SEMINA
Ciências Agrárias

DOI: 10.5433/1679-0359.2022v43n2p809

Trinexapac-ethyl application time in the crop corn agronomic performance grown under different plant arrangements

Épocas de aplicação de Trinexapac-etil no desempenho agronômico do milho cultivado sob diferentes arranjos de plantas

Mariana Alves de Oliveira[1]*; Claudemir Zucareli[2]; André Prechlak Barbosa[3]; Leandro Teodoski Spolaor[4]; Lucas Henrique Fantin[5]; Luiz Henrique Pricinotto[6]; Carmen Silvia Vieira Janeiro Neves[7]

Highlights

Trinexapac-ethyl later applications reduce plant and ear height no affect yield.
Stem diameter in 0.45 m spacing increase with TE application at the V9 stage.
TE application at V9 for 0.45 and 0.90 m row spacings changes the plant architecture.
Trinexapac-ethyl later applicataions increase the number of kernels per ear.
Higher corn plant density with reduced row spacing may increase grain yield.

Abstract

Reduced row spacing promotes more uniform spatial distribution of plants in the field. However, the adoption of reduced row spacing only is possible with smaller plants, which may be obtained with the use of plant growth regulator. This study aimed to evaluate the agronomic performance of the first corn crop with Trinexapac-ethyl applied at the different plant development stages and grown under different row spacing, with the same plant population. The experiments were arranged in a split-plot randomized block design with four replications, with row spacing for the plots (0.45 and 0.90 m) and Trinexapac-ethyl (TE) application time

[1] PhD Professor, Universidade Paranaense, UNIPAR, Umuarama, PR, Brazil. E-mail: agromariana.oliveira@gmail.com
[2] PhD Professor, Department of Agronomy, Graduate Program in Agronomy, Universidade Estadual de Londrina, UEL, Londrina, PR, Brazil. E-mail: claudemircca@uel.br
[3] PhD Professor, Pontifícia Universidade Católica do Paraná, PUCPR, Toledo, PR, Brazil. E-mail: andreprechlak@gmail.com
[4] Doctoral Student, Graduate Program in Genetics and Breeding, Universidade Estadual de Maringá, UEM, Maringá, PR, Brazil. E-mail: leandrotspolaor@hotmail.com
[5] Researcher, Fundação Chapadão, Chapadão do Sul, MS, Brazil. E-mail: fantinagro@gmail.com
[6] PhD, Agronomist, Secretaria da Agricultura e Abastecimento, Departamento de Desenvolvimento Rural Sustentável, DEAGRO, Cianorte, PR, Brazil. E-mail: luizpricinotto@seab.pr.gov.br
[7] PhD, Senior Professor, Department of Agronomy, Graduate Program in Agronomy, UEL, Londrina, PR, Brazil. E-mail: csvjneve@uel.br
* Author for correspondence

Received: Mar. 25, 2021 - Approved: Dec. 16, 2021

to subplots (control without application, at the V3, V6, V9 and V12 phenological stages). The Trinexapac-ethyl application time interacted with row spacings changing the growth and yield performance of the corn crop. For 0.45 m spacing Trinexapac-ethyl application at V12 and for 0.90 m spacing application at V9 and V12 reduced plant height and ear height. Trinexapac-ethyl application at V9 for both row spacings changed the plant architecture without changing the ear length and grain yield.
Key words: Plant growth regulator. Row spacing. Yield. *Zea mays* L.

Resumo

A redução do espaçamento entre linhas promove distribuição espacial mais uniforme das plantas na lavoura. Entretanto, a adoção do espaçamento reduzido só é possível com cultivares de menor porte, o que pode ser obtido com o uso de regulador de crescimento. Objetivou-se avaliar o desempenho agronômico do milho de primeira safra, submetido à aplicação de Trinexapac-etil (TE) em diferentes estádios de desenvolvimento vegetativo e cultivado sob diferentes espaçamentos entre linhas, com mesma população de plantas. Utilizou-se o delineamento experimental de blocos casualizados com parcelas subdivididas, com quatro repetições. As parcelas receberam os dois espaçamentos entre linhas (0,45 e 0,90 m) e as subparcelas as cinco épocas de aplicação de TE (testemunha sem aplicação, V3, V6, V9 e V12). A época de aplicação de Trinexapac-etil interage com os espaçamentos entre linhas alterando o crescimento e o desempenho produtivo da cultura. Para o espaçamento 0,45 m a aplicação de Trinexapac-etil em V12 e para o 0,90 m a aplicação em V9 e V12 reduz a altura de planta e de inserção de espiga. A aplicação de Trinexapac-etil em V9 para ambos os espaçamentos modifica a arquitetura da planta sem alterar o comprimento da espiga e produtividade de grãos.
Palavras-chave: Espaçamento entre linhas. Produtividade. Regulador de crescimento. *Zea mays* L.

Introduction

Corn crop (Zea mays L.) is very important in the grain production system and crop rotation in Brazil. This crop has been accompanied by constant crop production technologies changes, with the adoption of improved cultivars, rigid sowing recommendations and changes in plant arrangement that have resulted in significant corn yield increases and grain production (Sangoi et al., 2019).

Manipulation of plant spatial distribution is one of the most important management practices to enhance production components and corn grain yield and optimize environmental resources (Argenta, Silva, & Sangoi, 2001; Takasu, Rodrigues, Goes, Arf, & Haga, 2014). These changes include reduced row spacing, keeping constant plant density that promotes more uniform spatial plant distribution in the field and reduces intraspecific plant competition for environmental resources, which favors the interception of incident sunlight that increases sunlight use efficiency (Brachtvogel, Pereira, Cruz, Abreu, & Bicudo, 2012; Boiago et al., 2017).

Reduction of the 0.90 m conventional row spacing to 0.45 m, called reduced spacing, associated with higher plant densities, has many advantages including greater spatial uniformity of the plants on the row; better weed control, because spaces are closed faster; efficient water use due to early shading and optimal use of the sower and fertilizer machines, because the same regulation can be used between the rows for the summer crops, corn and soybean (Fornasieri, 2007). There is a tendency for higher grain yields in smaller spacing, especially with super-early and short-stature corn cultivars (Farinelli, Penariol, & Fornasieri, 2012; Takasu et al., 2014; Fumagalli et al., 2017).

