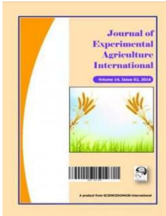

Journal of Experimental Agriculture International

16(5): 1-9, 2017; Article no.JEAI.33647
Previously known as American Journal of Experimental Agriculture
ISSN: 2231-0606

Trinexapac-ethyl Winter Wheat (*Triticum aestivum* L.) Cultivar Evaluations with Variable Rates of Nitrogen

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Authors' contributions

This work was carried out in collaboration between all authors. Author DBS managed the literature searches and wrote all drafts of the manuscript. Authors TLG and TMW, designed the study, wrote the protocol, performed the statistical analysis, managed the analyses of the study, and edited all drafts of the manuscript. Authors WF supplied technical support, research materials, data collection support, etc. from Syngenta. Author WKV edited all drafts of the manuscript. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JEAI/2017/33647
Editor(s):
(1) Aleksander Lisowski, Warsaw University of Life Sciences, Department Agricultural and Forestry Engineering, Poland.
Reviewers:
(1) Mustafa Ünlü, Cukurova University, Adana, Turkey.
(2) Leyla Idikut, Sutcu Imam Universty, Kahramanmaras, Turkiye.
(3) Ahmed Medhat Mohamed Al-Naggar, Cairo University, Egypt.
Complete Peer review History: http://www.sciencedomain.org/review-history/19552

Short Research Article

Received 24th April 2017
Accepted 14th May 2017
Published 15th June 2017

ABSTRACT

In the southeastern region of the United Sates, soft red winter wheat (*Triticum aestivum* L.) is grown in double-crop production systems. The plant growth regulator (PGR) trinexapac-ethyl is applied to improve wheat morphology by reducing height and increasing stem wall diameter, which can promote maximum yields. An experiment was conducted from 2014 to 2015 to evaluate the effects of trinexapac-ethyl with varying N rates on growth, lodging, and yield of five soft red winter wheat cultivars. Soft red winter wheat was treated with trinexapac-ethyl at 233 or 256 g ai ha^{-1}at 60 d after planting, or as a split application of 128 g ai ha^{-1} 60 and 108 d after planting. Nitrogen fertilizer at 112 or 168 kg ha^{-1} was applied at Feekes' stage 3-4. Crop heights, spike counts per m^2, and node length from the flag leaf to the base of the floral spike were collected 144 d after planting,

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with final yields, grain moisture, and test weight determined after harvest. There were no interactions for the main effects of PGR by nitrogen rate, PGR by cultivar, or cultivar by nitrogen rate. Trinexapac-ethyl at 256 at Feekes 4, or split applied at 128 g ha^{-1} at Feekes 4 and 7, significantly reduced soft red winter wheat height, and distance from the flag-leaf node to base of the floral spike as compared to the non-treated control. While there were no yield differences for trinexapac-ethyl treatments, height reductions and improved stem strength would reduce lodging that can often lead to crop failure.

Keywords: Soft red winter wheat cultivars; trinexapac-ethyl; N fertilizer.

ABBREVIATION

TE: Trinexapac-ethyl

1. INTRODUCTION

Soft red winter wheat (*Triticum aestivum* L.) is an autumn-seeded crop in the southeastern United States utilized for grain and forage. Soft red winter wheat is a secondary crop in multiple-cropping systems that can provide an economical way for farmers to produce two crops in one year [1,2]. From 2013 to 2016,17 million ha $year^{-1}$ of soft red winter wheat were harvested across the United States [3]. Due to the significance of wheat in many double-crop production systems, there has been a greater interest in wheat production practices, especially those that encourage high crop yield [4,5]. Primary requirements for high yields are uniform stand establishment followed by even tiller production which can be influenced by crop additives such as plant growth regulators and N fertilization [5].

Plant growth regulators (PGRs) are phytohormones that mimic or modify one or more specific physiological processes within a plant [6]. Organ development or photosynthetic properties are not negatively affected by PGRs but allow the crop to continue developmental sequence with retarded growth [7,8,9]. In small grain and forage production, PGRs reduce stem internodes and length (13-28%) and improve grain set, grain quality, development, and harvest ability [10,11,12,13]. PGRs have been reported to increase seed yields in tall fescue, creeping red fescue, perennial ryegrass, and annual ryegrass seed crops as much as 50% or greater [14,15,16,13,17]. Previous studies on Kentucky bluegrass displayed that trinexapac-ethyl reduced heat tolerance, total height, average clipping yield 30-45%, and growth rate but increased chlorophyll concentration [18,19, 20,21].

