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Trinexapac-ethyl as an Alternative to Reduce Lodging and Preserve Grain Yield and Quality of Rye

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Abstract

Trinexapac-ethyl (henceforth referred to as trinexapac) is a growth regulator that can mitigate some undesirable vegetative growth in Poaceae plants, reducing lodging and optimizing the distribution of photoassimilates to reproductive organs. The objective of this research was to evaluate the morphophysiological and productive responses of rye cultivars and trinexapac doses applied at different phenological stages of plants. Two field experiments were performed in two different seasons. In the 2015 growing season, 8 doses of trinexapac were evaluated: 0, 75, 85, 100, 115, 130, 150, 200 g ha^{-1} of active ingredient (a.i.), applied at the plant growth stage with the 4th node visible on the main stem (GS34). In the 2018 growing season, two cultivars (IPR 89 and BRS Serrano) and five doses of trinexapac were evaluated: 0, 50, 100, 150 and 200 g a.i. ha^{-1}, applied at the plant growth stage with the 6th node visible on the main stem (GS36). The morphophysiological, productive and qualitative characteristics of grains were evaluated. In the 2015 season, trinexapac applied to shoot plants at GS34 only have low response in decreased plant lodging from around 20% to 10%. However, in the 2018 season, the application of trinexapac on plants at GS36, resulted in lower plant height, associated with reduced lodging and better quality of rye grains. Cultivar IPR 89 showed higher values for yield components and grain quality in comparison to cultivar BRS Serrano. Reduced lodging is dependent on speed of resumption of plant height growth, and the magnitude of response to trinexapac is also stage-cultivar-dose-dependent; in rye, the best response to trinexapac was found at GS 36 in comparison to GS 34, and for IPR 89 in comparison to BRS Serrano cultivar, respectively, with a dose range from 100 to 150 g ai ha^{-1}. In conclusion, trinexapac (around 150 g a.i. ha^{-1}), when applied to plants at GS36, reduces plant height, reduces the lodging index and enables the harvest of high-quality grains.

Keywords: crop management, growth regulator, phenological stage, secale cereale

1. Introduction

Rye (*Secale cereale*) crops stand out for their adaptability to low temperatures (*e.g.*, their physiological growth starts at 0 ºC) and diverse environmental and edaphic conditions (Jung & Seo, 2019). In Brazil, rye is mostly cultivated in the states of Paraná and Rio Grande do Sul; most often, it is grown in acidic and degraded soils, at altitudes above 600 m (CONAB, 2020). High seeding density, excess nitrogen fertilization and lower dry matter accumulation, resulting from excessive rainfall and winds, favor the occurrence of lodging during cultivation (Wu et al., 2019). These conditions are common in areas above 600 m of altitude in the south of Brazil. In addition, rye plants grown in Brazil are taller, which may predispose susceptibility to lodging. Lodging significantly affects photosynthetic ability, carbohydrate transport, and water movement in plants (Acreche & Slafer, 2011), which may impair grain filling, thus reducing yield by up to 80% (Berry et al., 2003). Depending on severity and stage, lodging harms harvesting operations and favors the occurrence of leaf diseases and mycotoxin contamination (Ma et al., 2013), thereby deteriorating grains and significantly affecting their quality. Even when lodging occurs late, *i.e.*, at pre-harvest, it negatively affects harvesting operations.

Growth regulators act on the physiology and metabolic processes of plants by changing plant architecture, reducing height and optimizing photoassimilate partitioning, thus allowing increased productivity and higher grain quality (Rademacher, 2018; Pricinotto et al., 2019). Trinexapac application inhibits gibberellin formation and, as a result, it inhibits stem elongation. Therefore, plants have lower height and stronger stems (Rademacher, 2018).