The choice of highly productive genotypes associated with changes in the plant arrangement and high doses of nitrogen fertilization applied in topdressing provide increased grain yield. However, these practices increase plant height and ear height, making plants more susceptible stem lodging and breaking (Lana, Rampim, Ohland, & Fávero, 2014). This fact hinders mechanical harvesting and results in productivity and quality losses in the harvested product.

When adopting these practices short cultivars are recommended, but these cultivars are not always available and adapted to the crop growth region, so that alternative techniques such as the use of plant growth regulators need to be adopted. Among the plant growth regulators, Trinexapac-ethyl reduces the cells of the internode elongation, which interfere at the end of gibberellic acid biosynthesis (Rademacher, 2015) and reduces plant growth (Mendes Fagherazzi et al., 2018).

The use of Trinexapac-ethyl (TE) has been effective with an accentuated reduction in stem length and prevention of oat stem lodging (Hawerroth et al., 2015), increased wheat grain yield (Zagonel & Fernandes, 2007). In corn the use of Trinexapac-ethyl and the answers vary due to weather conditions, cultivar, dose and time of application (Zagonel & Ferreira, 2013; Pricinotto et al., 2015; Leolato, Sangoi, Durli, Panison, & Voss, 2017; Mendes Fagherazzi et al., 2018).

Significative effects were reported by C. Ferreira, Zagonel, Senger and Souza (2014), the response of two corn hybrids with application of 250 g ae ha^{-1} Trinexapac-ethyl, they observed the vegetative growth and leaf area were decreased, the production components and corn grain yield were not affected. With a view to reducing the elongation of the corn plant internodes, the performance of the plant growth regulator needs to be verified during the vegetative growth stages in corn, with application at different times.

For corn, the use of Trinexapac-ethyl is an alternative for cultivars of interest that do not have modern leaf architecture, which can change the plant size and anatomy, allowing reduction in row spacing. Thus, the present study aimed to evaluate the agronomic performance of the first corn crop with Trinexapac-ethyl applications at the different plant development stages and grown under different row spacing, with the same plant population.

Material and Methods

The study was conducted in the first corn crop in two crop years in 2012/2013 and 2013/2014 at the State University of Londrina, in Londrina, Paraná State, Brazil. Sowing was performed on October 9, 2012 and November 1, 2013 under the no till system and wheat was the previous crop. Climate data observed during the study period were obtained from a weather station at the Agronomic Institute of Paraná (IAPAR) in Londrina, Paraná State (Figure 1).

The experiments were installed in soil characterized as Dystrophic Red Latosol (Oxisol) (Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2006). Soil samples were collected at 0-20 cm in the experimental area for chemical analysis according to the methodology of Raij, Andrade, Cantarella and Quaggio (2001). The sowing fertilization (N-P-K) was performed according to the results of the soil chemical analysis (Table 1) and based on recommendations for the region (Instituto Agronômico do Paraná [IAPAR], 2003). Sowing fertilizer for the 2012/2013 experiment was 325 kg ha^{-1} formula (N-P-K) 08-20-10 and for the 2013/2014 experiment, it was 312 kg·ha^{-1} formula (N-P-K) 08-28-16.

The simple hybrid Status Viptera was used indicated for the first and second crop in the South, Southeast and Midwest Brazil. The cultivar was chosen based on the results of Pricinotto et al. (2015) who obtained a positive response to Trinexapac-ethyl applied to the cultivar Status, with TL technology (resistant to Lepidoptera).

The experiments were arranged in a split-plot randomized block design with four replications, with row spacing for the plots (0.45 and 0.90 m), and Trinexapac-ethyl (TE) application time for subplots (control without application, at the V3, V6, V9 and V12 phenological stages). The plots consisted of six 5.0 m long rows for the 0.45 m row spacing and for the 0.90 m row spacing they consisted of four 5.0 m long rows of 5.0 length. The working area consisted of four central rows (row spacing 0.45 m) and two central rows (row spacing 0.90 m) eliminating 0.5 m at the ends. The Trinexapac-ethyl was applied at times based on the plant phenological stages (Ritchie, Hanway, Benson, & Herman, 1993). Sowing was done mechanically in the proposed spacings and thinning was carried out at the V3 stage based on Ritchie et al. (1993) with a plant density of 80.000 plants ha^{-1}. Nitrogen fertilization in topdressing was carried out in both years when the plants were with six leaves, at the V6 stage, 32 days after sowing and 157,5 kg ha^{-1} N of urea (45% N) were applied to all treatments. The plant growth regulator was applied to the leaves using a pressurized backpack sprayer (CO_2) under pressure and spray volume of 150L ha^{-1} and adding 1L ha^{-1} (250 g ae ha^{-1} Trinexapac-ethyl Moddus®), based on Pricinotto et al. (2015). These applications were made according to the treatments according to the number of expanded true leaves following the plant phenological stages (Ritchie et al., 1993) and the control treatment that consisted only of water. During the crop development the experimental area was monitored for pests, diseases and weeds. The harvest was performed manually at the R6 stage, when the grains had an average water content of 200 g kg^{-1} grain water, in the working area of the plot.

