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Trinexapac-ethyl application doses and times on productive performance of white oat cultivars[1]

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ABSTRACT - This study aimed to assess the effect of different doses and times of application of the growth regulator trinexapac-ethyl on the productive performance of white oat cultivars. The experiment was carried out in Londrina, Paraná State, Brazil, in the 2019 and 2020 seasons using the white oat cultivars IPR Artemis and URS Corona. The experimental design was a randomized block with four replications arranged in a 4 × 3 factorial scheme, conducted separately for each cultivar, with four doses of trinexapac-ethyl (0, 50, 100, and 150 g ha^{-1}) and three times of application (T_1, first node noticeable; T_2, first node visible and second node noticeable; and T_3, second node visible and third node noticeable). The following agronomic characters were evaluated: plant height, panicle length, panicles per square meter, spikelets per panicle, grains per spikelet, grains per panicle, thousand grain weight,lodging percentage, and grain yield. Application of trinexapac-ethyl at doses of 100 or 150 g ha^{-1} at T_2 or T_3 reduced panicle length, spikelets per panicle, and grains per panicle in IPR Artemis and URS Corona. However, it also reduced plant height and increased panicles per square meter and yield in both cultivars. These same doses and times of application resulted in a significant reduction in lodging.

Key words: *Avena sativa* L. Growth regulator. Productivity. Lodging. Yield components.

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INTRODUCTION

Lodging, that is, the bending over or folding of stems toward the soil, is quite common in oat crops. The intensity of lodging depends on plant cultivar and environmental conditions. This phenomenon can limit yield, as it reduces the exposure of photosynthetic areas to sunlight. Furthermore, even if lodging occurs during ripening, panicles become exposed to high humidity conditions because of their proximity to soil, usually leading to losses in grain yield and quality. Another negative effect of lodging, regardless of the stage at which it occurs, is the increase in harvest difficulty (PENCKOWSKI; ZAGONEL; FERNANDES, 2009).

An alternative to circumvent this problem is to apply growth regulators. These chemical substances have gained importance for improving the productive efficiency of cultivated species, being generally used to prevent lodging without decreasing grain yield (RADEMACHER, 2000). Trinexapac-ethyl (TE) is one of the main growth regulators used in winter cereals. TE acts by reducing internode elongation, increasing stem diameter, altering leaf architecture, and minimizing plant lodging (DAVIES, 1987). In wheat (KOCH *et al*., 2017), rice (ARF *et al*., 2012), and soybean (SOUZA *et al*., 2013), TE was shown to be effective in reducing lodging. However, such effects depend on plant genotype, TE dose, time of application, and interactions with the environment.

Zagonel and Fernandes (2007), in studying the effect of TE on wheat, showed that the optimal dose and application time may vary according to cultivar, especially when applied to materials with high lodging susceptibility. According to the authors, TE should be applied at 100 g ha^{-1} when the first and second visible nodes emerge. However, this recommendation is very broad and does not take into account specific characteristics of each cultivar, which may respond differently to different doses.

Growth regulators may be an interesting option to minimize the negative effects of lodging while enhancing yield and yield components in white oat, as has been reported for other cereals (OLIVEIRA *et al*., 2021; KOCH *et al*., 2017; ARF *et al*., 2012; SWOISH *et al*., 2021). Because of the lack of specific studies on white oat, the recommended TE doses and times of application are extrapolated from wheat. Even for cereal crops that are commonly treated with growth reducers, the response to product doses and application times differs according to genotype and growing environment. Thus, specific recommendations are needed for oat, according to the genotype, environment, and management system used. Given the above, this study aimed to assess the effect of different TE doses and times of application on the productive performance of white oat cultivars.

MATERIAL AND METHODS

The experiment was conducted in the 2019 and 2020 growing seasons at the Experimental Station of the Paraná Institute of Rural Development (IAPAR-EMATER), located in Londrina (23°23′S 51°11′W, 545 m a.s.l.), Paraná State, Brazil. The soil is classified as eutroferric Red Latosol (EMBRAPA, 2018). The climate is of the Cfa type (Köppen classification), described as humid subtropical with hot summers. Maximum and minimum temperatures and rainfall data for the experiment period are shown in Figure 1.

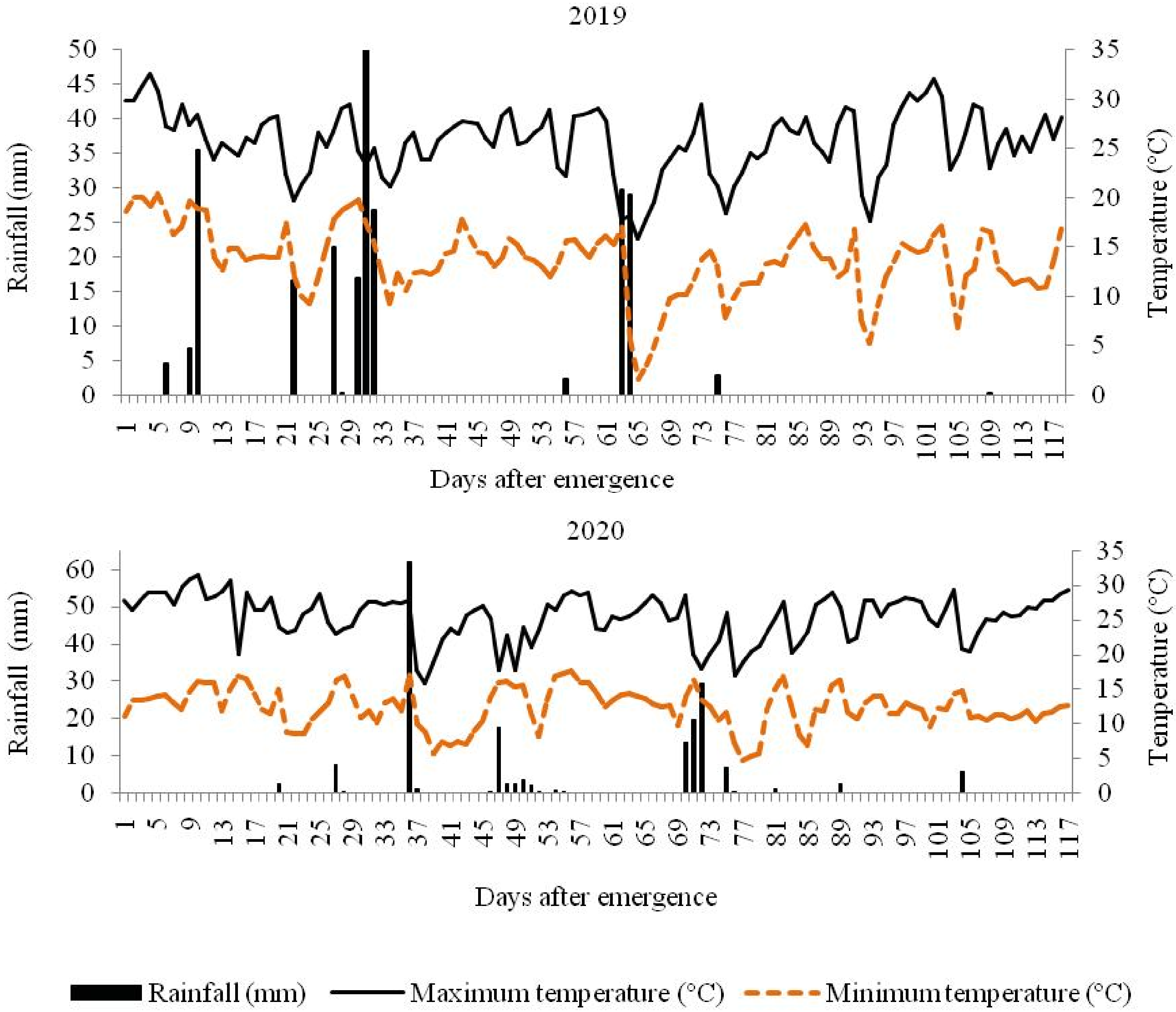
Soil chemical properties in the 0–20 cm depth layer was determined before the beginning of each experiment. In the 2019 season, soil analysis provided the following results: pH ($CaCl_2$) 5.00, 5.21 cmol$_c$ dm^{-3} H + Al^{3+}, 5.31 cmol$_c$ dm^{-3} Ca^{2+}, 0.98 cmol$_c$ dm^{-3}Mg^{2+}, 0.59 cmol$_c$ dm^{-3} K^+, 29.33 mg dm^{-3} P, and 16.98 g dm^{-3} organic matter. Soil results for the 2020 season were as follows: pH ($CaCl_2$) 4.85, 5.96 cmol$_c$ dm^{-3} H + Al^{3+}, 5.76 cmol$_c$ dm^{-3} Ca^{2+}, 0.65 cmol$_c$ dm^{-3} Mg^{2+}, 0.61 cmol$_c$ dm^{-3} K^+, 31.09 mg dm^{-3} P, and 15.92 g dm^{-3} organic matter.