In corn crops, the use of trinexapac led to lower plant height, favored solar radiation interception, optimized photoassimilate distribution, allowed increased crop density, and increased grain production (Espindula et al., 2009; Pricinotto et al., 2019). Application of trinexapac reduced the source-sink distance in wheat plants, which increased the translocation of photoassimilates to the components, and reduced plant height (Fioreze & Rodrigues, 2014). Bazzo et al. (2019) found a greater number of panicles per m² in the association between growth regulator and nitrogen fertilization in an oat crop (*Avena sativa*). Trinexapac reduced plant height when applied in increasing doses on white oat plants at growth stages 31 (1st visible node—GS31) and 32 (2nd visible node—GS32) on the Zadoks scale (Zadoks et al., 1974), and associated with different amounts of topdressing nitrogen fertilization. Moreover, lodging was reduced when there were favorable conditions for this phenomenon to occur, without negative effects on grain yield. However, the authors found instability in plant response to stage of development, with different behaviors occurring between cultivation environments and the evaluated cultivar (Hawerroth et al., 2015). Fagherazzi et al. (2018) found a significant reduction in height for corn plants (*Zea mays*) with sequential application of trinexapac, which was more effective when applied between stages V2-V7, compared to stages V2-V6. This result suggests that the plants were more susceptible to the regulator at stage V6 and subsequent stages. Plant growth may also be resumed when the regulator is applied at earlier stages, since trinexapac reduces the level of active gibberellin and induces the plant to inhibit—but only temporarily—the endogenous levels of this hormone. Although trinexapac is not yet registered in Brazil for use in rye; scientific research is needed to assess its potential for this crop.

To broaden the scientific knowledge of the action and effects of growth regulators as a management strategy in rye crops, the aim of this research was to evaluate the morphophysiological and productive responses of rye cultivars to the application of increasing doses of trinexapac at different stages of plant stem elongation.

2. Material and Methods

2.1 Description of Sites and Experimental Design

Two experiments were conducted: the first one from July to December 2015, and the second one from July to December 2018, in the experimental area of the State University of Santa Catarina, Centro de Ciências Agroveterinárias (UDESC/CAV), located in the municipality of Lages, South plateau of the state of Santa Catarina, Brazil, under the following geographic coordinates: 27°52′30″ south latitude, and 50°18′20″ west longitude, with an average altitude of 930 m. According to the Köppen-Geiger classification, the local climate is Cfb, mesothermal, with mild summers, with average temperatures of the hottest month below 22 °C, and well-distributed rainfall throughout the year (Kottek et al., 2006).

The meteorological data were collected at the automatic station of the National Meteorological Institute (INMET), at the experimental station of the Agricultural Research and Rural Extension Company of Santa Catarina (EPAGRI-Lages), located 4 km from the experimental area. Figure 1 shows information on maximum and minimum temperatures, and rainfall during the experiments. The soil of the experimental area was classified as Aluminum Humic Cambissol (Embrapa, 2017). Table 1 shows the analysis of the chemical and physical properties of the 0-20 cm layer, from the 2015 and 2018 growing seasons.