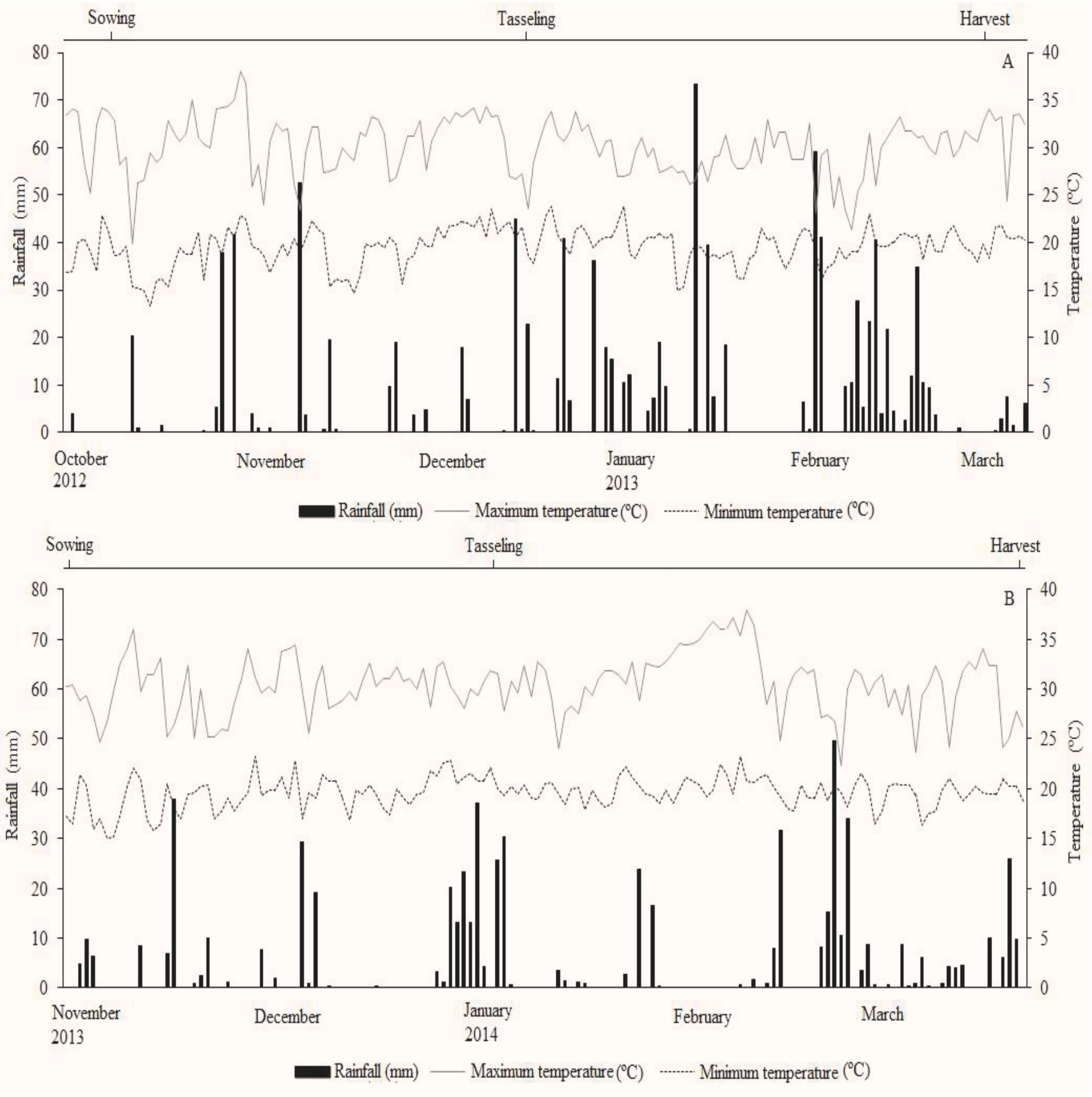

Figure 1. Daily data of maximum and minimum temperature and rainfall during the experimental period, A 2012/2013 and B 2013/2014.

Table 1
Soil chemical properties (0 – 20 cm) before installing the experiments in 2012/2013 and 2013/2014

Year	pH	H+Al	Ca^{2+}	Mg^{2+}	K^{+}	BS	CEC	V	P
	$CaCl_2$	----------------------cmolc dm^{-3}--------------------						%	mg dm^{-3}
2012/2013	5.26	3.37	4.28	1.05	0.30	5.63	9.00	62.50	9.08
2013/2014	5.18	4.11	3.97	0.96	0.25	5.18	9.29	55.70	9.54

Extractors: Ca, Mg, Al: KCl 1mol L^{-1}; P, K: $Mehlich^{-1}$; H+Al: SMP method BS: Basis saturation CEC: cationic exchangeable capacity.

Biometric indices, production components and grain yield were evaluated. The biometric indices were determined in ten random plants from the working area of each plot at corn tasseling and the following biometric indexes were evaluated: Plant height: taking the distance between the ground to the insertion of the flag leaf; ear height: distance between the ground to the corn first ear both in m; stem diameter: taken at the second internode above the ground, in cm. Leaf area index (LAI): evaluated at full crop flowering, expressed in m^2 leaf per m^2 soil surface, based on the measurement of the total length (L) and width of the middle third (W) of six actively photosynthetic leaves of six plants, totaling 36 leaves sampled in the useful area of each plot. The data were submitted to the following formula proposed by Francis, Rutger and Palmer (1969): $LAI = \frac{(0{,}75 * L * W)}{(s1 * s2)}$, where s1 refers to plant spacing in the row and s2 refers to row spacing, both in meters. The leaf area per plant and then the total leaf area index per plant were obtained and presented as the average of the plants evaluated per plot.

To evaluate the production components, ten ears were harvested from the working area of each plot and the following were determined: Number of kernels per corn ear; corn ear length of corn, in cm, and 100-kernel weight in g. Grain yield was obtained by threshing and weighing the grain harvested in the working area of the plot. Data were processed in kg ha^{-1} and correct to the average water content of 130 g kg^{-1} grain water (13%).

Individual analysis of variance was run to estimate the residuals with homogeneous variances and normal errors. Significant interactions between factors were unfolded. The qualitative factors were subjected to the comparison of means by the Tukey test ($p < 0.05$). Data were analyzed with the aid of the Sisvar software (D. F. Ferreira, 2010).

Results and Discussion

In the 2012/2013 crop year there was significant interaction between the factors row spacing and TE application time for plant height and ear height, stem diameter and leaf area index (Table 2). In the 2013/2014 crop year the plant height was affected by the TE application time and the ear height by row spacing and TE application time. There was no significant interaction between these factors for either variable (Table 2).

Table 3 shows the (decomposition) partitioning of interaction between row spacing and TE application time for the biometric indices evaluated in the 2012/2013 crop year. In the 0.45 m row spacing TE application at the V12 stage and in the 0.90 m row spacing e application at V9 and V12 reduced plant height, compared to the control treatment. The plant height was lower in the 0.45 m spacing than in the 0.90 m spacing when TE was applied at the V3 and V12 stages and to the control treatment. The TE application at V9 in the 0.90 m spacing resulted in lower plant height. The bigger plant height in the 0.90 m spacing may have been due to the plant concentration in the row increasing intraspecific competition for sunlight, promoting etiolation. When TE was applied at V6 there was no plant height difference between the evaluated spacings.

