Bruulsema, 1988). This can result in less photosynthesis and a smaller biomass accumulation by the corn plants (Andrade et al. 1993; Tollenaar, 1999; Lindquist et al., 2005). Cirilo and Andrade (1994a, b), Didonet et al. (2001) and Forsthofer et al. (2004) also found a reduction in common corn grain mass and attributed this to a smaller accumulation of photo-assimilates in the grains, caused by the smaller foliar area of late sowings. According to Didonet et al., (2001), the net growth rate of common corn grain for early sowings is higher than for late sowings, which results in grains having a greater accumulated biomass. In general, the vegetative growth was strongly reduced due to the delay in popcorn ST, as shown by the PH and LAI characteristics (Fig. 4). These had a direct impact on the production components, as well as EP and TGW characteristics (Fig. 5), which also showed a decrease between the first and the fifth ST. Frequently, foliar area is correlated with the reduction in production components (Andrade et al., 1993; Cirilo and Andrade, 1994a; Andrade, 1995; Didonet et al., 2001; Forsthofer et al., 2004). In GY corn, the leaves have a key role in the interception and conversion of solar irradiance into chemical energy by photosynthesis. (Tollenaar and Bruulsema, 1988; Andrade et al., 1993). The lower rate of photo-assimilate accumulation in corn grains under rising temperatures is most likely the cause for a lower GY in late sowings, as photo-assimilate production is directly linked to the vegetative growth prior to anthesis (Andrade et al., 1993; Cirilo and Andrade, 1994a; Andrade, 1995; Edreira and Otegui, 2012). Rising temperatures during vegetative growth leads to a reduction in enzymatic activity in carbohydrate metabolism (Chowdhury and Wardlaw, 1978), resulting in the formation of shorter plants with smaller foliar areas (Singletary et al., 1994; Keeling et al., 1994). The decrease in growth and development of the popcorn plants found in this study (Fig. 4 to 6) could be related to timing and decrease in vegetative growth of the popcorn plants (Andrade et al., 1993). The increase in temperature provided a reduction in thermal amplitude (Fig. 2 and 3), which resulted in a greater accumulated thermal sum, between the first and the fifth ST (Table 1). High temperatures, although below the maximum limits tolerated by the corn plants (Duncan and Hesketh, 1968; Shaw, 1988; Muchow, 1990; Edreira and Otegui, 2012), keeps biological activity at elevated rates (Chowdhury and Wardlaw, 1978; Singletary et al., 1994; Keeling et al., 1994, Lu et al., 1996; Vedel et al., 1999; Barnabás et al., 2008). Thus, it is suggested that the shorter vegetative cycle (Table 1) resulted in less exposure time of the plants to solar irradiance (Fig. 1), which was corroborated by the reduction in insolation between the first and the fifth ST, for both hybrids and agricultural years (Table 1). Consequently, such factors resulted in less dry mass accumulation in plants (Fig. 4) and in less vegetative growth (Tollenaar and Bruulsema, 1988; Andrade et al., 1993; Cirilo and Andrade, 1994a; Andrade, 1995; Tollenaar, 1999; Didonet et al., 2001; Forsthofer et al., 2004; Lindquist et al., 2005) under no water restrictions in either agricultural year (Fig. 1). Limiting the photo-assimilation sources (Tollenaar, 1989a, b; 1999) resulted in smaller GY popcorn (Fig. 6a), as well as the formation of grains with a shorter PPE in the late sowings (Fig. 6b). The smaller GY corn in the late sowings is also related to the growth rate of the endosperm (Brooking, 1993), which cannot compensate for the reduction of the fulfilling period of grains under high temperatures (Muchow, 1990; Cantarero et al., 1999), specially between anthesis (stage R_1) and the milky grain stage (stage R_3), resulting in a reduced rate of grains per ear (Cirilo and Andrade, 1994b; Edreira and Otegui, 2012). In addition, in the first season in southern Brazil and eastern Argentina, the corn plants presented early foliar senescence, negatively interfering with the GY (Cirilo and Andrade, 1994b; Didonet et al., 2001; Forsthofer et al., 2004). For the PPE characteristic, according to Green Junior and Harris Junior (1960), a good quality popcorn must present endosperm expansion superior to 32.0 mL g^{-1}, for popping either in a special or an ordinary pan. Nevertheless, Sawazaki (2001) states that for the popcorn popping in a microwave oven, expansion must be greater than 39.0 mL g^{-1}. The reduction of PPE observed in this study (Fig. 6b) might have been caused by a reduced deposition of starch in the grains (Andrade et al., 1993; Cirilo and Andrade, 1994a; Andrade, 1995) and the TGW characteristic (Fig. 5b), which produced smaller and less dense grains, consequently produced smaller popcorn flowers. Lu et al. (1996) found that temperature elevation caused a reduction in the amylase fraction and an increase in amylopectin medium chain concentrations when corn hybrids formed grains at 35 °C compared to plants grown at 25 °C. This may be one of the reasons why the observed PPE in this study was smaller for the later STs (Fig. 6b). According to Pordesimo et al. (1991), the PPE is positively related to the vitreous endosperm content in the popcorn grain. Hoseney et al. (1983) demonstrate that the starch deposited on the opaque endosperm portion is kept intact after popping. There is no starch expansion, the effective expansion results only from the vitreous endosperm portion. We suggest that the reduced starch deposition occurred in the vitreous portion of the endosperm of the popcorn grains, in this study, due to the delay in ST (Fig. 5b and 6).