Experiments were conducted using two genotypes of common oat (*Avena sativa*) with different heights, growth cycles, and lodging tolerance, namely IPR Artemis and URS Corona. IPR Artemis was developed by IAPAR and released commercially in 2016. It is a medium-cycle cultivar (mean time to maturity of 117 days) with moderate resistance to lodging and an average plant height of 100 cm. URS Corona was released in 2010 by the Federal University of Rio Grande do Sul. It is a medium-cycle genotype with moderate susceptibility to lodging and high plant height.

Mechanized sowing of oat seeds was carried out in a no-till system in succession to soybean in both seasons. The 2019 crop was sown on May 3, 2019; emerged on May 14, 2019; and was harvested on August 28, 2019. The 2020 crop was sown on Abril 17, 2020; emerged on April 25, 2020; and was harvested on August 11, 2020. Basal fertilization consisted of 200 kg ha^{-1} NPK (10-30-10) fertilizer. Nitrogen fertilization consisted of surface applications of 54 kg ha^{-1} N split in two parts, the first at a rate of 27 kg ha^{-1} applied 10 days after emergence and the second at a rate of 27 kg ha^{-1} applied 5 days after the first application, both by manual broadcasting. Control of foliar diseases and crop treatments were carried out in accordance with technical recommendations for oat.

Each experimental unit (plot) was composed of 6 rows measuring 5 m in length and spaced 0.17 m apart, with a density of 300 viable seeds per square meter. Only the four center rows were considered as useful area.

Figure 1 - Mean daily temperatures and rainfall during the 2019 and 2020 experimental periods in Londrina, Paraná, Brazil



The experimental design was a randomized block with a 4 × 3 factorial arrangement and four replications, conducted separately for each cultivar. Treatments consisted of four doses of TE (Moddus®) and three times of application. The evaluated doses were 0, 50, 100, and 150 g active product ha^{-1}. Times of applications were defined based on plant development: T_1, first node noticeable; T_2, stem elongation phase, with first node visible and second node noticeable; and T_3, second node visible and third node noticeable. Applications were performed using a CO_2-pressurized backpack sprayer equipped with two flat fan nozzles (XR 110-020) at a constant pressure of 30 lb in^{-2} and a spray volume equivalent to 200 L ha^{-1}.

Grains were harvested when plants reached the maturation stage, characterized by dry appearance, hardening of the caryopsis, and grain moisture below 20%. Agronomic characters and yield components were evaluated in the useful area of plots, as described below.

Plant height, measured from ground level to the end of the panicle. Measurements were carried out in five randomly chosen plants at the grain-filling stage. Mean values are expressed in centimeters.

Panicle length, measured from the point of insertion to the end of the panicle. Measurements were carried out in panicles of five plants selected at random at the grain-filling stage. Mean values are expressed in centimeters.

Number of panicles per square meter, determined by counting the number of panicles in 1.0 m^2 of each plot.

Number of spikelets per panicle, determined by manual counting of spikelets in 10 panicles harvested at random from each plot.

Number of grains per spikelet, determined by manual counting of grains from all spikelets in 10 panicles harvested at random from each plot.

Number of grains per panicle, manually counted after threshing 10 panicles harvested at random from each plot.

Thousand grain weight, determined by counting and weighing 8 replicates of 100 grains per plot and multiplying the mean value by 10.

Lodging percentage, assessed by visual observation of plants at the maturation phase. Plots were assigned values from 0 (no lodging) to 100% (complete lodging). Lodged plants were considered those with an angle of less than or equal to 45° in relation to the soil.

Grain yield, determined by harvesting all plants from the useful area of each plot. After mechanical separation, grains were weighed and values were adjusted to 13% moisture. Results are expressed in kg ha^{-1}.

Data were assessed for normality and homogeneity of errors and subsequently subjected to analysis of variance. Means were compared by Tukey's test and subjected to first- and second-order regression analysis at the 5% significance level. All statistical analyses were performed using Genes software (Cruz, 2013). Data were analyzed separately for each cultivar.

RESULTS AND DISCUSSION

Analysis of variance revealed that, in 2019, the plant height, panicle length, panicles per square meter, spikelets per panicle, grains per panicle, and thousand grain weight of IPR Artemis was significantly influenced by interaction effects of TE application time and dose. Yield was influenced by the main effects of both factors and lodging by the main effect of TE. Main and interaction effects of factors on grains per spikelet were not significant (Table 1). In the 2020 growing season, there were significant interaction effects on plant height, panicle length, panicles per square meter, spikelets per panicle, grains per panicle, and lodging. Yield, however, was only influenced by application time, whereas grains per spikelet and thousand grain weight were not influenced by application time, TE dose, or their interaction (Table 1). Except for lodging, all traits exhibited coefficients of variation of 17% or lower, indicating good experimental accuracy (Tables 1 and 4).

In both growing seasons, plant height decreased with increasing TE dose, from 100 g ha^{-1} onward, when applied at T_2 or T_3. Plant height was 116.13 cm at 0 g ha^{-1} TE and 78.80 cm at 150 g ha^{-1} TE in 2019. In 2020, plant height decreased from 105.50 cm (0 g ha^{-1} TE) to 83.35 cm (150 g ha^{-1} TE) (Table 2, Figure 2a and b). Such values represent a reduction of 32% and 20% in plant height in 2019 and 2020, respectively. Kaspary *et al*. (2015), in applying different TE doses to white oat cultivars, found a similar behavior: with the increase in TE dose, reductions of up to 60% in plant height (150 g ha^{-1} TE) were observed. Reductions in plant height by TE were also reported in studies with rice (ARF *et al*., 2012), maize (SANGOI *et al*., 2020), wheat (KOCH *et al*., 2017), fescue (CHASTAIN *et al*., 2015), barley (SWOISH *et al*., 2021), and white oat (HAWERROTH *et al*., 2015), demonstrating the effectiveness of the growth regulator in cereals.

When absorbed by plants, TE acts selectively by reducing the level of active gibberellic acid, which is responsible for promoting cell elongation; therefore, TE induces a temporary inhibition or reduction of growth. Given that the action of gibberellins on cell elongation is negatively affected, TE-treated plants grow at a slower rate (ARF *et al*., 2012). Thus, the decrease in the number and length of plant cells affects internode elongation during the vegetative period, reducing plant height without causing morphological deformation of the stem (TAIZ; ZEIGER, 2004).