Table 2
Summary of analysis of variance for plant height (PH), ear height (EH), stem diameter (SD) and leaf area index (LAI), a function of row spacing and Trinexapac-ethyl application times in the first corn crop

Causes of variation		2012/2013				2013/2014	
		Biometric indices					
		PH (m)	EH (m)	SD (cm)	LAI	PH (m)	EH (m)
Row spacing							
0.45		1.95	1.25	2.03	3.29	1.90	1.13 b
0.90		1.98	1.24	2.02	3.28	2.01	1.21 a
TE application time							
Control treatment		2.05	1.27	2.04	3.10	2.01 ab	1.23 a
V3		2.03	1.27	1.96	3.16	2.09 a	1.24 a
V6		2.04	1.26	2.05	3.31	1.95 b	1.10 b
V9		1.96	1.25	2.03	3.37	1.72 c	1.03 b
V12		1.74	1.18	2.03	3.50	2.00 ab	1.24 a
	DF	Mean square					
Block	3	0.0003	0.0001	0.0034	0.0095	0.0146	0.0128
Row spacing	1	0.0104*	0.0006^{ns}	0.0007^{ns}	0.0005^{ns}	0.1113^{ns}	0.0672*
Error 1	3	0.0001	0.0001	0.0006	0.0020	0.0240	0.0064
TE application time	4	0.1371*	0.0113*	0.0097*	0.2122*	0.1503*	0.0769*
TE x Row spacing	4	0.0096*	0.0019*	0.0107*	0.1124*	0.0076^{ns}	0.0008^{ns}
Error 2	24	0.0008	0.0005	0.0012	0.0022	0.0067	0.0031
CV 1 (%)		0.58	1.09	1.21	1.38	7.96	6.87
CV 2 (%)		1.47	1.90	1.77	1.45	4.19	4.83

ns = non-significant by the F test; * significant at p < 0.05 probability error by the F test. Average data followed by different letters in columns are significantly different according to the Tukey test (p < 0.05). Cv: coefficient of variation, DF: degrees of freedom.

Mendes Fagherazzi et al. (2018) analyzed the sequential applications of Trinexapac-ethyl in different phenological stages for two corn varieties grew in a greenhouse. The sequential applications of 100 g ae ha^{-1} TE among stages V2 to V7 were effective at reducing plant height in both corn genotypes by 45% of final height, it indicating that there is a greater response to TE from stage V6 onwards.

However, Zagonel and Ferreira (2013) evaluated the same hybrid Status in the first corn crop, using TL technology (resistance to lepidopterous) and Maximus TLTG, found no change in plant height with the use of TE at doses 0; 187.5; 375.0 and 562.5 g ae ha^{-1} regardless of the application time at the V2, V4, V6 and V8 stages. The discrepant results between these studies may be linked to the genotype, environment and crop management interaction and to differences in the TE application times studied. The disagreement of results between the studies is possibly associated with the interaction between genotype, environment and management of the culture, as well as with the differences in the periods of application of TE and doses studied.

Among the TE application time in the present study, the later applications caused a greater response to reduction in plant height, as in the wheat crop in which the TE acts in the internodes that form later, being the longest, as observed by Zagonel and Fernandes (2007). The results of the present study suggest that the action of ET in early applications may be lost, due to the plant's ability to recover vegetative development, especially for corn crops that have a vegetative cycle that is generally longer than other cereals.

Performance similar to the plant height was found for ear height in the 0.45 and 0.90 m spacings and was lower when TE was applied at the V12 stage. In V6, TE application resulted in smaller ear height for the 0.90 m compared to the 0.45 m spacing but in the other application times there was no difference between the row spacings. The plant height and ear height were highly correlated, as observed when TE was applied late and reduced both variables.

Corroborating the results obtained, Pricinotto et al. (2015) studied the same cultivar and obtained lower ear height in corn plants grown in a greenhouse with increased Trinexapac-ethyl doses (0; 125; 250 and 375 g·ae·ha^{-1}) applied at the V6 stage. Mendes Fagherazzi et al. (2018) also reported the highest reductions in plant ear insertion in both years of evaluation of corn plants submitted to sequential application of TE at V2 to V7 accumulating 600 g ae ha^{-1}.

In the 2013/2014 crop year, TE application at the V9 stage showed greater plant height reduction compared to the other treatments (Table 2). The ear height was lower in the 0.45 m compared to the 0.90 m spacing and TE application at the V6 and V9 stages also reduced the ear height in relation to the other treatments. As observed, the plants submitted to the regulator at the V6 and V9 stages had a significant reduction in cell division and elongation during the period considered as a large increase in stem elongation, (Ritchie et al., 1993), resulting in smaller plants and lower ear height. The lower ear height in the 0.45 m spacing, that was probably due to less between plant competition for environmental resources, especially sunlight in the early development until the ear knot elongation, provided the best plant arrangement, since there was no change in plant density. According Sangoi, Ender, Guidolin, Almeida and Heberle (2001) lower plant height and ear insertion height results in plants nearer the ground which reduces the crop pre-disposition to lodging and stem breakage, in addition it may improve the plants ability to intercept solar radiation, which can provide greater grain yield.

Stem diameter in 0.45 m spacing increased with the use of TE at the V9 stage and decreased with application at V3 compared to the other application times. In the 0.90 m spacing, TE applied at the V3 and V9 stage reduced the stem diameter compared to the control treatment. There was a significant difference in the stem diameter between the spacings only for TE application at V9. The stem diameter in the 0.90 m spacing was smaller than the 0.45 m (Table 3). Competition for sunlight by plants in the 0.90 m spacing expressed intense stem elongation directing assimilates for vertical growth with less thickness development (Sangoi, Almeida, Silva, & Argenta, 2002). Pricinotto et al. (2015) observed increases in stem diameter with proportional additions of Trinexapac-ethyl doses (0; 125; 250 and 375 g·ae·ha-1) to the Status Viptera cultivar. Zagonel and Ferreira (2013) did not observe stem diameter response for the TE application time for the hybrids Status TL and Maximus TLTG, but for Status TL they observed that for lower doses there was decrease in stem diameter, but that stem diameter then increased with increasing doses. Similarly, Durli (2016) verified different performance of stem diameter for two corn hybrids with Trinexapac-ethyl application.

Increased stem diameter can be favorable when the internode length is reduced, because the stem acts as a soluble solids storage structure for use in grain formation, because the when the diameter is smaller, apparently this ability is less to store assimilates to be translocated to grains (Dourado Neto, Fanceli, & Lopes, 2001). Internodes shortening combined with higher density stem tissuepromotes greater stiffness, reducing the potential for lodging, with increased external stem diameter as observed in the wheat crop by Zagonel, Venancio and Kunz (2002).