Trinexapac-ethyl is a plant growth regulator for turf grass seed production and small grains in the southeast [22,15,10]. Trinexapac-ethyl is a unique Type II PGR in that it interferes with the production of gibberellins (GAs) later in gibberellin biosynthetic pathway with respect to other Type II PGRs [23,24,25]. Trinexapac-ethyl is an acyl cyclohexanedione derived from cyclohexanecarboxylate. It inhibits the hydroxylation of GA_{20} to the physiologically active GA_1 by inhibiting 3-β-hydroxylase, a regulatory enzyme [26,27,28]. The inhibition of this key enzyme prevents cell elongation (i.e. expansion) which causes a shortening of internodes, a strengthening of the stem, an increase in stem diameter, and reduction in lodging [11,29,13].

Trinexapac-ethyl applications interact with other management practices including canopy closure date, crop residue destruction, and nitrogen application [13,30,15,31]. There has always been interest in using timing and rate of N fertilizer application for intense soft red winter wheat management that maximize yield [5,32,33,34,35,36]. One study evaluated N uptake and use efficiency prior to and during the grain filling period in soft red winter wheat [37]. Another previous study noted that there was a strong correlation between grain protein/yield and N uptake under non-limiting N conditions [37]. Multiple research has shown that grain yield has been directly linked with the uptake of N [38,39,40,41].

University of Georgia recommendations for a N application are 90 to112 kg ha^{-1}in a season for small grains production. In the autumn season, the cropping rotation strategy and previous crop can affect the amount of N fertilizer applied [42,43]. During the winter season, several applications of N can be made prior to stem elongation in wheat. Once tillers are being promoted, excessive N fertilization can lead to lodging and reductions in flour quality and milling properties, so applications are not recommended after Feekes' growth stage 4-5 [44,42]. Soft red winter wheat cultivars are continuously changing due to breeding programs that seek to improve disease tolerance, quality, and grain yield [45,46,47,48,49].

There is limited information available on trinexapac-ethyl effects on wheat cropping systems in the southeastern US. Given variability in wheat cultivar response to plant growth regulators and N fertilization [50,51,38,52,37,36], a field study was designed to evaluate the effects of trinexapac-ethyl and varying N rates on winter wheat lodging and yield to five different wheat cultivars.

2. MATERIALS AND METHODS

A field trial was conducted from 2014 to 2015 at the Southwest Georgia Branch Experiment Station (SWGREC) located in Plains Georgia (Latitude 32.036638; Longitude -84.397595). Soil type was a Faceville sandy loam (clayey, kaolinitic, thermic, Typic Kandiudults) with < 1% organic matter and pH of 6.1. The soil was conventionally prepared by disk harrowing, moldboard plowing 25 to 30 cm deep, then rotary tilling. Single plots were 1.8 m wide and 9.1 m long.

Soft red winter wheat cultivars AGS 2026, AGS 2060, Coker 9553, Coker 9700, and Cypress were sown at 323-377/m^2 into seedbeds on 5 Dec 2014 at 101 kg ha^{-1} [53,54,55]. Higher seeding rates are not recommended for standard cultural practices because of the increased potential for disease and lodging [33]. Main effect of cultivar was blocked by replication. Within each cultivar block, N fertilizer rate and PGR applications were randomized.

Nitrogen fertilizer at 112 or 168 kg ha^{-1} was applied with a Gandy TM Spreader (The Gandy Co., Mankato, MN) on 22 Jan 2015 when wheat was in Feekes' growth stage 3-4. Trinexapac-ethyl was POST applied to wheat at 233 or 256 g ai ha^{-1}60 d after planting, or as a split application of 128 g ai ha^{-1} each time at 60 and 108 d after planting. The PGR treatments were applied with a CO_2-pressurized broadcast sprayer with FF11002 nozzles calibrated to deliver187 L ha^{-1} volume of water. Standard culture practices for wheat production were followed using University of Georgia recommendations for pest control [56].

At Feekes' stage 10.5 data for crop heights from soil to apex of the spike (cm), along with apical stem length from the flag-leaf node to the base of the floral spike (cm), was measured on 5 random plants for each variable. Data for spike counts per m^2 were also recorded. These data were collected 144 d after planting. Grain was harvested at Feekes' growth stage 11 after natural desiccation, using a small plot combine, grain was mechanically cleaned, and then for each plot grain moisture, yield, and test weight determined. Final grain yield was based on 13% moisture.

The experimental design was a three-way factorial arranged in a randomized complete block with four replications. Data was subjected to mixed-model ANOVA analysis in SAS 9.4®, and all two-way interactions were subjected to GLM procedures. Means were separated using an LSD at the P = 0.05 level.

3. RESULTS AND DISCUSSION

The two-way interactions for crop height, head count, yield, and test weight for cultivar (C) x fertilizer (F), C x trinexapac-ethyl treatment (TE), and F x TE were not significant for any variable (Table 1). For flag-leaf to apex, C x F was significant (P = 0.0099), but not for C x TE or F x TE. As cultivars will vary for height due to genotype differences, the C x F difference is an indication of this variability [47]. Therefore, data for all variables for the main effects for TE were combined across N fertilizer treatment and cultivars, main effects of F were combined across TE and cultivars, and main effects of cultivars were combined across TE and F for analysis.