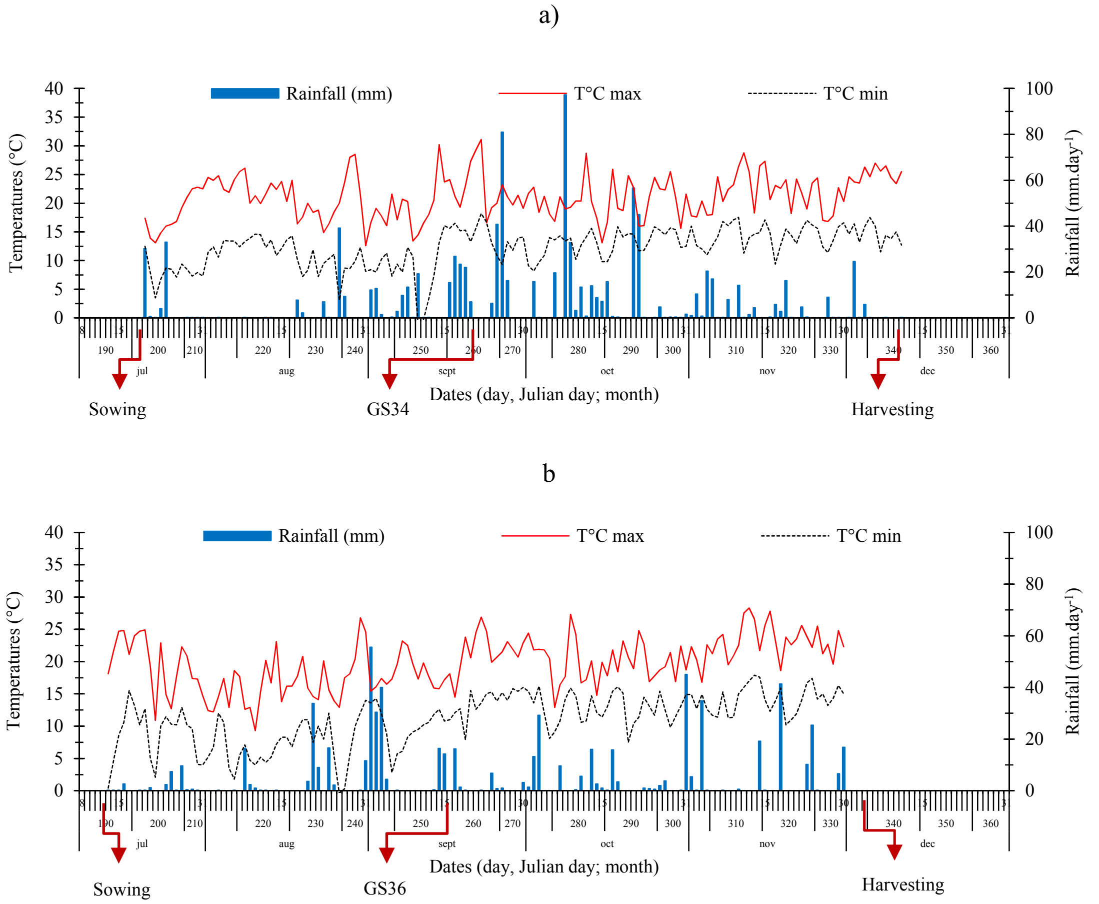

Figure 1. Daily maximum and minimum temperatures and rainfall at a) 2015 and b) 2018 growing seasons

Table 1. Physical and chemical traits of soil

Season	Clay	V	M.O.	$pH_{(H_2O)}$	Mehlich-I P	K	Ca	Mg	$H^+ + Al^{+3}$	CTC < 7
	----------- % -----------				------- mg dm^{-3} --------		---------------- cmol$_c$ dm^{-3} -----------------			
2015	51	79	3.0	5.6	37.9	85	7.7	3.1	8.7	18.2
2018	48	83	3.3	6.4	26.1	104	10.1	5.2	3.3	18.8

Note. V = base saturation, O.M. = organic matter, Mehlich-I P = Mehlich-1 extractable P, CTC = cation exchange concentration, pH = hydrogenionic potential, $H^+ + Al^{3+}$ = exchangeable aluminum.

Maintenance fertilization was carried out according to the results of the chemical and physical analysis of the soil, following the technical recommendations of the Soil Chemistry and Fertility Commission-RS/SC (CQFS RS/SC, 2016) with a view to achieving grain yields of 5 tons ha^{-1}. In the 2015 growing season, seeding fertilization consisted of the application of 30 kg ha^{-1} of N, 30 kg ha^{-1} of P_2O_5 and 20 kg ha^{-1} of K_2O with the 07-28-14 formulation. In the 2018 growing season, the application of NPK in commercial formulation 05-20-10, lead to the amount of 18.8 kg ha^{-1} of N, 75 kg ha^{-1} of P_2O_5 and 37.5 kg ha^{-1} of K_2O. In both seasons, the N topdressing rate of 25 kg of N ha^{-1} (urea source) was applied on rye plants at GS 22 (two visible tillers).

In both seasons, soil tillage involved plowing and harrowing. The experimental units consisted of five rows of 6 meters in length, with spacing of 0.20 m between rows. For the purposes of evaluations, 5 linear meters of the three central rows were used as useable area, in a total of 3.0 m^2. In the 2015 growing season, a single rye cultivar, BRS Serrano, was sown on July 20, 2015, and in the 2018 growing season, two cultivars were used, namely BRS Serrano and IPR 89, which were sown on June 13, 2018. In both growing seasons, sowing density was 300 viable seeds m^{-2}.

In the 2015 growing season, the experiment used a randomized block design, with four replications. The treatments consisted of eight doses of growth regulator trinexapac, namely 0 (control; no product) 75; 85; 100;

115; 130; 150 and 200 g ha ha^{-1}. Trinexapac was applied only once, when the plants were at phenological GS34 (fourth visible node). In the 2018 season, the experimental design consisted of randomized blocks in a 2 × 5 factorial design, with four replications. The first factor was made up of two rye cultivars: IPR 89 and BRS Serrano; the second factor consisted of five doses of growth regulator trinexapac: 0; 50; 100; 150 and 200 g ha ha^{-1}, applied at phenological GS36 (sixth visible node). In both experiments, the commercial product MODDUS® was used as a source of trinexapac. The application was carried out by a CO_2-pressurized sprayer at a constant pressure of 30 lb in.$^{-2}$, fitted with tips containing XR 110-015 flat fan nozzles, calibrated for a spray volume equivalent to 200 L ha^{-1}.