Table 3
(Decomposition) Partitioning of interaction for average plant height (PH), ear height (EH), stem diameter (SD) and leaf area index (LAI) in function of row spacing and Trinexapac-ethyl application times in the first corn crop

TE	PH (m)		EH (m)		SD (cm)		LAI (cm^2)	
	Row spacing							
	0.45	0.90	0.45	0.90	0.45	0.90	0.45	0.90
Control	2.01 Bb	2.09 Aa	1.27 ABa	1.26 Aa	2.02 Ba	2.07 Aa	3.17 Aa	3.02 Db
V3	1.97 Bb	2.09 Aa	1.27 ABa	1.27 Aa	1.96 Ca	1.97 Ba	3.16 Ba	3.16 Ca
V6	2.05 Aa	2.03 Ba	1.29 Aa	1.23 Bb	2.04 Ba	2.05 Aa	3.12 Bb	3.50 Aa
V9	1.99 Ba	1.94 Cb	1.24 Ca	1.25 ABa	2.10 Aa	1.97 Bb	3.49 Aa	3.25 Bb
V12	1.72 Cb	1.75 Da	1.17 Da	1.19 Ca	2.01 Ba	2.05 Aa	3.52 Aa	3.49 Aa

Average data followed by the same capital letters in the column for TE application time effect and lower letters on the line for row spacing effect are not significantly different according to the Tukey test ($p < 0.05$).

Ritchie et al. (1993) affirm that from 30 days after emergence to flowering the corn stem goes through a period of great growth and elongation, with large dry matter great accumulation. From that moment there will be no further cellular differentiation, but only growth and multiplication of the number of cells in the plant. Thus, applying Trinexapac-ethyl during the vegetative growth period tends to reduce the size of the plant with different responses for different application times during vegetative growth, which influences the definition of biometric indices, as observed in this study. Trinexapac-ethyl reduces the internode elongation cells due to the reduction of the active gibberellic acid level (Rademacher, 2015), and reduces plant growth.

This study has shown promising results for Trinexapac-ethyl application to decrease plant and ear height of corn plants with increase stem diameter, in order to reduce the occurrence of plant lodging and stem breakage on the field. It shows the possibility to use the TE as a tool with reduced row spaces, keeping constant plant density that promotes more uniform spatial plant distribution in the field; consequently, it reduces intraspecific plant competition for environmental resources, which improves the interception and efficiency of incident sunlight (Brachtvogel et al., 2012; Boiago et al., 2017).

The leaf area index in the 0.45 m spacing was reduced with TE application at the V3 and V6 stages. In the 0.90 m spacing the control treatment showed lower LAI, but application at the V6 and V12 stages increased the LAI. The absence of TE provided greater LAI for the of 0.45 m spacing. Trinexapac-ethyl application at the V6 stage reduced the LAI in the 0.45 m spacing in relation to the 0.90 m spacing, and application at V9 reduced the LAI in the 0.90 m spacing compared to the 0.45 m spacing. For the application at the V3 and V12 stages there was no significant difference between the row spacings in the study. According Espindula et al. (2009) for the wheat crop, obtaining more compact and less decumbent plants prevents self-shadowing and increases photosynthesis by capturing sunlight. In the present study, the leaf area reduction caused by applying Trinexapac-ethyl in the 0.45 m spacing allowed better use of environmental resources with less competition among plants for sunlight. It also allows increases in plant density and increased nitrogen levels, depending on the genotype, the production system and the time of crop implantation in order to optimize the environmental resources with possible increase in quality and yield.

The effects of TE applied at V9 along with the intraspecific competition present in cropping in 0.90 m spacing may have influenced the vegetative development of the corn crop reducing plant height (reducing the crop pre-disposition to lodging), stem diameter and LAI (reducing self-shadowing and favoring sunlight interception). While reduction in row spacing, for example to 0.45 m, maintaining constant plant density, promotes the increase in the between-plant distance in the row, providing more uniform plant spatial distribution in the area that favors the use of sunlight, water and nutrients (Brachtvogel et al., 2012).

In the 2012/2013 crop year the number of kernels per ear, ear length and grain yield were affected by the interaction between the factors row spacing and TE application times. For the variable 100-kernel weight, significance effect was found for the row spacing and TE application times. In the 2013/2014 crop year, there was a significant change in the number of kernels per ear and ear length in function of TE application times. The 100-kernel weight and grain yield were not affected by factors in this study (Table 4).

Table 4
(Decomposition) Partitioning of interaction for average plant height (PH), ear height (EH), stem diameter (SD) and leaf area index (LAI) in function of row spacing and Trinexapac-ethyl application times in the first corn crop

CV[1]		2012/2013				2013/2014			
		Production components							
		NKE	EL (cm)	100KW (g)	GY (kg ha^{-1})	NKE	EL (cm)	100KW (g)	GY (kg ha^{-1})
RS									
0.45		520.16	16.78	32.51b	9,586.62	525.73	16.36	26.24	5,345.32
0.90		529.84	17.45	33.99a	8,942.82	515.14	15.84	24.29	4,698.05
TE									
Control		529.97	17.16	34.12a	9,115.21	581.53a	17.20 a	23.86	5,385.40
V3		524.31	16.76	32.62bc	9,842.35	555.42a	17.00 a	24.39	5,379.94
V6		514.73	17.06	33.22ab	9,376.94	481.92ab	15.99a	26.65	4,993.70
V9		524.38	17.57	32.14 c	9,743.10	429.46b	13.55b	27.09	4,165.29
V12		531.59	17.03	34.15 a	8,245.99	553.82a	16.76 a	24.33	5,184.07
V[1]	DF	Mean square							
Block	3	84.26	0.1204	0.3166	168838.24	3207.13	1.872	24.599	1161662.1
RS	1	936.79^{ns}	4.4242*	21.9543*	4144778.60*	1121.69^{ns}	2.621^{ns}	38.064^{ns}	4189571.5^{ns}
Error 1	3	311.68	0.0501	0.1509	195229.54	6030.03	0.376	11.838	1930449.1
TE	4	348.71*	0.6942*	6.3919*	3270521.42*	31661.25*	17.890*	17.773^{ns}	20424063^{ns}
TE x RS	4	2565.78*	0.7760*	0.5063^{ns}	4218336.37*	884.400^{ns}	0.412^{ns}	3.108^{ns}	1454936.7^{ns}
Error 2	24	91.34	0.0297	0.3963	101427.16	6821.27	2.447	5.174	1391698.2
CV 1 (%)		3.36	1.31	1.17	4.77	14.92	3.81	13.62	27.67
CV 2 (%)		1.82	1.01	1.89	3.44	15.87	9.72	9.00	23.49

ns = non-significant by the F test; * significant at $p < 0.05$ probability error by the F test. Average data followed by different letters in the columns are significantly different according to the Tukey test ($p < 0.05$). Cv: coefficient of variation, CV1: causes of variation, DF: degrees of freedom.