Materials and Methods

Experimental description

The experiments were performed and evaluated during the first seasons of the 2009/2010 and 2010/2011 agricultural years, in Maringa County, in the northwestern region of Parana State (geographic coordinates 23°20'48"S and 52º04'17"W, altitude of approximately 510 m).

The soil of the experimental area was classified as a Ferralic Nitisol, clayey to the touch. The main chemical and physical characteristics of the soil samples from the experimental area were:

a) Year 2009: pH = 5.0, $H^{+}+Al^{3+}$ = 5.0 $cmol_c\ dm^{-3}$, Ca^{3+} = 3.3 $cmol_c\ dm^{-3}$, Mg^{2+} = 1.6 $cmol_c\ dm^{-3}$, K^{+} = 0.6 $cmol_c\ dm^{-3}$, P = 8.2 mg dm^{-3}, C = 12.8 g dm^{-3};

b) Year 2010: pH = 5.6, $H^{+}+Al^{3+}$ = 4.8 $cmol_c\ dm^{-3}$, Ca^{3+} = 4.3 $cmol_c\ dm^{-3}$, Mg^{2+} = 2.2 $cmol_c\ dm^{-3}$, K^{+} = 0.9 $cmol_c\ dm^{-3}$, P = 9.7 mg dm^{-3}, C = 13.9 g dm^{-3}; and

c) Clay = 520 g kg^{-1}, silt = 140 g kg^{-1} and sand = 340 g kg^{-1}.

In early July 2009, 1.0 Mg ha^{-1} of limestone (85% total neutralization relative strength) was applied to the experimental area with the goal of bringing base saturation above 60% (EMBRAPA, 2009). Treatments consisted of the combination of five ST (2009/2010, Oct. 6th; Oct. 29th; Nov. 12th; Nov. 26th, and Dec. 10th; and 2010/2011, Oct. 4th; Oct. 18th; Nov. 1st; Nov. 15th, and Nov. 30th), and two commercial popcorn hybrids (IAC-112, a modified simple hybrid and IAC-125, a top cross hybrid). The experimental design was a randomized complete block in a 5 × 2 factorial scheme, with four replications, using the mathematical statistical model that follows:

$Y_{ijk} = m+S_i+H_j+SH_{ij}+B_k+\varepsilon_{ijk}$,

where $\boldsymbol{Y_{ijk}}$ = observed value in the treatment in the *i*-th level of ST, in the *j*-th level of popcorn hybrid, in the *k*-th block; $\boldsymbol{m}$ = general mean of the experiment; $\boldsymbol{S_i}$ = effect of the *i*-th level of ST; $\boldsymbol{H_j}$ = effect of the *j*-th level of popcorn hybrid; $\boldsymbol{SH_{ij}}$ = effect of the *ij*-th level of the interaction between ST and popcorn hybrid; $\boldsymbol{B_k}$ = effect of the *k*-th block; and $\boldsymbol{\varepsilon_{ijk}}$ = residual effect associated with the *i*-th level of ST, in the *j*-th level of popcorn hybrid, in the *k*-th block. Each 6.0 m × 4.5 m experimental plot contained five rows of plants, 6.0 m in length, spaced at 0.9 m, totaling 27.0 m². The useful area was 13.5 m² and consisted of three central rows, excluding 0.5 m from each final row. Unwanted plants within the experimental area were removed ten days prior to each ST, by using the herbicide glyphosate [N-(phosphonomethyl) glycine] with 1.92 kg of i.a. per hectare (Embrapa, 2009). Sowing in both agricultural years followed cultivation with common corn in 2009/2010 and black oat (*Avena strigosa* Scheb.) under a no-tillage system. According to the soil chemical analysis, 20, 80, 60 kg NPK per hectare was applied (in the sowing line) in the forms of ammonium sulfate (20% N), triple superphosphate (45% P_2O_5) and potassium chloride (60% K_2O) (Embrapa, 2009). Thinning was performed in the V_3 phenological stage (Ritchie et al., 1993), resulting in approximately 55,500 plants ha^{-1} (Sawasaki, 2001). Subsequently, a topdressing of N, at the rate of 90 kg ha^{-1} in the form of ammonium sulfate (20% N), was applied in the V_4 stage (Embrapa, 2009). For all trials, the agricultural management procedures and chemical plant protection products used were those recommended for the common corn crop in Brazil (Embrapa, 2009). To eliminate the effect of water deficit on the development of the plants, supplemental sprinkler irrigation was supplied whenever rainfall was less than 5.0 mm, from sowing to the R_6 stage (Ritchie et al., 1993). The depth of irrigation was 14 mm every three days, totaling 224, 210, 182, 210 and 238 mm in 2009/2010 (for each ST), and 308, 322, 280, 252 and 280 mm applied in 2010/2011.