The harvest of rye, in the 2015 season, was carried out on December 12th, 2015, and in the 2018 season, on December 4th, 2018.

2.2 Evaluations

The following traits were evaluated: plant height at 0, 7, 14 and 21 days after application (DAA) of trinexapac (PHv) and plant height at maturity (PH); at pre-harvest of rye, evaluations were made of ear insertion height (EIH); peduncle length (PL); lengths of internodes 1 (I-1) and 2 (I-2); stem diameter (SD), plant lodging index (Lodg). Plant height (PH) was evaluated with the aid of a ruler graduated in cm, by measuring the distance from the ground level to the end of the plant. EIH, PL, I-1, and I-2 were evaluated with the aid of a ruler graduated in cm, by measuring the distance between each structure. SD was evaluated in the second basal internode of the plant with the aid of a digital caliper and by the average of the evaluation in the largest and smallest diameter of this internode. The result was expressed in mm. All of these characteristics were evaluated in a sample of 10 plants from each experimental plot. Lodg was validated using the method described by Moes & Stobbe, modified in our previous study (Sponchiado et al., 2020), according to the Equation 1:

$$\text{Lodg}\ (\%) = \text{I} \times \text{A} \times 2 \qquad (1)$$

where, “I” represents the degree of plant inclination, which ranges from 0-5, where “0” is absence of inclination, *i.e.*, plants with an angle close to 90° in relation to the soil surface; and “5” represents completely lodged plants, with an angle close to 0° in relation to the surface. “A” represents the percentage of the plot area with lodged plants; its range is 0-10, where “0” corresponds to the absence of lodged plants in the plot and “10” means that 100% of the plot area has lodged plants, regardless of their inclination, and “2” is the coefficient to generate the lodging index as a percentage.

At post-harvest, the following evaluations were made: thousand-grain weight (TGW), quantified from the grains obtained from ten ears that were harvested from the useable area of the plot and then threshed; grain count (Sanick, model ESC2011); hectoliter weight (HW), determined in a specific device (Dalle Molle, model 0.25L); grain sieve (G > 2) with grains larger than 2.00 mm in transversal diameter, evaluated in a sample of 100 g of sieved grains with the aid of a rectangular sieve measuring 30 × 40 cm and containing 2 × 20 mm-hole sieve. At post-harvest, ten ears were harvested from the useable area of the plot to determine: number of grains per ear (NGE); number of spikelets per ear (NSE); number of grains per spikelet (NGS). The harvest index (HI) was determined from the data of 10 plants sampled in the useable area of each plot, according to Equation 2:

$$\text{HI}\ (\%) = (\text{GY}/\text{BY}) \times 100 \qquad (2)$$

Where, HI, harvest index; GY = grain yield, based on grain weight of ten plants; BY = biologic yield, based on the weight of plant shoots with their grains, from ten plants. They were all expressed in g, after previous drying on an oven set to 65 °C for 72 h or sufficient time to reach constant weight.

Grain yield (GY, kg ha^{-1}) was determined from the harvest of grains from the useable area of the plots, corrected to standard grain humidity of 13% (corrected weight-CW, see Equation 3); the resulting value was converted to 1 hectare.

$$\text{CW (g)} = \text{WH} \times [(100 - \text{RH})/(100 - 13)] \qquad (3)$$

Where, CW = corrected weight of grains; WH = weight humidity of grains; RH = real humidity of grains at harvest and, 13 = standard humidity, as the value of stable humidity of grains suitable for long-time storage.

2.3 Statistical Analysis

The data were previously tested for normality by the Shapiro-Wilk test, and homogeneity, by the Bartlett test. Data (NGE, NSE, HI, Lodging) that did not comply with ANOVA requirements were transformed by $(x + 0.5)^{0.5}$. When significant variances were detected, the means were submitted to Tukey’s means comparison test, accepting a 5% probability of error. Parameterization was performed using regression analysis, accepting a 5% probability of error. The statistical software Sisvar version 5.6 (Ferreira, 2011) was used.