Table 2 and Figures 2c and d show that the panicle length of IPR Artemis was influenced by TE dose and time of application in 2019 and 2020. When applied at T_1, regardless of the dose, TE exerted a nonsignificant effect on panicle length. When applied at T_2 or T_3 at a dose of 100 g ha^{-1}or higher, TE decreased panicle length. In 2019, the parameter decreased from 15.20 cm (0 g ha^{-1}, regardless of application time) to 13.81 cm (150 g ha^{-1} applied at T_2 or T_3). In 2020, panicle length decreased from 15.45 to 11.70 cm by application of 0 and 150 g ha^{-1} TE, respectively. Alvarez *et al*. (2007), in investigating the influence of TE dose and time of application on yield components of upland rice, reported that the decrease in panicle size might be related to time of application. TE is typically applied during differentiation of the floral primordium, possibly interfering with the formation of this structure, characterized by constant cellular multiplication.

Spikelets per panicle and grains per panicle decreased with application of TE at 100 g ha^{-1} or higher at T_2 or T_3 in both growing seasons (Table 2, Figure 2G–J). This result is certainly related to the lower panicle length afforded by these treatments. Similar findings were reported by Guerreiro and Oliveira (2012), who observed a reduction in number of grains per panicle in white oat as a result of increased TE doses. Alvarez *et al*. (2007) argued that the decrease in panicle length from TE application is likely responsible for the reduction in number of spikelets; such a response results in a greater balance of photoassimilates in the plant, possibly leading to activation of basal buds and late tillering, consequently increasing tiller number and panicle formation. This hypothesis, however, goes against our results for the 2019 and 2020 growing seasons. We observed a decrease in panicle length concomitantly with an increase in number of panicles per square meter with TE application (Table 2).

Table 1 - Mean squares from analysis of variance and coefficients of variation (CV) for agronomic characters of white oat IPR Artemis grown under different doses (D) and times of application (T) of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons

Cultivar (year)	Variable	Mean squares					CV (%)	Mean
		Blocks	D	T	D × T	Residuals		
IPR Artemis 2019	Plant height	4.43	24.55**	376.38**	62.62**	7.1	2.56	104.11
	PL	0.55	2.29**	2.051**	0.864**	0.322	3.82	14.86
	P/M²	65.72	6798**	3813**	32.687**	35.95	1.92	311.41
	SP	0.8	14.77**	42.65**	6.41**	0.72	2.14	39.71
	GS	0	0.00ns	0.00ns	0.00ns	0	2.28	2.13
	GP	0.6	50.88**	57.04**	18.97**	2.22	1.82	81.65
	TGW	0.61	22.05**	3.51**	4.57**	0.44	2.19	30.5
	lodging	6.74	419.79**	10.8ns	13.73ns	14.09	70.88	5.29
	GY	16474	17729**	14537*	59373ns	28014	3.23	5175
IPR Artemis 2020	Plant height	18.35	562.90**	234.75**	131.22**	7.97	2.84	99.43
	PL	3.86	14.18**	9.82**	6.54**	1.03	7.12	14.31
	P/M²	858.1	29801**	21479**	10498**	697.73	5.71	461.93
	SP	14.19	179.67**	163.57**	110.82**	15.29	16.54	23.63
	GS	0.01	0.01ns	0.01ns	0.01ns	0	4.32	2.08
	GP	82.04	885.64**	855.04**	510.92**	68.33	16.71	49.44
	TGW	2.64	12.95ns	9.10ns	3.64ns	5.51	7.31	32.11
	lodging	407.2	454.76*	205.09**	204.41*	69.01	75.75	10.96
	GY	12882	13043ns	64132*	18339ns	126793	6.17	5764

* Significant at $p < 0.05$ (F-test). ** Significant at $p < 0.01$ (F-test). ns, not significant.Degrees of freedom: 3 (Blocks), 3 (Dose), 2 (Time of application), 6 (D × T), and 33 (Residuals). plant height (cm); PL, panicle length (cm); P/M^2, panicles per square meter; SP, spikelets per panicle; GS, grains per spikelet; GP, grains per panicle; TGW, thousand grain weight (g); lodging (%); GY, grain yield (kg ha^{-1})

Table 2 - Mean values for agronomic characters of white oat IPR Artemis grown under different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons

Variable	Time of application	2019				2020			
		Trinexapac-ethyl (g ha^{-1})				Trinexapac-ethyl (g ha^{-1})			
		0	50	100	150	0	50	100	150
Plant height	T1	117.2 a	115.2 a	111.0 a	95.0 a	104.5 a	102.7 a	105.0 a	103.0 a
	T2	117.2 a	112.7 ab	100.0 b	78.6 b	105.5 a	104.0 a	97.0 b	84.7 b
	T3	114.0 a	109.7 b	99.2 b	79.0 b	106.5 a	102.5 a	95.7 b	82.0 b
PL	T1	15.2 a	15.2 a	15.2 a	15.2 a	15.2 a	14.4 a	15.9 a	15.3 a
	T2	15.2 a	15.1 a	15.0 a	13.9 b	15.8 a	15.0 a	13.3 b	11.8 b
	T3	15.2 a	15.1 a	13.9 b	13.7 b	15.1 a	15.3 a	12.8 b	11.6 b

Continuations Table 2

P/M²	T1	294.0 a	294.7 a	295.5 b	297.5 b	422.2 a	415.5 b	417.7 c	429.0 c
	T2	290.2 a	294.0 a	302.5 b	363.5 a	419.0 a	429.0 ab	483.7 b	559.0 b
	T3	291.2 a	292.2 a	355.2 a	366.2 a	405.5 a	445.5 a	527.7 a	589.3 a
SP	T1	41.1 a	41.4 a	41.2 a	39.2 a	27.2 a	23.4 a	31.4 a	26.9 a
	T2	41.5 a	41.0 a	39.0 b	36.5 b	28.9 a	26.3 a	18.0 b	16.3 b
	T3	41.4 a	41.1 a	36.3 c	36.6 b	27.3 a	27.6 a	15.2 b	14.8 b
GP	T1	83.5 a	83.6 a	83.0 b	84.5 a	57.9 a	49.3 a	66.8 a	56.6 a
	T2	83.7 a	83.7 a	80.5 b	77.4 b	62.1 a	55.3 a	37.1 b	32.9 b
	T3	83.2 a	82.7 a	76.6 a	77.1 b	57.8 a	55.7 a	30.7 b	30.6 b
GY	T1	5062 a	5078 a	5090 b	5090 b	5621 a	5525 a	5781 a	5235 b
	T2	5095 a	5067 a	5104 b	5436 a	5772 a	5609 a	5838 a	6084 a
	T3	5090 a	5093 a	5419 a	5480 a	5791 a	5772 a	5989 a	6154 a

Means within a column followed by the same letter are not significantly different by Tukey's test ($p < 0.05$). PH, plant height (cm); panicle length (cm); P/M², panicles per square meter; SP, spikelets per panicle; GP, grains per panicle; GY, grain yield (kg ha^{-1}); T_1, first node noticeable; T_2, first node visible and second node noticeable; T_3; second node visible and third node noticeable

