

Genetic gain in grain yield across the historical serie of forage triticale cultivars released by the Universidad Autónoma Agraria Antonio Narro

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ABSTRACT

Objective: To evaluate genetic progress in grain yield and associated agronomic traits in forage triticale (\times Triticosecale Wittmack) cultivars developed by the Universidad Autónoma Agraria Antonio Narro (UAAAN) between 1992 and 2022.

Design/Methodology/Approach: Seven winter-habit cultivars, classified as older, intermediate, and modern, were evaluated at 19 locations in northern Mexico (2019-2023) for grain yield (GY) and at three locations (2023-2024) for yield components (YC). A randomized complete block design with three replications was used. Analysis of variance and linear regression were performed to estimate absolute and relative genetic gains.

Results: Significant differences were detected between release periods for GY and YC. Modern cultivars obtained the highest average (6.105 t ha^{-1}), with absolute genetic gains of $70 \text{ kg ha}^{-1} \text{ year}^{-1}$ and relative gains of $2.1\% \text{ year}^{-1}$. A sustained increase in grains m^{-2} and a reduction in plant height without affecting biomass production were observed.

Limitations on study/Implications: The study focused solely on UAAAN winter cultivars under conditions in northern Mexico. Extrapolation to other programs should be done with caution.

Findings/Conclusions: The UAAAN breeding program has achieved significant genetic advances in forage triticale, combining increases in GY and YC with height reduction. The results provided key information for strengthening the institutional program, with a focus on GY and productive stability, while maintaining forage potential and adapting to current systems.

Keywords: triticale, genetic gain, grain yield, yield components, breeding.

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INTRODUCTION

Triticale (\times Triticosecale Wittmack), a synthetic hybrid derived from the cross between wheat (*Triticum* spp.) and rye (*Secale cereale*), combines the high yield and grain quality of wheat with the hardiness and tolerance to adverse conditions of rye (Mergoum *et al.*, 2009). Since its development, it has shown outstanding potential as a forage crop and, to a lesser extent, as a grain source for animal and human consumption. Its adaptability to different

agroclimatic conditions, efficient use of nitrogen, and high biomass production have positioned it as a strategic alternative in regions with water and soil limitations (Varughese *et al.*, 1987; Plana *et al.*, 2016).

In Mexico, the area planted with triticale has grown in forage production areas, particularly in the Laguna Region, due to its ability to produce quality forage and seed at relatively low costs. However, although genetic improvement of triticale in the country has historically prioritized forage production, the demand for high-yield, high-quality seed has increased the need to develop cultivars that optimize both production objectives.

The Universidad Autónoma Agraria, Antonio Narro (Mexico) UAAAN has promoted the development of winter-habit forage cultivars, registering 10 cultivars between 1992 and 2022. Initially, these genotypes yielded more than 45 t ha⁻¹ of green matter but with grain yields lower than 2.5 t ha⁻¹. In response, the breeding program incorporated crosses with spring and facultative cultivars, increasing grain yield without sacrificing forage potential. This approach is consistent with global trends in cereal breeding, which seek to maximize harvest index and stability under different environments (Royo *et al.*, 2007; Fischer *et al.*, 2014).

Estimating genetic gain from historical series of cultivars is a key tool for evaluating the effectiveness of breeding programs. This method, widely used in crops such as wheat, maize, and rice, allows quantifying annual progress in yield and associated components, separating genetic from environmental effects through statistical analyses such as linear regression and mixed models (Valvo *et al.*, 2018; Stoyanov & Baychev, 2023). In triticale, studies on genetic gain are scarce, especially in forage production contexts. In this sense, the present study had the following objectives: 1) to evaluate the genetic progress in grain yield in a historical series of seven winter-habit triticale forage cultivars released by the UAAAN between 1992 and 2022, and 2) to determine the agronomic characteristics associated with these changes in order to generate information that will contribute to guiding future genetic improvement strategies for the crop.

MATERIALS AND METHODS

Genetic material

Seven forage cultivars of triticale with winter and intermediate-winter habits, developed by UAAAN between 1992 and 2022, were evaluated. The cultivars were classified into three release periods, Modern: AN330 and AN388 (2022); Intermediate: ANPELÓN, AN66, and AN184 (2014); and Older: AN31 and AN34 (1992).

Study locations

The experiments were conducted under irrigation in 19 production environments located in northern Mexico (Aldama, Chihuahua; Miguel Auza, Zacatecas; Matamoros, San Pedro de las Colonias; and La Soledad, Coahuila) during the 2019-2023 agricultural cycles. For the evaluation of yield components, three representative locations in the Laguna Region (Soledad, Campanario, and Centenario) were considered during the 2023-2024 autumn-winter cycle.