3. Results

3.1 Trinexapac Application to the 4th Visible Node

The doses of trinexapac applied at growth stage GS34 only promote significant variances ($P < 0.05$) on lodging index and TGW, but on plant height, hectoliter weight, sieve index of grains and grain yield no alterations were observed ($P > 0.05$) in the 2015 growing season in the cultivar BRS Serrano, as shown in the probabilities (Figure 2; $P > 0.05$). Are important highlight that lodging decreasing at a trinexapac doses of 115 and 130 g a.i. ha^{-1} to values from around 30% to lower of 10%.

3.2 Trinexapac Application to the 6th Visible Node

In the 2018 growing season, there was a simple cultivar effect for morphometric and productive/qualitative characteristics of grains. For cultivar IPR 89, peduncle length was 2.3 cm higher and stem diameter was 0.57 mm thicker when compared to cultivar BRS Serrano. However, cultivar BRS Serrano showed a larger size that was reflected in its final height, *i.e.*, it was 7.9 cm higher (Table 2).

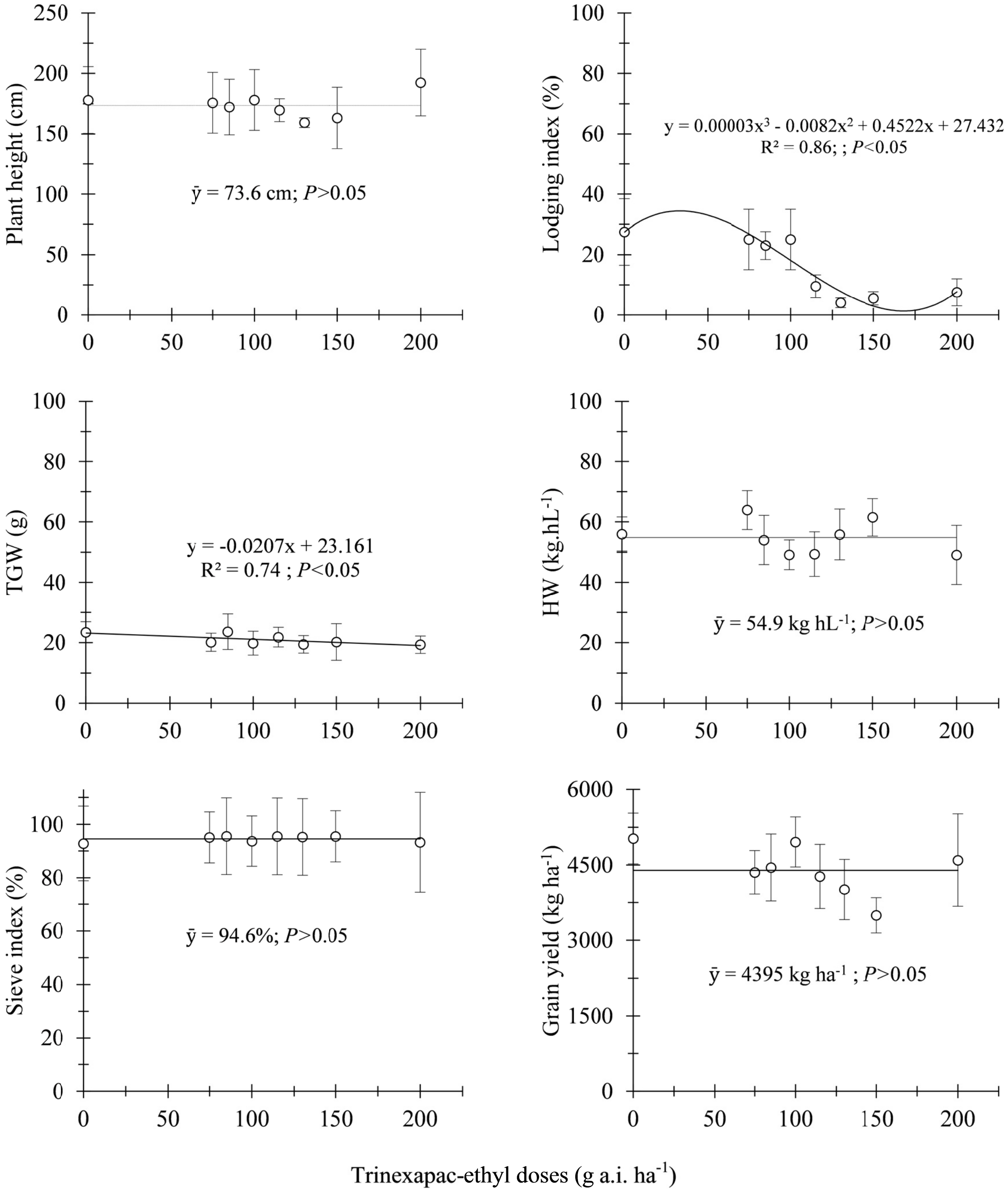

Figure 2. Plant height (PH), lodging index (Lodg), thousand grain weight (TGW), hectoliter weight (HW), grain sieve (sieve index-G > 2) and grain yield (GY) of rye as function of the application of eight doses of trinexapac-ethyl at the GS34. 2015 growing season