3.1 Trinexapac-ethyl

Wheat height varied amongst the four different PGR treatments. There were significant height reductions when TE was applied at 256 g ai ha^{-1}, and for the split application of 128 g ai ha^{-1} at Feekes' stage 4 and 7 (Table 2). Data indicated that the single TE application of 256 g ai ha^{-1} and split application of 128 g ai ha^{-1}, reduced plant heights to 80 and 76 cm, respectively as compared to the NTC with 83 cm. Similarly, there was a significant reduction in length of the stem for flag-leaf to the base of the floral apex, ranging from 9 to 11 cm, for any TE application treatment as compared to the NTC with 12 cm (Table 2). These findings correspond with previous research results that applications of trinexapac-ethyl at later wheat growth development stages reduce plant height [12]. There were no differences for any treatment for wheat head count per m^2 or grain test weight (Table 2). These results confer with previous research that reported PGR interactions were nonsignificant for test weight measurements [50].

Table 1. Analysis of variance for TE and N effects on wheat cultivars in Georgia[a]

Variable	Effect	F-value	Pr > R	
Crop height (cm)	Cultivar x Fertilizer	2.09	.11	NS[b]
	Cultivar x TE	1.46	.30	NS
	Fertilizer x TE	0.43	.79	NS
Flag-leaf to base of floral spike (cm)	Cultivar x Fertilizer	3.47	.01	**
	Cultivar x TE	0.83	.62	NS
	Fertilizer x TE	1.31	.27	NS
Head count/m^2	Cultivar x Fertilizer	1.90	.09	NS
	Cultivar x TE	1.19	.15	NS
	Fertilizer x TE	0.35	.73	NS
Test weight (kg hL^{-1})	Cultivar x Fertilizer	1.45	.22	NS
	Cultivar x TE	0.91	.54	NS
	Fertilizer x TE	0.44	.72	NS
Yield (kg ha^{-1})	Cultivar x Fertilizer	0.61	.65	NS
	Cultivar x TE	0.85	.63	NS
	Fertilizer x TE	0.25	.86	NS

[a]Location was Plains, GA conducted in 2014-2015. Cultivars were AGS 2026, AGS 2060, Coker 9553, Coker 9700, and Cypress. MIXED model analysis was performed.
*[b]Abbreviation: NS, not significant; ** = level of probability at P = 0.01 to 0.001, respectively*

Table 2. Crop height, head count, and flag-leaf to apex as influenced by cultivar, fertilizer application, and growth regulator application conducted for 2014-2015.[a]

Variable	Rate	Timing	Crop height		Flag-leaf to base of floral spike		Head count		Test Weight[b]	
Main effect of growth regulator	**g ha^{-1}**	**Feekes' stage**	**cm**		**cm**		**# m^2**		**kg hL^{-1}**	
Nontreated			83	a	12	a	412	a	67	a
Trinexapac-ethyl	233	4	81	ab	11	b	423	a	67	a
Trinexapac-ethyl	256	4	80	b	11	b	425	a	66	a
Trinexapac-ethyl	128 + 128	4 + 7	76	c	9	c	415	a	67	a
Main effect of fertilizer	**kg ha^{-1}**									
Nitrogen fertilizer	112	3-4	79	b	11	a	408	b	67	a
Nitrogen fertilizer	168	3-4	81	a	11	a	430	a	67	a
Main effect of cultivar										
Coker 9553			87	a	12	b	420	a	67	b
Coker 9700			82	b	9	e	442	a	69	a
Cypress			78	c	13	a	427	a	68	a
AGS 2026			78	c	11	c	427	a	64	d
AGS 2060			75	d	10	d	382	b	65	c

[a]The two-way interactions of cultivar x fertilizer and fertilizer x trinexapac-ethyl were not significant; therefore, data were combined across variables. However, the two-way interaction of cultivar x fertilizer was significant for flag-leaf to base of floral spike measurements.
[b]Means with a variable followed by the same letter are not significant according to Fisher's protected LSD test at $P \le 0.05$

Trinexapac-ethyl treatments had similar yields as compared to the non-treated control, 3,470 kg ha^{-1} and 3,660 kg ha^{-1}(Table 3). None of the TE treatments impacted these soft red winter wheat yields, indicating the crop safety for this PGR. It can be used to effectively reduce plant height, which could reduce potential for lodging. Previous research noted no differences in yield for TE applied to wheat in an experiment in South America, however they did not indicate the type of wheat [47]. Similar results have been reported with ethephon [50, 57].