Experimental design and agronomic management

A randomized complete block design with three replications was used. Experimental plots consisted of five rows, each 5 m long, spaced 30 cm apart (7.5 m^{-2} per plot), sown at a seeding rate of 140 kg ha^{-1} . Fertilization was applied in two stages: at planting and during tillering, with a dose equivalent to 38-0-0 (N) plus 11-52-0 (P_2O_5). Phytosanitary control consisted of preventative applications of fungicide against yellow rust (*Puccinia striiformis* W.) and pre- and post-emergence herbicides. No significant pest problems were recorded.

Variables evaluated

At physiological maturity, plant height (cm) was measured from the base of the stem to the tip of the spike (without awns), as well as the number of spikes m^{-2} (NSM2). At harvest maturity, the number of grains per spike (NGPS), the number of grains m^{-2} (NGM2) (calculated as $\text{NSM2} \times \text{NGPS}$), and the grain yield (GY), estimated after harvesting and threshing a 5 m row and expressed in kg ha^{-1} , were quantified.

Estimated genetic gain

Absolute genetic gain (AGG, $\text{kg ha}^{-1} \text{ yr}^{-1}$) and relative genetic gain (RGG, $\% \text{ yr}^{-1}$) were calculated based on the differences between means for each release period, divided by the number of years elapsed, following the methodology of Royo *et al.* (2007).

Statistical Analysis

A combined analysis of variance was performed for grain yield and yield components, considering locations and release periods as fixed factors, and replicates nested within locations as a random factor. Means were compared using the Tukey test ($p \leq 0.05$).

A simple linear regression analysis was also applied between the year of release and the agronomic variables to estimate genetic progress. Analyses were performed using the Statistical Analysis System (SAS) version 9.4 (SAS Institute, 2013).

RESULTS AND DISCUSSION

Grain Yield

The combined analysis of variance showed highly significant effects ($p \leq 0.01$) of location, release period, and their interaction on grain yield, with a coefficient of variation (CV) of 7.4% (Table 1), indicating high experimental precision. The variability between locations confirms the strong influence of soil and climate factors on triticale yield, consistent with reports for winter cereals (Cooper *et al.*, 2022).

Modern cultivars (AN330 and AN388) recorded the highest average yield (6.105 t ha^{-1}), significantly outperforming intermediate (4.223 t ha^{-1}) and older (3.914 t ha^{-1}) cultivars (Table 2). These increases are associated with improvements in components such as the number of spikes per m^2 , grains per spike, and grain density, traits that have been identified as key drivers of cereal yield (Fischer *et al.*, 2014; Slafer *et al.*, 2015).

Table 1. Mean squares and significance of the combined analysis of variance between locations and release periods for the grain yield variable, cycles 2019 to 2023.

SV	DF	Mean square (t ha ⁻¹)
Location	18	15.66 **
Location × Replication	38	0.56 **
RP	2	80.09 **
Location × RP	36	1.48 **
Error	76	0.12
CV (%)		7.4

SV=Source of variation; DF=Degrees of freedom; CV=Coefficient of variation; RP=Release periods. ** Significant at $p \leq 0.01$.

Table 2. Results of the mean comparison test for the grain yield variable for the release period factor.

Release period	Cultivar	Mean (t ha ⁻¹)
Modern	AN330	6.105 ^a
	AN388	
Intermediate	ANPELÓN	4.223 ^b
	AN66	
	AN184	
Older	AN31	3.914 ^b
	AN34	

Different letters indicate significant differences according to Tukey's multiple comparison test ($p \leq 0.05$).

Yield components

In the 2023-2024 crop cycle, modern cultivars had higher values of spikes per m⁻² (464), grains per spike (61), and grains per m² (27,559), followed by intermediate and older cultivars (Table 3). These differences reflect the effectiveness of genetic improvement in increasing spike fertility and reproductive organ density, patterns also documented in wheat and barley (Sadras & Slafer, 2012; Han *et al.*, 2020).

Table 3. Results of the mean comparison test of yield components between release periods. 2022-2023 cycle.

Release period	Cultivar	NSM2 (Spikes m ⁻²)	NGPS (Grains spike ⁻¹)	NGM2 (Grains m ⁻²)
Modern	AN330	464 ^a	61 ^a	27559 ^a
	AN388			
Intermediate	ANPELÓN	381 ^b	49 ^b	18773 ^b
	AN66			
	AN184			
Older	AN31	350 ^c	42 ^c	15366 ^c
	AN34			

NSM2=Number of spikes m⁻²; NGPS=Number of grains per spike; NGM2=Number of grains m⁻². Different letters indicate significant differences according to Tukey's multiple comparison test ($p \leq 0.05$).

The number of spikes m^{-2} was mainly influenced by the location, demonstrating the sensitivity of this trait to management and environmental factors, while the number of grains per spike and grains m^{-2} were more consistent between locations, indicating greater genetic stability (Table 4).