The 100-kernel weight in the 2012/2013 crop year shows significant effect for the isolated factors row spacing and Trinexapac-ethyl application times. There was bigger 100-kernel weight in the conventional 0.90 m spacing, but Torres et al. (2013) and Nascimento et al. (2012) found no significant differences for this variable in the same spacings evaluated, as also observed in the 2013/2014 crop year for the present study. However, in the 2012/2013 crop year the ET application at the V3 and V9 stages reduced the 100-kernel weight. Zagonel and Ferreira (2013) found no statistically significant effect for 1000-kernel weight by applying Trinexapac-ethyl at the V2, V4, V6, and V8 stages to the hybrids Status TL and Maximus TLTG. However, Pricinotto et al. (2015) observed a reduction of 100-kernel weight in the Status Viptera cultivar, when increased Trinexapac-ethyl doses were applied at the V6 stage. Leolato et al. (2017) described which application of Trinexapac-ethyl reduced 1,000 grains dry mass of maize hybrid P30F53YH, regardless of plant density and sowing date.

The decomposition of the interaction between the factors studied for the variables number of kernel per ear, ear length and grain yield are shown in Table 5. Analysis of the effect of TE application times shows that the 0.45 m spacing with a presence of TE reduced the number of kernels per ear compared to the control treatment. In the 0.90 m spacing, TE applied at the V9 and V12 stages favored increasing the number of kernels per ear relation to the control treatment. Observing the effect of row spacing, in the absence of TE there were increases in the number of kernels per ear in the 0.45 m spacing in relation to the 0.90 m spacing. At the V6 and V9 stages the 0.90 m spacing favored this variable. For the other times there was no significant difference between the row spacings. Similar performance was observed in the wheat crop, where the application of 125 g ea ha^{-1} Trinexapac-ethyl resulted in an increase in kernels per ear (Zagonel et al., 2002). However, Zagonel and Ferreira (2013) found no change in the number of rows per ear and kernels per row that composes the number of kernels per ear when TE was applied at the V2, V4, V6 and V8 stages.

Table 5

Decomposition of interaction for the average of number of kernels per ear (NKE), ear length (EL) and grain yield (GY) for the 2012/2013 year crop in function of row spacing and Trinexapac-ethyl application times in the first corn crop

TE	NKE		EL (cm)		GY (kg ha^{-1})	
	Row spacing					
	0,45	0,9	0,45	0,9	0.45	0.90
Control	553.83 Aa	506.11 Bb	16.8 Bb	17.5 BCa	9839.82 Ba	8390.60 Cb
V3	521.41 Ba	527.22 ABa	16.5 Bb	17.0 Da	9049.93 Cb	10634.77 Aa
V6	502.96 Bb	526.51 ABa	16.9 Bb	17.2 CDa	10492.99 Ab	8260.88 Ca
V9	499.72 Bb	540.30 Aa	17.5 Aa	17.6 ABa	9835.06 Ba	9651.14 Ba
V12	522.87 Ba	549.03 Aa	16.2 Cb	17.9 Aa	8715.29 Ca	7776.69 Cb

Average data followed by the same capital letters in the column for TE application time effect and lower letters in the line for row spacing effect are not significantly different according to the Tukey test ($p < 0.05$).

The increase in kernels per ear with TE application at the V6 and V9 stages coincides with the phase, which starts the definition of the number of rows per ear (Ritchie et al., 1993). However, this improvement in the production of components by the growth regulator has not been elucidated for the corn crop, so that the growth regulator can show, or not, increments for these components depending on the application time, influenced by genotype, crop management and weather conditions, as noted for the wheat crop by Zagonel et al. (2002). In the 2013/2014 crop year the number of kernels per ear was lower when Trinexapac-ethyl was applied at the V9 stage in relation to the control treatment and application at the V3 and V12 stages (Table 4).

The increase in the number of kernels per ear for the 0.45 m spacing in relation to the 0.90 m spacing in the absence of the regulator is explained by Sangoi, Ender and Guidolin (2000), because in the reduced spacing the plants are spaced equidistant and are minimally competive for nutrients, sunlight and other factors, favoring better ear development. According to Andrade, Calviño, Cirilo and Barbieri (2002), corn response to reduced row spacing is related to the incident radiation at the time of flowering, which is the critical period in determining the number of fertilized kernels and grain mass, which will determine assimilate translocation to the ears and increases in yield.

Increase in ear length was obtained in the 0.45 m spacing when TE was applied at the V9 and V12 stages and reduction with application at V12. Ear length increased in the 0.90 m spacing when TE was applied at the V9 and V12 stages and reduction with application at the V3 stage. In the control treatments, the V3, V6 and V12 stages in the 0.90 m spacing resulted in increased ear length. When TE was applied at V9 there was no significant difference for the row spacings studied. Divergent results for the same cultivar under study were observed by Pricinotto et al. (2015) who reported 1.10 cm reduction in ear length with the application of 375 g ae ha^{-1} applied at V6. In the 2013/2014 crop year, the result was different from the 2012/2013 crop year when the use of TE at the V9 stage reduced ear length. According to Ritchie et al. (1993) during the female inflorescence development in at the V10 stage the definition begins of the number of kernels and the size of the ear that continues until V17 , and external factors have more influence on the V12 stage in determining the ear length. These changes occurred in the phases of determining the productive potential of the ear with Trinexapac-ethyl applications.

Grain yield at the 0.45 m spacing was higher when TE was applied at the V6 stage, and less when TE was applied at the V3 and V12 stages and in the 0.90 m spacing the grain yield was greater when TE was applied at the V3 for the 2012/2013 crop year. For row spacing effect, the grain yield was higher in the control treatments and TE application at V12 in the 0.45 m spacing than in the 0.90 m spacing, while application at the V3 and V6 stages in the 0.90 m spacing resulted in higher yield. Application at V9 resulted in no difference between the row spacings studied, as also observed for ear length.

Zagonel and Fernandes (2007) observed increases in yield of wheat grown with the use of TE and these increases are directly linked to the morphological changes caused by the plant growth regulator. During the 2012/2013 crop year there were favorable weather conditions for the establishment, growth and flowering and grain swelling for the crop, with a well distributed total rainfall of 984 mm (Figure 1A), favoring the grain productive performance an average minimum yield of 8245.99 kg ha^{-1} was obtained while the maximum reached 9743.10 kg ha^{-1}.