Environmental conditions

Climatological data for each season were obtained from the Instituto Simepar and from the Estação Climatológica Principal de Maringá at Universidade Estadual de Maringá. Data for the accumulated rainfall, incident solar irradiation, insolation and photoperiod for each of the agricultural years were compiled for the characterization of environmental variables.

Data for air temperature were used to determine the daily thermal amplitude and thermal sum, occurring between seedling emergence (V_E stage) and grain maturity (R_6 stage) (Ritchie et al., 1993) for each ST. The accumulation of thermal energy by popcorn plants was determined by the thermal sum daily units, according to Cross and Zuber (1972):

$$ATS = \sum_{N=1}^{N} TS \quad [(T_{mx} + T_{mn}) / 2] - T_b,$$

where $\boldsymbol{ATS}$ = accumulated thermal sum (ºC day^{-1}); $\boldsymbol{\Sigma TS}$ = thermal sum daily (ºC day^{-1}); $\boldsymbol{N}$ = number of days; $\boldsymbol{T_{mx}}$ = maximum air temperature (ºC); $\boldsymbol{T_{mn}}$ = minimum air temperature (ºC); and $\boldsymbol{T_b}$ = base air temperature of the corn crop (for which 10 ºC was adopted) (Monteith e Elston, 1993). Popcorn ears were harvested 20 days after grains had reached physiological maturity (R_6 stage) (Ritchie et al., 1993) in all STs. Following typical methods of production, ears were dried in the sun until 13% moisture was reached. Then, manual threshing was carried out for further evaluation of grain yield and grain quality.

Traits measured

The following phenotypic characteristics were evaluated:

a) PH (in m) was obtained by measuring the distance between the ground and the tassel insertion, in the V_T stage (Ritchie et al., 1993) for five randomly selected plants in each plot;

b) LAI was obtained from the measurement of length (L) and largest width (W) of all leaves of five randomly selected plants from each plot (Francis et al., 1969), at the V_T stage (Ritchie et al., 1993). Leaf area (LA) was subsequently calculated according to the equation LA = 0.75*L*W, then used to obtain the LAI from the equation LAI = LA/(e1*e2), in which e1 and e2 refer to the spacing in meters between plants and between rows, respectively;

c) EP was the ratio between the total number of ears and number of plants in the sampling area at each plot, counted at the R_6 stage (Ritchie et al., 1993);

d) TGW (in g) was obtained by means of a digital scale, with moisture corrected to 13% (Brasil, 2009). Moisture was measured with a digital meter (Dickey-John brand, GAC®500 XT model);

e) GY (in Mg ha^{-1}) was obtained by means of a digital scale, with moisture corrected to 13% (Brasil, 2009). Moisture was measured with a digital meter (Dickey-John brand, GAC®500 XT model), and the grain mass was expressed in kg per plot, data being extrapolated to one hectare;

f) PPE (in mL g^{-1}). Popcorn grains were popped, without the addition of vegetable oil, in an electric popcorn maker (Embrapa-CNPDIA model) at 280 °C for two minutes and ten seconds, under constant spinning. After this, the volume of formed popcorn was measured in a graduated cylinder (2,000 mL) (Roshdy et al., 1984; Metzger et al., 1989; Song et al., 1991). PPE values were obtained from the ratio of expanded popcorn volume and grain mass of 30 g of raw grains. Prior to expansion, the samples were cold-stored for 30 days to stabilize the water content between 11% and 13%.

Statistical analysis

Data from the evaluated phenotypic characteristics were subjected to a variance homogeneity test and an error normality test. Subsequently, individual variance analysis was performed (taking into consideration the level of 5% by F test) (Steel and Torrie, 1980). Statistical analysis was performed using the SAS computer program (Statistical Analysis System, version 9.2) and Sisvar (Computer Statistical Program Sisvar, version 5.3). All factors were considered fixed effects. Due to the different periods of sowing in each agricultural year, we chose to use the individual variance analysis, although variance analysis by Hartley's Maximum F test would also have been possible.

Conclusion

In conclusion, during spring/summer, both the growth and vegetative development of plants were limited by the delay in ST, being the first ST in each agricultural year (October 6th 2009 and October 4th 2010) (the ST representing the best phenotypic characteristics of popcorn in northwestern Parana, Brazil). Temperature was the environmental factor with the greatest influence on the phenology, growth and vegetative development of the popcorn plants. GY showed a daily decrease of 1.12% (46.8 kg ha^{-1} dia^{-1}) in the first ST in 2009/2010 and 1.18% (53.2 kg ha^{-1} dia^{-1}) in 2010/2011. The IAC-125 hybrid surpassed the IAC-112 hybrid and presented the best results for the phenotypic characteristics evaluated.

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