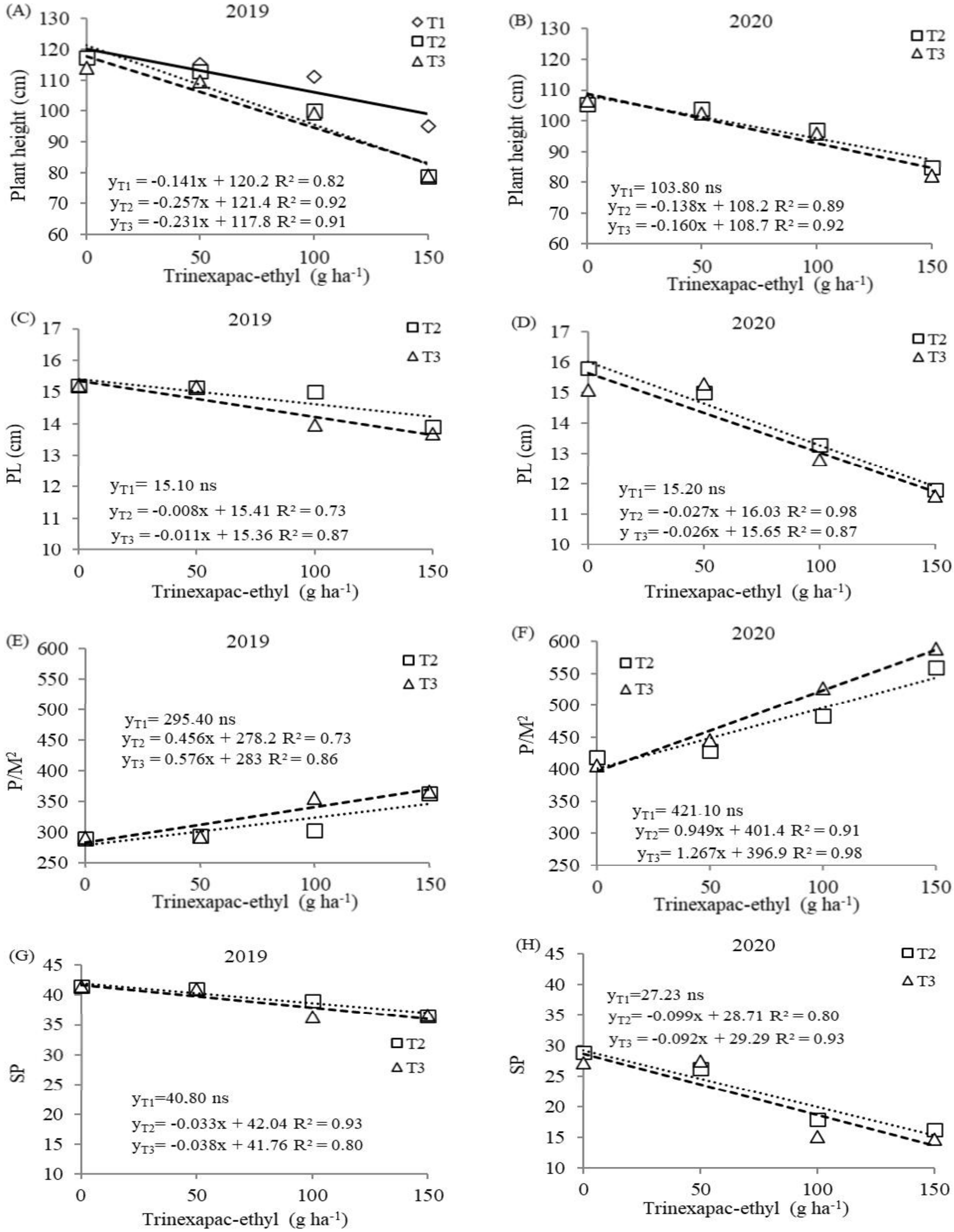
Number of panicles per square meter was positively influenced by application of TE (≥ 100 g ha^{-1}) at T_2 or T_3 in IPR Artemis. In 2019, we observed 292.80 panicles m^{-2} at 0 g ha^{-1} TE and 365.85 panicles m^{-2} at 150 g ha^{-1} TE applied at T_2 or T_3. In 2020, 415.57 and 574.15 panicles m^{-2} were obtained by treatment with 0 and 150 g ha^{-1} TE, respectively (Table 2, Figure 2e and f). Bazzo *et al.* (2019), in studying the effect of 100 g ha^{-1} TE applied at T_2, observed an increase in number of panicles per square meter in different white oat cultivars. According to Zagonel *et al.* (2002), small, compact plants can distribute photoassimilates more efficiently, increasing the number of reproductive structures per square meter, resulting in higher yields.

The results for number of panicles per square meter can be explained by the fact that 100 g ha^{-1} TE applied at T_2 or T_3 reduced plant height in IPR Artemis. This response probably provided more favorable conditions for the development of fertile tillers, consequently enhancing panicles per square meter. It should be noted that the increase in number of panicles per square meter possibly contributed to the reduction in spikelets per panicle and grains per panicle, stemming from increased competition between fertile tillers for photoassimilates.

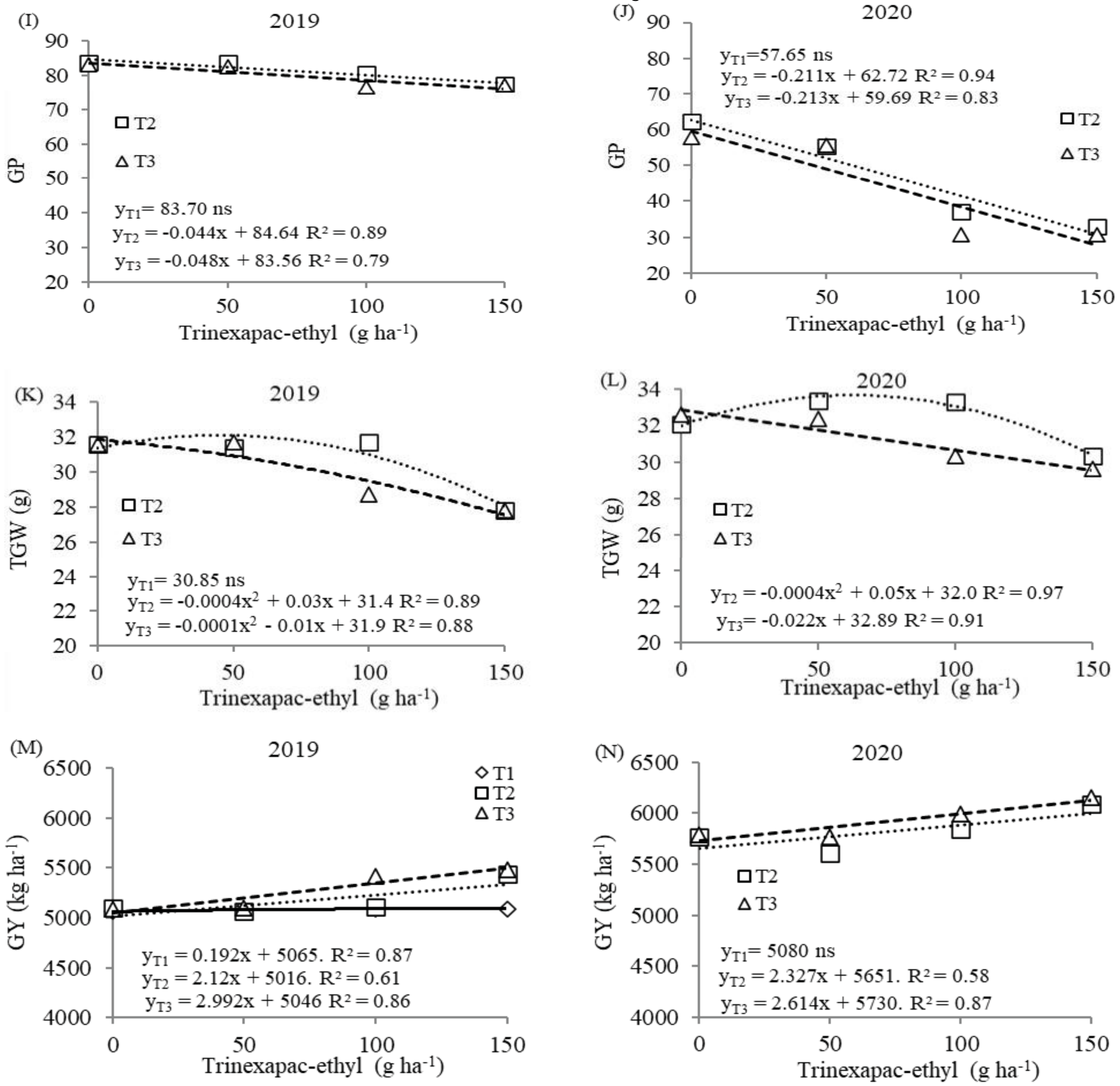
It is possible to observe that the thousand grain weight of IPR Artemis was negatively influenced by TE application in 2019 (Table 3, Figure 2K). When applied at T_2 at a dose of 150 g ha^{-1}, TE reduced thousand grain weight by 11.54% compared with 0 g ha^{-1} TE. Application of 100 g ha^{-1} TE at T_3 resulted in a 10.11% reduction in thousand grain weight compared with 0 g ha^{-1} TE. Such a reduction in grain filling might be due to the higher number of panicles per square meter (Table 2). Bazzo *et al.* (2019) investigated the influence of different doses of TE and N on white oat cultivars in two cultivation environments (Mauá da Serra and Londrina, Paraná State, Brazil). The authors observed that IPR Artemis grown in Mauá da Serra suffered a reduction in thousand grain weight with TE treatment. Martins *et al.* (2021), in assessing the effects of TE on upland rice cultivars, found that doses greater than 75 g ha^{-1} led to a reduction in thousand grain weight depending on application time. Kaspary *et al.* (2015) reported that the use of 150 g ha^{-1} TE affected the thousand grain weight of white oat cultivars. Zagonel, Fernandes, and Kunz (2002) and Zagonel *et al.* (2002) studied different wheat cultivars and N doses and observed a negative effect of the growth reducer on thousand grain weight, regardless of the cultivar. A reduction in thousand grain weight indicates low energy reserves in grains, which may influence seed germination and vigor. In general, high-vigor seeds can germinate and emerge more quickly under adverse conditions (VIEIRA; CARVALHO, 1994).