In the 2013/2014 crop year grain yield was not affected by the factors studied. Considering that TE application reduced plant height and ear insertion without affecting grain yield, productivity gains can be achieved with increased plant density, especially using reduced spacing, aiming to increase area productivity. The hybrid response difference in the two seasons possibly occurred due to interactions between the factors studied with meteorological elements during cultivation. It is probable that the low rainfall (53.4 mm) that occurred after the crop flowering from 01/07 until 02/13/2014 (Figure 1B), comprising the reproductive stages of R2 to R4, reduced the 100-kernel weight and the yield grain in relation to the 2012/2013 year crop. It is understood that both rainfall volume and distribution during cultivation is a limiting factor for the maximum expression of the hybrid potential.

Radin, Bergamaschi, Santos, Bergonci and França (2003) estimate that the demand for water by the corn crop during stages R2 to R4 is approximately 120 mm, with a record in this 20-day interval of only 43.2 mm. The period of low water availability coincided with the grain filling stage R3 (milky grains) in which there is intense expansion and cell filling due to sugar translocation from stalk to grain, with fast dry matter accumulation defining the grain density. This is followed by the R4 stage (dough) approximately 28 days after flowering with continuous starch accumulation; low water availability during this phase leads to the formation of light, small grains as found in the 2013/2014 crop year (Ritchie et al., 1993), and is the hybrid response to row spacing and growth regulator. In view of these limitations, the minimum average yield of 4165.29 kg ha^{-1} and average maximum of 5379.94 kg ha^{-1} were obtained.

The results presented in this study demonstrate the potential for the use of growth regulators corn, TE may be a management tool for cultivars of interest that do not have modern architecture to obtain more compact plants with a better architecture to take advantage of environmental resources, especially solar radiation. Changing the plant size and leaf anatomy can reduce productivity per plant, but plant compaction allows interaction with other management factors such as reduced row spacing, the adoption of high plant populations s and nitrogen fertilizer levels, that favor grain yield per area.

However, the variable response obtained in this study for first corn crop suggest new studies for further clarification of Trinexapac-ethyl action in corn for both the reduction and increase in production components, and for understanding of the physiological aspects of assimilate partition, as expressed by the harvest index that is the grain yield matter in relation to the total plant matter.

Conclusion

The Trinexapac-ethyl application time interacts with row spacings changing the growth and yield performance of the corn crop.

For the 0.45 m spacing the Trinexapac-ethyl application at V12 and in the 0.90 m spacing TE application at V9 and V12 reduced plant height and ear height.

Trinexapac-ethyl application at V9 for both row spacings altered plant architecture without changing the ear length and grain yield.

Acknowledgements

The authors offer their heartfelt thanks to CAPES (Coordination of Superior Level Staff Improvement) for the financial resources to the author and to the Graduate Program in Agronomy at the State University of Londrina for the resources provided and all support.

References

Andrade, F. H., Calviño, P., Cirilo, A., & Barbieri, P. (2002). Yield responses to narrow rows depend on increased radiation interception. *Agronomy Journal, 94*(5), 975-980. doi: 10.2134/agronj2002.0975

Argenta, G., Silva, P. R. F., & Sangoi, L. (2001). Arranjo de plantas em milho: análise do estado da arte. *Ciência Rural, 31*(6), 1075-1084. doi: 10.1590/S0103-84782001000600027

Boiago, R. G. F. S. R., Mateus, R. P. G., Schuelter, A. R., Barreto, R. R., Silva, G. J., & Schuster, I. (2017). Combinação de espaçamento entrelinhas e densidade populacional no aumento da produtividade em milho. *Revista Brasileira de Milho e Sorgo, 16*(3), 440-448. doi: 10.18512/1980-6477/rbms.v16n3p440-448

Brachtvogel, E. L., Pereira, F. R. S., Cruz, S. C. S., Abreu, M. L., & Bicudo, S. J. (2012). População, arranjo de plantas uniforme e a competição intraespecífica em milho. *Revista Trópica Ciências Agrárias e Biológicas, 6*(1), 75-83. doi: 10.1590/s0100-83582018360100012

Dourado, D., Neto, Fancelli, A. L., & Lopes, P. P. (2001). Milho: população e distribuição de plantas. In A. L. Fancelli, & D. Dourado Neto, (Eds.), *Milho: tecnologia e produtividade* (pp. 120-125). Piracicaba, SP: ESALQ/USP.

Durli, M. M. (2016). *Uso do regulador de crescimento etil trinexapac como alternativa para aumentar a resposta do milho à adubação nitrogenada em cobertura.* Dissertação de Mestrado, Universidade Estadual de Santa Catarina, Lages, SC, Brasil.

Empresa Brasileira de Pesquisa Agropecuária (2006). *Sistema brasileiro de classificação de solos* (2a ed.). Rio de Janeiro, RJ: EMBRAPA Solos.

Espindula, M. C., Rocha, V. S., Grossi, J. A. S., Souza, M. A., Souza, L. T., & Favarato, L. F. (2009). Use of growth retardants in wheat. *Planta Daninha, 27*(2), 379-387. doi: 10.1590/S0100-83582009000200022

Farinelli, R., Penariol, F. G., & Fornasieri, D., Fº. (2012). Características agronômicas e produtividade de cultivares de milho em diferentes espaçamentos entre linhas e densidades populacionais. *Científica, 40*(1), 21-27. doi: 10.15361/1984-5529.2012v40n1p21+-+27

Ferreira, C., Zagonel, J., Senger, M., & Souza, A. C. de. (2014). Dessecação em pré-semeadura e modos de aplicação de herbicidas em pós-emergência combinados ou não a regulador de crescimento em híbridos de milho. *Revista Eixo, 3*(1), 39-46. doi: 10.19123/eixo.v3i1.119

Ferreira, D. F. (2010). *SISVAR: Sistema de análise de variância.* Versão 5.3. Lavras, MG: UFLA.

Fornasieri, D., Fº. (2007). *Manual da cultura do milho.* São Paulo, SP: FUNEP.