Table 2. Single effects of cultivar, on average of doses of trinexapac applied on rye plants at the GS36, on the traits spike length (SL), peduncle length (PL), internode-1 (I-1), internode-2 (I-2), stem diameter (SD), plant height (PH), thousand grain weight (TGW), number of grains per ear (NGE), number of spikelets per ear (NSE), number of grains per spikelet (NGS), hectoliter weight (HW), grain yield (GY) and harvest index (HI) of rye. Lages, Brazil, 2018 growing season

Cultivar	**Morphometric traits**					
	SL (cm)	PL (cm)	I-1 (cm)	I-2 (cm)	SD (mm)	PH (cm)
BRS Serrano	11.29	37.56 b	34.15	24.10	3.10 b	144.81 a
IPR 89	10.95	39.89 a	34.45	24.25	3.67 a	136.92 b
P	0.24	<0.001	0.74	0.86	<0.001	<0.001

Cultivar	**Productive and qualitative traits of grains**						
	TGW (g)	NGE (n°)	NSE (n°)	NGS (n°)	HW (kg hL^{-1})	GY (kg ha^{-1})	HI (%)
BRS Serrano	19.21 b	37.57 b	31.01 b	1.13 b	68.47 b	4158.16 b	39.97
IPR 89	23.92 a	45.81 a	33.12 a	1.48 a	72.25 a	5504.18 a	40.31
*P**	<0.001	0.02	<0.001	<0.001	<0.001	<0.001	0.72

Note. * Probability.

Cultivar IRP 89 outperformed in all the productive and qualitative characteristics of grains when compared to cultivar BRS Serrano—except for harvest index. Although HI was higher, it did not exceed the minimum significant difference ($P > 0.05$). For yield components (NGE, NSE, NGS), this difference was more evident in the number of grains per spikelet (+ 23.7%) and in the number of grains per ear, *i.e.*, 18% more grains were found in cultivar IPR 89. This fact, associated with greater thousand-grain weight (+ 4.7 g), had a direct effect on grain yield, which was higher for IPR 89, with a difference of 1347 kg ha^{-1} (equivalent to 22.4 bags per hectare) when compared with BRS Serrano. Cultivar IPR 89 still surpassed its competitor indirectly in grain quality when considering hectoliter weight, which was 3.8 kg hL^{-1} greater.

The parameterization of canopy height as a function of time also showed that cultivar BRS Serrano had a lower response to trinexapac. There was an upward increase in height on the basis of days after application with a more vertical angle for this cultivar. At the time of application, plant height of cultivar IPR 89 was 41.6 cm greater than BRS Serrano; however, at 21 days after application, BRS Serrano and IPR 89 had a similar plant height of about 150 cm (Figures 3A and 3B).

Trinexapac doses applied at GS36 acted independently on plant height (21 DAA and final height) (Figure 3C and 3D), with decreases at a rate of 6.2 and 8.7 cm for every 100 g. a.i. ha^{-1} of trinexapac applied. For peduncle length, there was a quadratic negative response at a dose of 150 g a.i. ha^{-1} with only 36.5cm (Figure 3E). However, for thousand-grain weight, there was a quadratic positive response at a dose of 77.1 g a.i. ha^{-1} with TGW of 22.0 g (Figure 3E). For lodging, the response was dependent on the cultivar; lodging decreased, as the analysis of BRS Serrano showed a cubic function and IPR 89, a quadratic one (Figure 3F). Cultivar IPR 89 showed a stable reduction of lodging because an increase in the rate of the growth regulator resulted in a quadratic adjustment. There was a significant reduction of lodging at a level of 4.9% when using (theoretically) 221 g a.i. ha^{-1}. On the other hand, cultivar BRS Serrano showed a cubic behavior, demonstrating a decrease in the lodging index below 15% only in trinexapac doses above 150 to 200 g a.i. ha^{-1} (Figure 3F).