IPR Artemis lodging was found to have a quadratic relationship with TE dose for the three application times in the 2019 growing season (Figure 3). The minimum point (0.0%) was estimated to be reached at 140.57 g ha^{-1} TE. It was found that lodging decreased with increasing TE doses. In the study of Bazzo *et al.* (2019), with different TE and N doses at two experimental sites, TE was effective in reducing lodging in white oat cultivars. Zagonel and Fernandes (2007), in evaluating the effects of TE dose and application time in wheat treated with two different N doses, observed lower lodging percentage resulting from a reduction in plant height.

Figure 2 - Agronomic characters of white oat IPR Artemis as influenced by different doses and times of application of the growth regulator trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons



Continuation Figure 2



Plant height (cm); PL, panicle length (cm); P/M², panicles per square meter; SP, spikelets per panicle; GS, grains per spikelet; GP, grains per panicle; TGW, thousand grain weight (g); GY, grain yield (kg ha^{-1}); T_1, first node noticeable; T_2, first node visible and second node noticeable; T_3; second node visible and third node noticeable

Table 3 - Mean values for thousand grain weight (TGW) of white oat IPR Artemis grown under different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons

Variable	Time of application	Trinexapac-ethyl (g ha^{-1})			
		0	50	100	150
	T1	31.1 a	31.1 a	31.1 a	30.1 a
TGW	T2	31.6 a	31.4 a	31.7 a	27.8 b
	T3	31.6 a	31.7 a	28.7 b	27.8 b

Means within a column followed by the same letter are not significantly different by Tukey's test ($p < 0.05$). T_1, first node noticeable; T_2, first node visible and second node noticeable; T_3; second node visible and third node noticeable

In 2020, treatment of IPR Artemis with TE at T_1 did not lead to significant differences in lodging percentage (Figure 4). However, when applied at T_2 or T_3, TE was found to have a quadratic effect on lodging. For T_2, the minimum lodging percentage (5%) was estimated to be achieved with 116.42 g ha^{-1} TE. For T_3, the maximum lodging percentage (16.7%) was estimated at a TE dose of 1.60 g ha^{-1}. A TE dose of 150 g ha^{-1} applied at T_2 or T_3 was effective in controlling lodging (Figure 4).

IPR Artemis yield was positively influenced by TE application in 2019 (Table 2, Figure 2 m and n). Application of 150 g ha^{-1} TE at T_2 led to an increase in grain yield. For application at T_3, yield was increased with doses of 100 g ha^{-1} TE or higher. On the other hand, in 2020, application of TE at T_3 resulted in higher yields than application at T_1 or T_2, independent of TE dose (Table 2, Figure 2k and l). A yield of 5.927 kg ha^{-1} was achieved with application at T_3 and yields of 5.541 and 5.826 kg ha^{-1} with application at T_1 and T_2, respectively. Bazzo *et al.* (2019) observed similar results: TE application increased grain yield and number of panicles per square meter in white oat PR Afrodite. According to the authors, it is likely that panicles per square meter was the variable that most contributed to the increase in grain yield. These findings agree with those of the current study, in that panicles per square meter had a great influence on IPR Artemis grain yield. Marcos Junior *et al.* (2013), in studying different TE doses and wheat cultivars, concluded that TE increases number of panicles per square meter and grain yield at doses of 75 and 150 g ha^{-1}. In rice, Martins *et al.* (2021) found that grain yield decreased with application of TE at 75 g ha^{-1} or higher. In wheat, TE is known to maintain or increase yield compared with control groups (SWOISH; STEINKE, 2017; KNOTT *et al*., 2016).

Figure 3 - Lodging percentage of white oat IPR Artemis as a function of different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 crop season

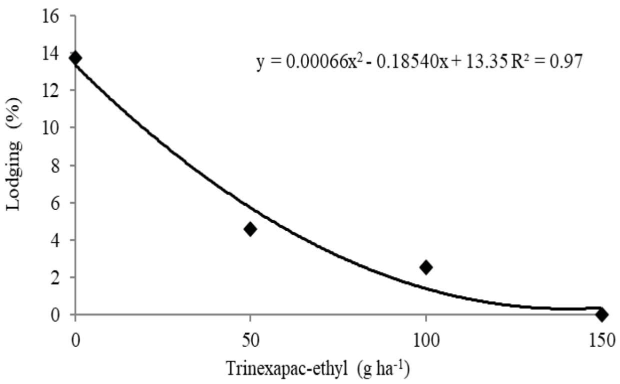
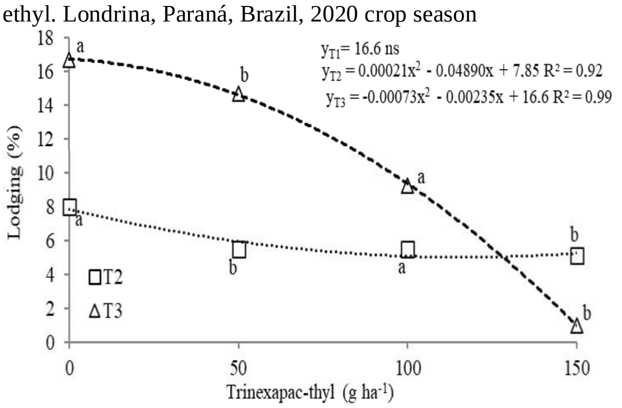


Figure 4 - Lodging percentage of white oat IPR Artemis as a function of different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2020 crop season



Different letters indicate significant differences by Tukey's test ($p < 0.05$). T_1, first node noticeable; T_2, first node visible and second node noticeable; T_3; second node visible and third node noticeable

Analysis of variance of URS Corona data showed that, in 2019, there were significant interaction effects between TE dose and application time on plant height, panicle length, panicles per square meter, spikelets per panicle, grains per panicle, thousand grain weight, lodging, and yield. Grains per spikelet was not influenced by the main or interaction effects of factors (Table 4). In 2020, significant interaction effects were observed on plant height, panicle length, panicles per square meter, spikelets per panicle, grains per panicle, and thousand grain weight. Lodging was influenced by the main effects of TE application and dose, whereas yield and grains per spikelet were not influenced by the factors (Table 4).