Table 3. Yield as influenced by cultivar, fertilizer treatments, and growth regulator applications conducted for 2014-2015.[a]

Variable	Rate	Yield[b]
Main effect of growth regulator	**g ha^{-1}**	**kg ha^{-1}**
Nontreated		3660 a
Trinexapac-ethyl	233	3570 a
Trinexapac-ethyl	256	3470 a
Trinexapac-ethyl	128 + 128	3520 a
Main effect of fertilizer	**kg ha^{-1}**	
Nitrogen fertilizer	112	3440 b
Nitrogen fertilizer	168	3670 a
Main effect of cultivar		
Coker 9553		3920 a
Coker 9700		3660 bc
Cypress		3590 c
AGS 2026		3720 b
AGS 2060		2960 d

[a]The two-way interactions of cultivar x fertilizer, fertilizer x trinexapac-ethyl, and cultivar x fertilizer were not significant for yield; therefore, data were combined across variables.
[b]Means with a variable followed by the same letter are not significant according to Fisher's protected LSD test at $P \leq 0.05$

3.2 N Fertilizer

Significant differences for wheat head count per m^2 were observed between the two N fertilizer applications. The 168 kg N ha^{-1} fertilizer treatment produced more wheat heads than the 112 kg N ha^{-1} application (Table 2). Previous research noted reduced spike number $plant^{-1}$ and grain number $spike^{-1}$ when lower nitrogen levels were present [36]. Crop height measurements displayed a similar response to the 112 and 168 kg N ha^{-1} applications in which the larger application rate produced a larger plant (Table 2). Previous research on dryland winter wheat indicated higher nitrogen rates result in larger plants with greater above-ground biomass than with lower application rates [58]. However, a taller height could potentially lead to lodging issues later in the growing season. With respect to crop height, the results differ from a previous study in which researchers reported no influence over wheat height due to nitrogen application rates [47]. For flag-leaf to the base of the floral apex measurements and grain test weights, no differences were detected between the 112 or 168 kg ha^{-1} treatments (Table 2).

For N application rates, there were significant differences in yield. The 168 kg N ha^{-1} application yielded 3,670 kg ha^{-1}, while the 112 kg N ha^{-1} rate yielded 3,440 kg ha^{-1} (Table 3). Previous research on soft red winter wheat indicated similar results and concluded that a positive linear correlation exists between the increase in yield and increase in amount of N fertilizer applied [32]. More recent research noted that increases in nitrogen fertilizer applications had a positive influence on wheat grain protein and yield [36,59]. Furthermore, one researcher reported that a split fall and spring application of high nitrogen rates may be important for maximizing grain yield in soft red winter wheat [34].

3.3 Cultivar

Between all five cultivars, there were differences for each of the measurements recorded. With respect to wheat height, there were no differences between the Cypress and AGS 2026 cultivars but all other cultivars were significantly different (Table 2). AGS 2060 was the shortest of the cultivars at 75 cm while Coker 9553 was the tallest at 87 cm. However, previous research reported no difference in crop height across all seven winter wheat cultivars tested [50]. AGS2060, which had the smallest average with 382 heads, was the only significant cultivar for head count per m^2. All five cultivars were significantly different from one another for flag-leaf to the base of the floral apex measurements, with Cypress as the tallest and Coker 9700 as the shortest (Table 2). Wheat cultivar was the only significant (P < 0.0001) main effect observed for test weight. Amongst the cultivars, Coker 9700 and Cypress were statistically similar at 68 and 69 kg hL^{-1}. These cultivars differed from Coker 9553, AGS 2026, and AGS 2060 in which wheat cultivars AGS 2026 and Coker 9700 had the lowest and highest average test weights, respectively (Table 2).

With respect to yield, PGRs are designed to allow the full yield potential of wheat to be realized due to interfering with plant development [60]. It is the reduction in lodging of the cultivar that allows for the yield potential to be increased over other scenarios [61]. There were significant differences in yield among the cultivars, with Coker 9553 (3,290 kg ha^{-1}) having the greatest yield and AGS 2060 having the least (2,960 kg ha^{-1}). Coker 9700 was similar to both AGS 2026 and Cypress, even though AGS 2026 yielded greater at 3,720 kg ha^{-1} (Table 3). Variable cultivar yield response corresponds with previous research using ethephon on seven winter wheat cultivars [50].

4. CONCLUSION

In conclusion, the split application of trinexapac-ethyl at Feekes' stage 4 and 7 significantly reduced overall stem length. While it did not improve wheat yield, trinexapac-ethyl could assist growers by preventing lodging from occurring which would improve harvest efficiency promoting greater yield. Each of the five cultivars had a varying degree of response to fertilizer and trinexapac-ethyl treatments. AGS 2060 had the least amount of response to all treatments and produced the lowest yield as compared to all other cultivars. Higher N fertilizer rates resulted in larger and higher yielding wheat as was expected. Future research will focus on repeating this study.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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