However, in both cultivars, lodging was lower at a dose around 150 g a.i. ha^{-1}. This finding suggests that doses greater than 150 g a.i. ha^{-1} can be used for maximum efficiency of the product to reduce canopy height. However, these doses of trinexapac have to be related to the productive behavior and lodging index of each cultivar.

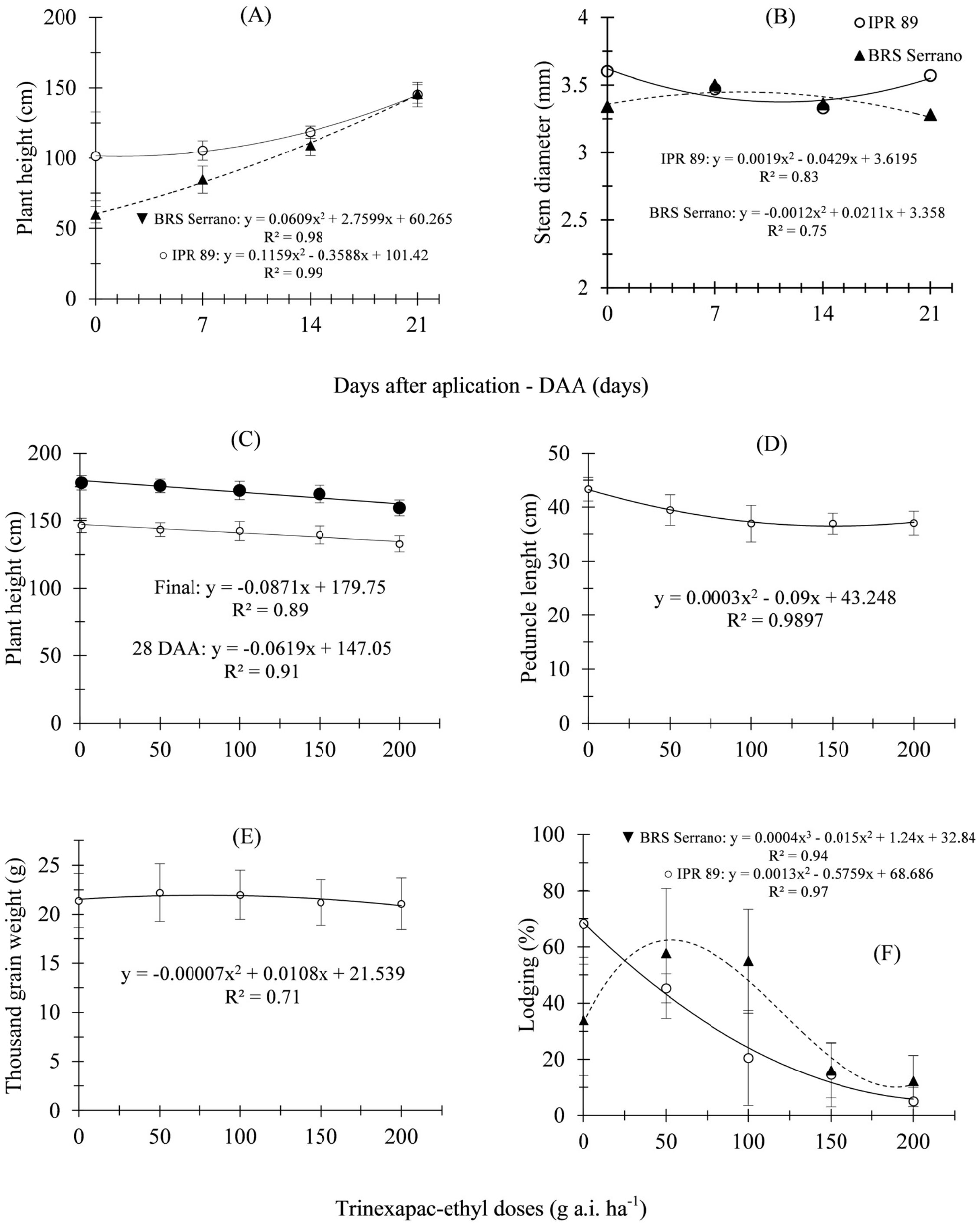

Figure 3. Plant height and stem diameter on the basis of days after trinexapac application on plants of rye at GS36 × cultivar interactions (A and B). Single effects for plant height (end of cycle and at 28 DAA) (C), peduncle length (D), thousand-grain weight (E) and cultivar interactions for lodging index doses (F) on the basis of trinexapac doses. Lages, Brazil, 2018 growing season