URS Corona plant height was significantly influenced by TE dose and application time in both growing seasons (Table 5, Figure 5a and b). In 2019, application of TE at T_1 did not lead to significant changes in plant height; however, when applied at T_2 at a dose of 150 g ha^{-1}, TE reduced plant height by 32%. For application at T_3, significant reductions in plant height were observed using doses of 100 g ha^{-1} TE or higher. In 2020, there was a reduction in plant height with TE application at T_2orT_3 from 100 g ha^{-1} TE onward. Plant height decreased from 105.13 cm (0 g ha^{-1}) to 74 cm (150 g ha^{-1} at T_2 or T_3). Our results agree with those of Guerreiro and Oliveira (2012), who found a reduction of about 50% in white oat plant height when applying a TE dose of 175 g ha^{-1} compared with the control. In wheat, height decreased by 30 cm in plants treated with 210 g ha^{-1} TE (PAGLIOSA *et al*., 2013).

URS Corona panicle length was influenced by TE dose and application time in 2019 and 2020 (Table 5, Figure 5c and d). In both growing seasons, application at T_1 did not result in significant effects on panicle length. Application at T_2 or T_3 at doses of 100 g ha^{-1}or higher led to significant reductions in this trait, in agreement with the results of Bazzo *et al*. (2019).

Table 4 - Mean squares from analysis of variance and coefficients of variation (CV) for agronomic characters of white oat URS Corona grown under different doses (D) and times of application (T) of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons

Cultivar (year)	Variables	Mean squares					CV (%)	Mean
		Blocks	D	T	D × T	Residuals		
URS Corona 2019	Plant height	53.72	4110.72**	2052.77**	1128.24**	35.46	1.92	309.17
	PL	0.42	10.90**	5.61**	3.10**	0.44	3.76	17.75
	Pm	1.24	2245.52**	1187.06**	1260.95**	17.04	3.36	123.06
	SP	1.74	40.68**	20.25**	13.30**	1.27	3.3	34.18
	GS	0.01	0.00^{ns}	0.00^{ns}	0.01^{ns}	0	3.81	2.38
	GP	3.5	214.94**	135.56**	56.67**	3.62	2.32	56.67
	TGW	0.06	40.00**	32.44**	10.10**	1.44	3.84	31.31
	lodging	30.24	2572.13**	2018.58**	757.02**	9.09	4.76	63.22
	GY	14998	87262**	68410**	25642**	33191	5.13	3546
URS Corona 2020	Plant height	1569.19	11738**	8101.89**	3551.96**	435.89	5.72	364.54
	PL	4.98	28.97**	11.62**	6.49**	1.69	7.06	18.43
	Pm	1.68	1247.13**	749.81**	470.34**	10.47	3.38	95.68
	SP	13.16	193.27**	127.75**	37.86**	10.75	12.73	25.75
	GS	0.00	0.00^{ns}	0.00^{ns}	0.01^{ns}	0.00	4.36	2.05
	GP	58.33	770.38**	485.06**	152.95**	42.21	12.31	52.75
	TGW	3.98	51.5*	16.21 ns	30.89*	9.98	9.86	32.03
	lodging	600.85	1689.74**	1158.33*	621.88^{ns}	328.46	67.17	26.97
	GY	22584	90369^{ns}	35580^{ns}	71499^{ns}	20304	10.26	4389

* Significant at $p < 0.05$ (*F*-test). ** Significant at $p < 0.01$ (*F*-test). ns, not significant. Degrees of freedom: 3 (Blocks), 3 (Dose), 2 (Time of application), 6 (D × T), and 33 (Residuals). plant height (cm); PL, panicle length (cm); P/M^2, panicles per square meter; SP, spikelets per panicle; GS, grains per spikelet; GP, grains per panicle; TGW, thousand grain weight (g); lodging (%); GY, grain yield (kg ha^{-1})

As observed for panicle length, spikelets per panicle and grains per panicle decreased with application of ≥100 g ha^{-1} TE at T_2 or T_3 in both growing seasons (Table 5, Figure 5g–j). These treatments produced opposite effects on number of panicles per square meter: values increased significantly with increasing TE dose in both 2019 and 2020 (Table 5, Figure 5e and f).

In 2019, number of panicles per square meter increased by about 20.14% at 150 g ha^{-1} TE compared with the control. In 2020, the increase was even more expressive (25.88%), resulting from TE application at 150 g ha^{-1} (Table 5, Figure 5e and f).

The thousand grain weight of URS Corona was positively influenced by TE application in 2019 (Table 5, Figure 5k). Application of 150 g ha^{-1} TE at T_2 or T_3 resulted in a thousand grain weight of 35.35 g; in the control, the value was 29.63 g. In 2020, TE negatively influenced thousand grain weight. The parameter was 33 g for plants treated with 0 g ha^{-1} TE and 24 g for plants treated with150 g ha^{-1} TE (T_3) (Table 5 and Figure 5l). This result can be explained by the fact that lodging was more intense in 2019 (Table 6), reaching 80% at low TE doses. Thus, because of the increased exposure to soil moisture, grains were more likely to suffer weight loss. It can be said that TE indirectly contributes to minimizing losses in thousand grain weight by decreasing lodging and, therefore, the exposure of panicles to soil. The low grain filling observed in plants treated with higher TE doses at later application times in 2020 might be related to the increase in number of panicles per square meter, which likely enhanced competition for photoassimilates (Table 5, Figure 5k).

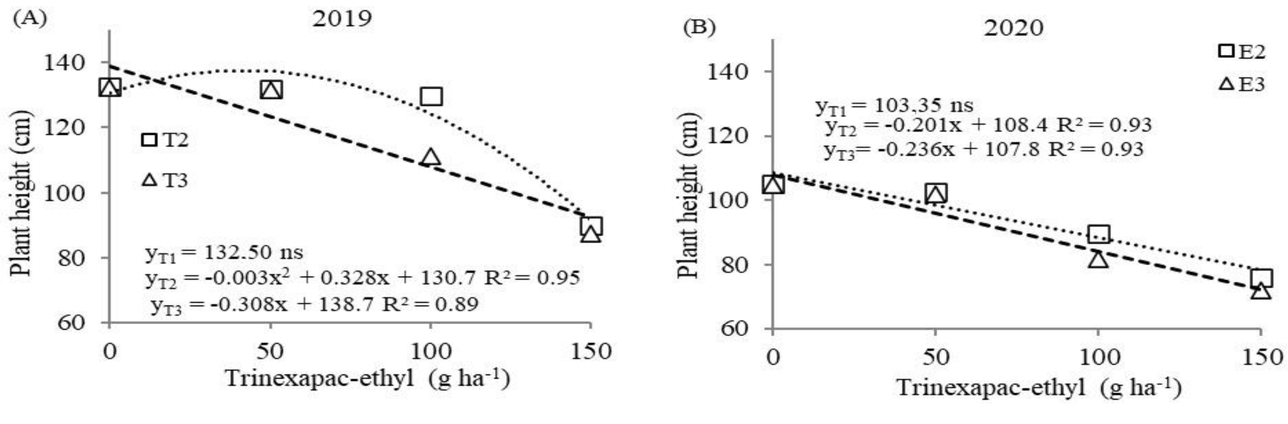
In URS Corona, lodging percentage decreased with increasing doses of TE (from 100 g ha^{-1}onward) applied at T_2 or T_3 (Table 6), ranging from 75.20% (0 g ha^{-1} TE) to 32.35% (150 g ha^{-1} TE at T_2 or T_3) in 2019 (Table 6). Such effects were probably associated with the reduction in plant height afforded by these treatments.