Francis, C. A., Rutger, J. N., & Palmer, A. F. E. A. (1969). Rapid method for plant leaf area estimation in maize (*Zea mays* L.). *Crop Science, 9*(5), 537-539. doi: 10.2135/cropsci1969.0011183X000900050005x

Fumagalli, M., Machado, R. A. F., Fiorini, I. V. A., Pereira, C. S., Pires, L. P. M., & Pereira, H. D. (2017). Desempenho produtivo do milho híbrido simples em função de espaçamentos entre fileiras e populações de plantas. *Revista Brasileira de Milho e Sorgo, 16*(3), 426-439. doi: 10.18512/1980-6477/rbms.v16n3p426-439

Hawerroth, M. C., Silva, J. A. G. da, Souza, C. A., Oliveira, A. C. de, Souza Luche, H. de, Zimmer, C. M.,... Sponchiado, J. C. (2015). Redução do acamamento em aveia-branca com uso de regulador de crescimento etil-trinexapac. *Pesquisa Agropecuária Brasileira, 50*(20), 115-125. doi: 10.1590/S0100-204X2015000200003

Instituto Agronômico do Paraná (2003). *Sugestão de adubação e calagem para culturas de interesse econômico no Estado do Paraná.* (Circular Técnica, 128). Londrina, PR: IAPAR.

Lana, M. C., Rampim, L., Ohland, T., & Fávero, F. (2014). Spacing, population density and nitrogen fertilization in corn grown in an Oxisoil. *Revista Ceres, 61*(3), 424-433. doi: 10.1590/S0034-737X2014000300018

Leolato, L. S., Sangoi, L., Durli, M. M., Panison, F., & Voss, R. (2017). Growth regulator and maize response to the increase in plant density. *Pesquisa Agropecuária Brasileira, 52*(11), 997-1005. doi: 10.1590/S0100-204X2017001100005

Mendes Fagherazzi, M., Souza, C. A., Stefen, D. L. V., Zanesco, P. R., Junkes, G. V., Coelho, C. M. M., & Sangoi, L. (2018). Phenological sensitivity of two maize cultivars to Trinexapac-ethyl. *Planta Daninha, 6*(1), 1-10. doi: 10.1590/s0100-83582018360100012

Nascimento, E. S., Gilo, E. G., Torres, F. E., Silva, C. A., Jr., Oliveira, L. V. A. E., & Lourenção, A. S. (2012). Resposta de híbridos de milho a diferentes espaçamentos entre linhas. *Nucleus, 9*(2), 131-140. doi: 10.3738/nucleus.v9i2.726

Pricinotto, L. F., Zucareli, C., Fonseca, I. C. B., Oliveira, M. A., Ferreira, A. S., & Spolaor, L. T. (2015). Trinexapac-etil in the vegetative and reproductive performance of corn. *African Journal of Agricultural Research, 10*(14), 1735-1742. doi: 10.5897/AJAR2014.8613

Rademacher, W. (2015). Plant growth regulators: backgrounds and uses in plant production. *Journal of Plant Growth Regulators, 34*(1), 845-872. doi: 10.1007/s00344-015-9541-6

Radin, B., Bergamaschi, H., Santos, A. O., Bergonci, J. I., & França, S. (2003). Evapotranspiração da cultura do milho em função da demanda evaporativa atmosférica e do crescimento das plantas. *Pesquisa Agropecuária Gaúcha, 9*(2), 7-16. doi: 10.1007/s00344-015-9541-6

Raij, B. V., Andrade, J. C., Cantarella, H., & Quaggio, J. A. (2001). *Análise química para avaliação da fertilidade de solos tropicais.* Campinas, SP: Instituto Agronômico de Campinas.

Ritchie, S. W., Hanway, J. J., Benson, G. O., & Herman, J. C. (1993). *How a corn plant develops.* Iowa, USA: Iowa State University of Science and Technology, Cooperative Extension Service.

Sangoi, L., Almeida, M. L., Silva, P. R. F., & Argenta, G. (2002). Bases morfológicas para maior tolerância dos híbridos modernos de milho a altas densidades de plantas. *Bragantia, 61*(2), 101-110. doi: 10.1590/S0006-87052002000200003

Sangoi, L., Ender, M., & Guidolin, A. F. (2000). Incremento da densidade de plantas, uma alternativa para aumentar o rendimento de grãos de milho em regiões de curta estação de crescimento. *Ciência Rural, 30*(1), 23-29. doi: 10.1590/S0103-84782000000100004

Sangoi, L., Ender, M., Guidolin, A. F., Almeida, M. L., & Heberle, P. C. (2001). Influence of row spacing reduction on maize grain yield in regions with a short summer. *Pesquisa Agropecuária Brasileira, 36*(6), 861-869. doi: 10.1590/S0100-204X2001000600003

Sangoi, L., Schmitt, A., Durli, M. M. L., Leolato, L. S., Coelho, A. E., Kuneski, H. F., & Oliveira, V. L. (2019). Estratégias de manejo do arranjo de plantas visando otimizar a produtividade de grãos do milho. *Revista Brasileira de Milho e Sorgo, 18*(1), 47-60. doi: 10.18512/1980-6477/rbms.v18n1p47-60

Takasu, A. T., Rodrigues, R. A. F., Goes, R. Q., Arf, O., & Haga, K. I. (2014). Desempenho agronômico do milho sob diferentes arranjos populacionais e espaçamento entrelinhas. *Revista Agrarian, 7*(23), 34-41.

Torres, F. E., Langhi, G., Teodoro, P. E., Ribeiro, L. O., Corrêa, C. C. G., & Oliveira, E. P. (2013). Desempenho de híbridos de milho cultivados em diferentes espaçamentos na Região do Cerrado Brasileiro. *Revista de Ciências Agrárias, 36*(4), 411-416. doi: 10.19084/rca.16326

Zagonel, J., & Fernandes, E. C. (2007). Doses e épocas de aplicação de redutor de crescimento, afetando cultivares de trigo em duas doses de nitrogênio. *Planta Daninha, 25*(2), 331-339. doi: 10.1590/S0100-83 582007000200013

Zagonel, J., & Ferreira, C. (2013). Doses e épocas de aplicação de regulador de crescimento em híbridos de milho. *Planta Daninha, 31*(2), 395-402. doi: 10.1590/S0100-83582013000200017

Zagonel, J., Venancio, W. S., & Kunz, R. P. (2002). Efeito de regulador de crescimento na cultura do trigo submetido a diferentes doses de nitrogênio e densidades de plantas. *Planta Daninha, 20*(3), 471-476. doi: 10.1590/S0100-83582002000300019