4. Discussion

The hypothesis that trinexapac doses applied on rye plants at the phenological stage GS34 would have an effect on reduction of final plant height and increase in grain yield and grain quality was refuted. However, the effect was confirmed for plant lodging index. This effect was possibly due to the long cycle of rye crops and the resumption of stem growth after the period of action of the growth regulator on the plant. When absorbed by plants, trinexapac acts and temporarily reduces the activity of active gibberellic acid. Moreover, in this period, it prevents complete cell elongation, reducing plant growth doses (Bazzo et al., 2019). However, in the second experiment, the hypothesis was confirmed with trinexapac doses applied at GS36, based on the following traits: plant height, lodging index and on thousand grain weight.

Based on the results, it can be assumed that the crop is more sensitive to the responses of trinexapac when applied between the middle and the end of stem elongation. Stefen et al. (2014), and Quinn and Steinke (2018), in studies with wheat crops; Souza et al. (2013), and Novakoski et al. (2020) with soybeans; and Peron et al. (2019), in rice crops, also reported a reduction in plant height after application of trinexapac doses. In this study, the reduction in plant height in response to trinexapac application was associated with a reduction in peduncle length, a characteristic that is related to the lodging index. According to Espindula et al. (2009), these responses are due to the ability of regulators, particularly trinexapac, to reduce plant lodging owing to combination of shorter and stronger plant internodes.

Fioreze and Rodrigues (2014) also found a reduction in the source-sink distance in a wheat crop after application of trinexapac. Such response corroborates the reduction of dry matter accumulation of the plant owing to an increase in the rate of the regulator. Consequently, there is less translocation of assimilates from the source to the grains, which results in a reduction of thousand-grain weight, but without affecting yield, however. Turek et al. (2018) also found that thousand-grain weight decreased with increased doses of trinexapac (0, 125 and 188 g a.i. ha^{-1}), without, however, affecting wheat grain yield.

Regarding the response of trinexapac in the different rye genotypes, cultivar IPR 89 was more sensitive to reduction in the response of the lodging index because of its higher resistance to lodging and the slightly lower development cycle in comparison to the BRS Serrano genotype. This stability of the IPR 89 directly led to higher yield. Furthermore, plant height behavior of the genotypes resulted in a different response to the one reported by Espindula et al. (2010) in an experiment carried out with wheat cv. Pioneiro. It turned out that peduncle length was the structure that most contributed to longitudinal growth and final height of the plants, unlike the results of the present work. There was a slight effect of decreasing peduncle length form 43 cm to 36.5 cm with 150 g a.i. ha^{-1} trinexapac. The greater vegetative growth is closely linked to changes in the biophysical properties of the stem, mainly in the reduction of its basal diameter.

The higher values of the yield components and the industrial quality of IPR 89 resulted in higher grain yield, possibly because of the lower longitudinal growth of this genotype in comparison to BRS Serrano, which has greater capacity for translocation of assimilates to the grains. In wheat, semi-dwarfing genes resulted in cultivars with shorter stems, which were strong enough to support the heavy grains and extra yield owing to improved assimilate partitioning into the grains (Hedden, 2003). These Reduced height (Rht) genes have been widely used, and in the 1990s, their molecular basis was found to be due to mutations in a gibberellic acid signaling gene, which reduced responsiveness to this hormone (Annunziata, 2018). This ideotype (reduced height) is absent on both rye cultivars (IPR 89 and BRS Serrano) used in the present research.

4. Conclusions

The application of trinexapac to the fourth visible node (GS34) is not effective for the morphophysiological and productive characters of rye, although it shows a slight response in mitigating plant lodging; by contrast, when application is performed to the sixth visible node (GS36), plants have smaller height at the end of the cycle and lower lodging than control, which leads to better grain quality, with consistent results in trinexapac doses around 150 g a.i. ha^{-1}.

The reduction in lodging is dependent on the speed of resumption of plant height growth and the stability of response to trinexapac by each cultivar; cultivar IPR 89 showed greater response stability to the growth regulator than BRS Serrano.

These results are promising because grain yield was not affected (neither negatively nor positively) by application of trinexapac in either GS34 or GS36 phenological stages. However, it was only in GS36 that the favorable combination of lower plant lodging and lower plant height was achieved. As a consequence, rye farmers cope with an environment with less lodging and, hence, more harvestability and higher grain quality.

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