Table 5 - Mean values for agronomic characters of white oat URS Corona grown under different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons

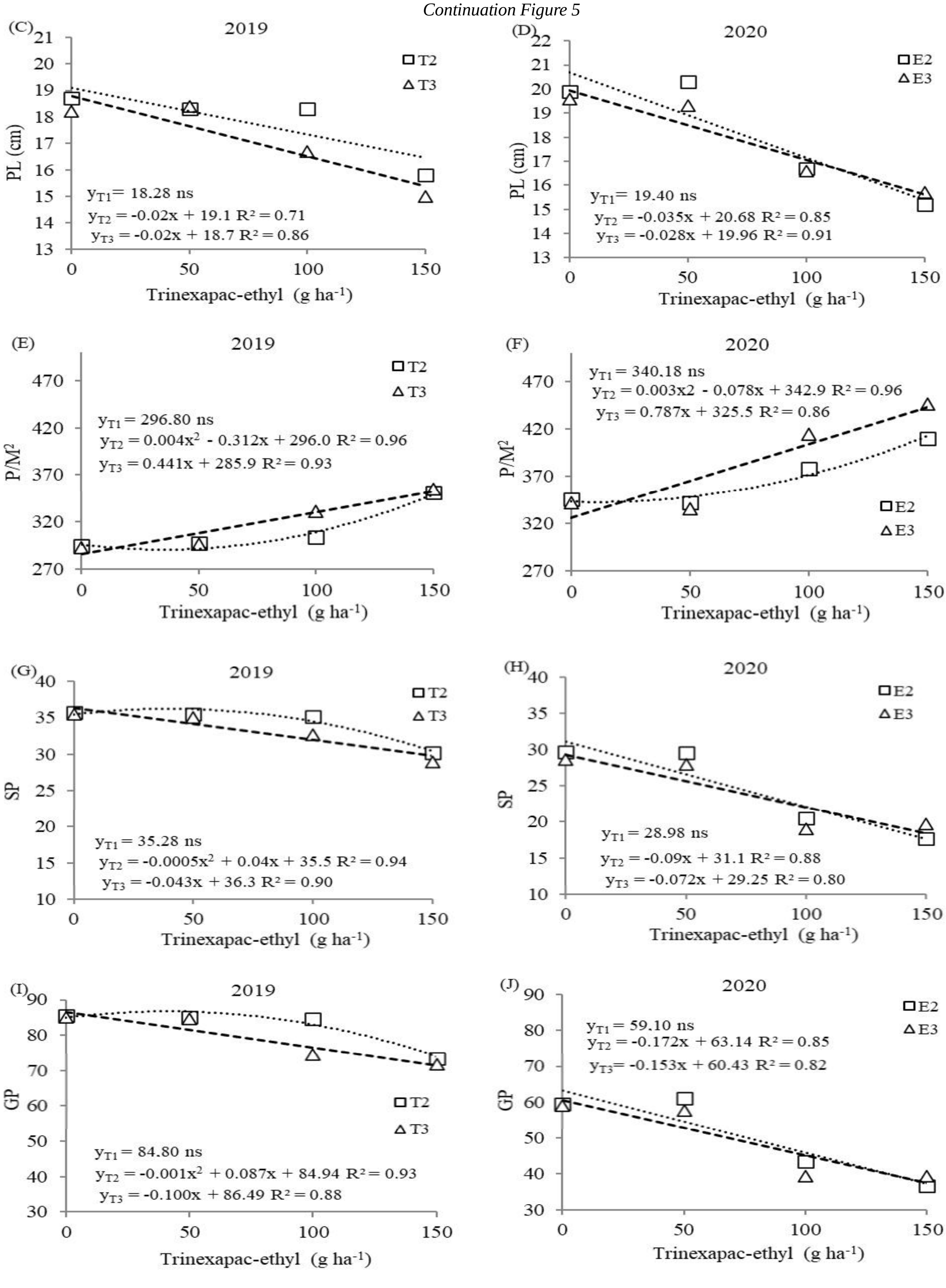
Variable	Time of application	2019				2020			
		Trinexapac-ethyl (g ha^{-1})				Trinexapac-ethyl (g ha^{-1})			
		0	50	100	150	0	50	100	150
Plant height	T1	133.0 a	132.5 a	132.0 a	132.5 a	105.5 a	103.7 a	102.7 a	101.5 a
	T2	132.5 a	132.0 a	129.7 a	90.0 b	105.2 a	102.7 a	89.7 b	76.0 b
	T3	132.2 a	131.5 a	111.2 b	87.5 b	104.7 a	102.0 a	81.7 c	72.0 c
PL	T1	18.4 a	18.3 a	18.1 a	18.3 a	19.9 a	19.0 a	20.0 a	18.7 a
	T2	18.7 a	18.3 a	18.3 a	15.8 b	19.9 a	20.3 a	16.7 b	15.2 b
	T3	18.2 a	18.4 a	16.7 b	15.0 b	19.6 a	19.3 a	16.6 b	15.7 b
P/M^2	T1	294.5 a	296.5 a	299.2 b	297.0 b	334.2 a	336.5 a	338.5 c	351.5 c
	T2	294.2 a	297.2 a	303.7 b	351.2 a	345.2 a	341.5 a	378.0 b	410.5 b
	T3	293.0 a	296.7 a	331.5 a	355.0 a	342.0 a	335.0 a	414.5 a	446.7 a
SP	T1	35.2 a	35.2 a	35.5 a	35.2 a	30.5 a	28.5 a	29.7 a	27.2 a
	T2	35.7 a	35.5 a	35.2 a	30.2 b	29.7 a	29.5 a	20.5 b	17.7 b
	T3	35.5 a	35.0 a	32.7 b	29.0 b	28.7 a	28.0 a	19.0 b	19.7 b
GP	T1	85.0 a	85.5 a	85.5 a	83.2 a	62.5 a	57.7 a	58.0 a	58.0 a
	T2	85.5 a	85.0 a	84.7 a	73.5 b	59.5 a	61.2 a	43.5 b	36.7 b
	T3	85.0 a	84.7 a	74.5 b	71.7 b	59.0 a	57.7 a	39.5 b	39.5 b
TGW	T1	29.3 a	29.6 a	29.7 b	30.5 b	33.1 a	32.8 a	32.9 a	32.9 a
	T2	29.9 a	30.1 a	30.5 b	35.5 a	32.3 a	33.0 a	33.0 a	30.1 a
	T3	29.7 a	30.7 a	34.7 a	35.2 a	33.5 a	33.4 a	33.3 a	23.6 b
GY	T1	3331 a	3316 a	3297 c	3328 b	4424 a	4413 a	4330 a	4389 a
	T2	3336 a	3327 a	3641 b	4094 a	4479 a	4386 a	4500 a	4378 a
	T3	3346 a	3301 a	4029 a	4208 a	4450 a	4389 a	4502 a	4025 a

Means within a column followed by the same letter are not significantly different by Tukey's test ($p < 0.05$). PH, Plant height (cm); PL, Panicle length (cm); P/M^2, panicles per square meter; SP, spikelets per panicle; GP, grains per panicle; TGW, thousand grain weight (g); GY, grain yield (kg ha^{-1}); T_1, first node noticeable; T_2, first node visible and second node noticeable; T_3; second node visible and third node noticeable

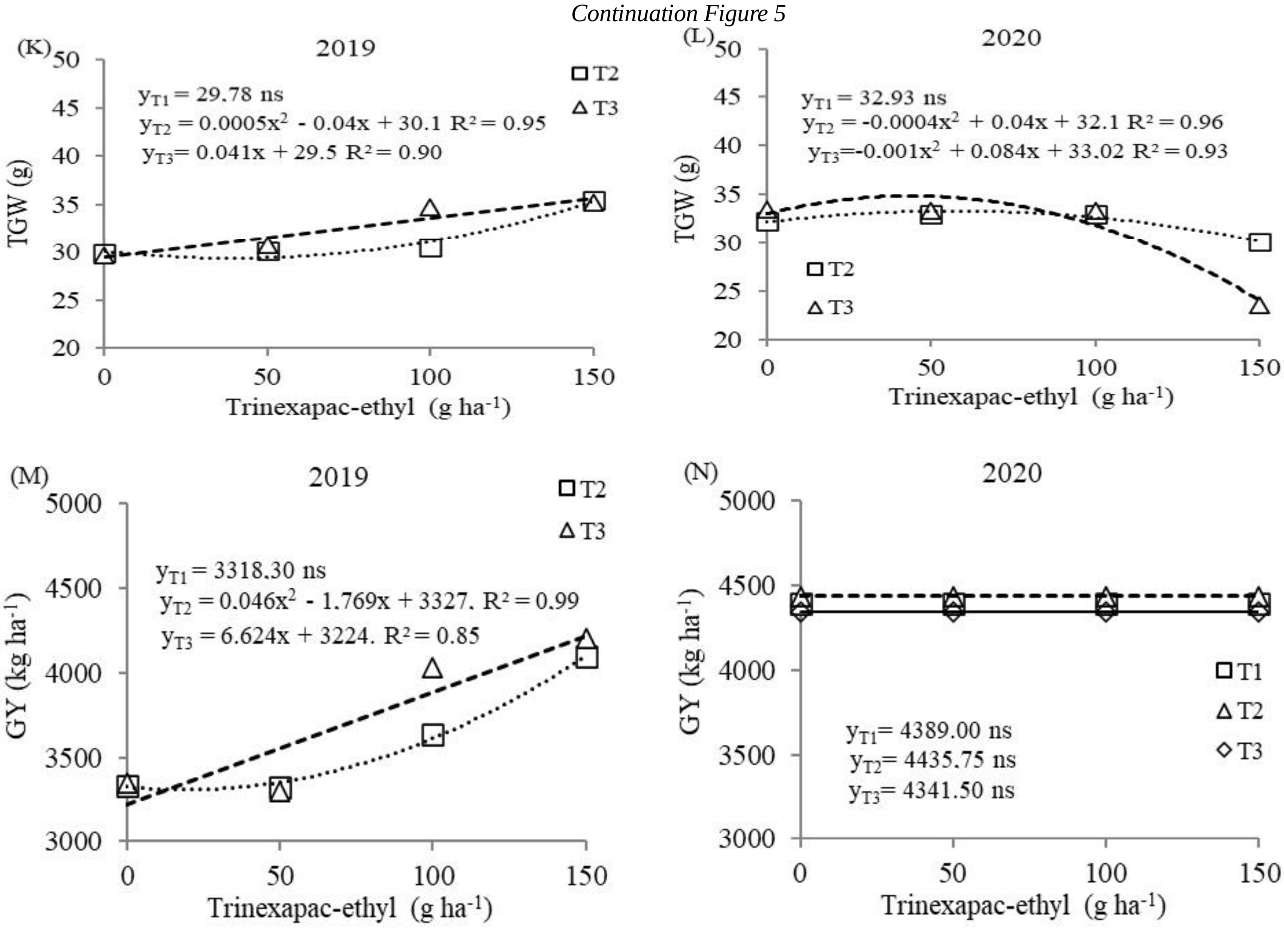
Figure 5 - Agronomic characters of white oat URS Corona as influenced by different doses and times of application of the growth regulator trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 and 2020 crop seasons



Continuation Figure 5



Continuation Figure 5



In 2020, lodging was found to have a quadratic relationship with TE dose for the three application times (Figure 6). Maximum lodging (35%) was estimated to be achieved by treatment with 37.5 g ha^{-1} TE. Lodging was mainly controlled with application of TE at 150 g ha^{-1}. Bazzo *et al.* (2019) found that TE was effective in reducing lodging percentage.

URS Corona grain yield was positively influenced by TE application in 2019 (Table 5, Figure 5m). Application at T_1 did not lead to significant changes in yield, but application of 150 g ha^{-1}TE at T_2 increased grain yield by 22.67%. A yield of 3.338 kg ha^{-1}was obtained at 0 g ha^{-1} TE, regardless of application time, and a yield of 4.095 kg ha^{-1} was achieved with 150 g ha^{-1} TE applied atT_2. For application atT_3, an increase in yield was achieved at a dose of 100 g ha^{-1} TE, which did not differ significantly from the yield obtained at 150 g ha^{-1} TE. Yield was not significantly influenced by TE application in 2020 (Table 4). The positive effect of TE application on grain yield is probably associated with its influence on lodging and plant height, leading to alterations in plant architecture and an increase in number of panicles per square meter.

The results show that TE application effectively decreased lodging without affecting yield in URS Corona. Interestingly, increased lodging did not impair grain yieldin the studied genotype. However, this result might stem from the fact that mechanized harvesting was carried out with great care, which substantially minimized losses that could have been caused by lodging.

Kaspary *et al.* (2015), in applying different TE doses to white oat cultivars, found that TE increased grain yield by about 30%. These results differ from those of Guerreiro and Oliveira (2012), who did not observe gains in white oat yield with any of the tested doses (43.75, 87.5, and 175 g ha^{-1}TE). Zagonel and Fernandes (2007), by contrast, in assessing TE application in wheat, reported significant gains in yield. Fioreze and Rodrigues (2014) did not find differences in wheat yield with TE application.

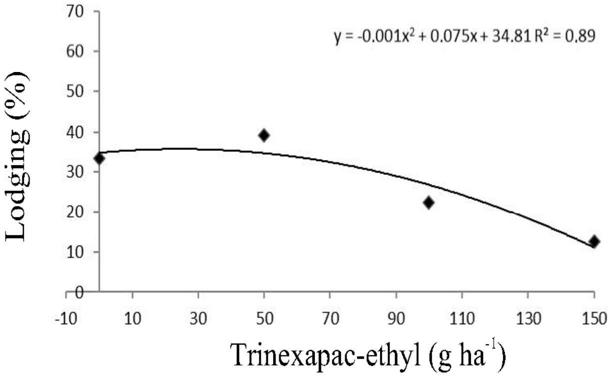
Overall, for IPR Artemis and URS Corona, application of 100 or 150 g ha^{-1} atT_2 orT_3 led to reductions in plant height and lodging, promoting an increase in grain yield. These values represent a safe interval for the use of the growth regulator to reduce plant lodging without compromising grain yield.

Table 6 - Mean values for lodging percentage of white oat URS Corona grown under different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2019 crop season

Variable	Time of application	Trinexapac-ethyl (g ha^{-1})			
		0	50	100	150
Lodging	T1	75.2 a	76.0 a	76.5 a	76.5 a
	T2	74.2 a	76.0 a	51.5 b	32.0 b
	T3	76.2 a	76.0 a	35.7 c	32.7 b

Means within a column followed by the same letter are not significantly different by Tukey's test ($p < 0.05$). T_1, first node noticeable; T_2, first node visible and second node noticeable; T_3; second node visible and third node noticeable

Figure 6 - Lodging percentage of white oat URS Corona as a function of different doses and times of application of trinexapac-ethyl. Londrina, Paraná, Brazil, 2020 crop season



It is noteworthy that number of panicles per square meter increased at doses of 100 or 150 g ha^{-1} TE applied atT_2 orT_3 in both cultivars. This effect contributed to the reduction in number of spikelets per panicle and number of grains per panicle probably because of increased competition for photoassimilates by fertile tillers.

CONCLUSION

1. Application of TE at doses of 100 or 150 g ha^{-1} at T_2 or T_3 reduces panicle length, spikelets per panicle, and grains per panicle in the white oat cultivars IPR Artemis and URS Corona. However, it also reduces plant height and increases number of panicles per square meter and grain yield in both cultivars. These doses and times of application promote a significant reduction in lodging.
2. The results obtained with 100 or 150 g ha^{-1} TE applied at T_2 or T_3 provide a safe interval in which lodging is reducing without compromising grain yield.

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