Plant height

Significant differences in plant height (Table 5) were detected between groups of triticale cultivars (release periods), demonstrating a genetic shift toward more moderate plant heights, consistent with trends reported for triticale and wheat (Trini *et al.*, 2021).

A progressive reduction in plant height was observed (Table 6) from the older cultivars (128 cm) to the modern ones (113 cm). This change is related to the incorporation of dwarfing genes (*Rht*) and selection toward more compact phenotypes to reduce lodging and improve the partitioning of assimilated nutrients into the grain, without affecting forage potential (Reynolds *et al.*, 2009; Velasco-López *et al.*, 2025).

Genetic Gain

Linear regression analysis between year of release and yield (Figure 1) indicated a genetic gain of 70 to 236 $\text{kg ha}^{-1} \text{ year}^{-1}$, depending on the comparison between the periods, ($R^2=0.49$). The components most associated with the increase were the number

Table 4. Results of the analysis of variance for the yield components of 7 triticale cultivars classified by release periods, evaluated at three locations. Autumn-winter cycle 2023-2024.

SV	DF	NSM2 (Spikes m^{-2})	NGPS (Grains spike $^{-1}$)	NGM2 (Grains m^{-2})
Location	2	16771.90 **	11.37	9550836.50
Location × Replication	6	1399.40	25.21 *	3840150.90
RP	2	1133.40 **	1351.21 **	1542287771 **
Location × RP	4	2010	11.16	362370
Error	12	4981.20	5.63	19447541.60
CV (%)		6.30	5.60	9.50

SV=Source of variation; DF=Degrees of freedom; RP=Release periods; CV=Coefficient of variation; NSM2=Number of spikes m^{-2} ; NGPS=Number of grains per spike; NGM2=Number of grains m^{-2} .
** Significant at $p \leq 0.01$.

Table 5. Results of the analysis of variance for the plant height (PH) variable of triticale cultivars released by the UAAAN between 1992 and 2023.

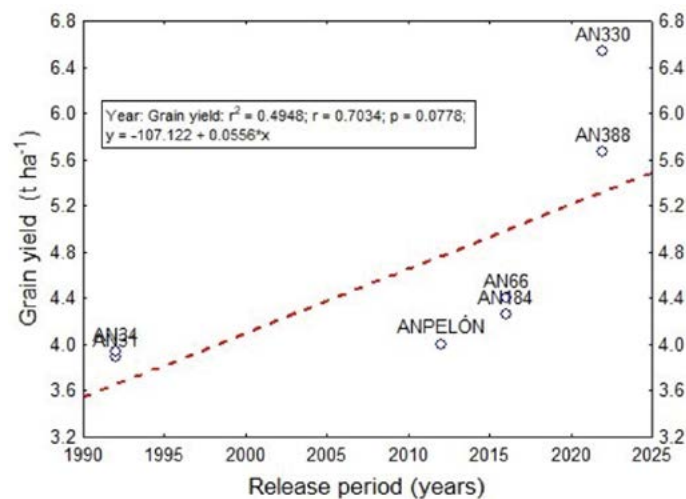
SV	DF	PH (cm)
Release period	2	282.18 *
Replication	2	29.12
Error	4	12.14
CV (%)		2.8

SV=Source of variation; DF=Degrees of freedom; CV=Coefficient of variation; * Significant at $p \leq 0.05$.

Table 6. Results of the comparison of means between release periods for the plant height (PH) variable.

Release period	Cultivar	PH (cm)
Modern	AN330	113 c
	AN388	
Intermediate	ANPELÓN	123 b
	AN66	
	AN184	
Older	AN31	128 a
	AN34	

Different letters indicate significant differences according to Tukey's multiple comparison test ($p \leq 0.05$).

**Figure 1.** Relationships between the release period (1992–2022) of winter triticale cultivars developed by UAAAN and grain yield.

of grains m^{-2} ($R^2=0.62$) and grains per spike ($R^2=0.61$) (Figure 2), confirming that the increase in grain number has been the main driver of genetic progress in triticale, as is the case with other small-grain cereals (Ferrante *et al.*, 2013).

The decrease in height showed a negative relationship with the year of release ($\beta = -7.02$ $cm\ year^{-1}$), consistent with trends in cereal breeding aimed at improving stability and reducing lodging losses.

Recent studies have reported that yield regression over the year of release is a practical tool for quantifying the effectiveness of breeding schemes in cereals (Fischer *et al.*, 2014).

Tables 7 and 8 show the absolute genetic gain (AGG) and relative genetic gain (RGG) by year in winter-habit triticale cultivars, evaluating key variables such as GY, NSM2, NGPS, NGM2, and plant height (PH). Overall, a positive trend in genetic gains for yield and its components was observed when comparing modern cultivars with older and intermediate cultivars, which is consistent with current reports on genetic improvement in triticale and other cereals.

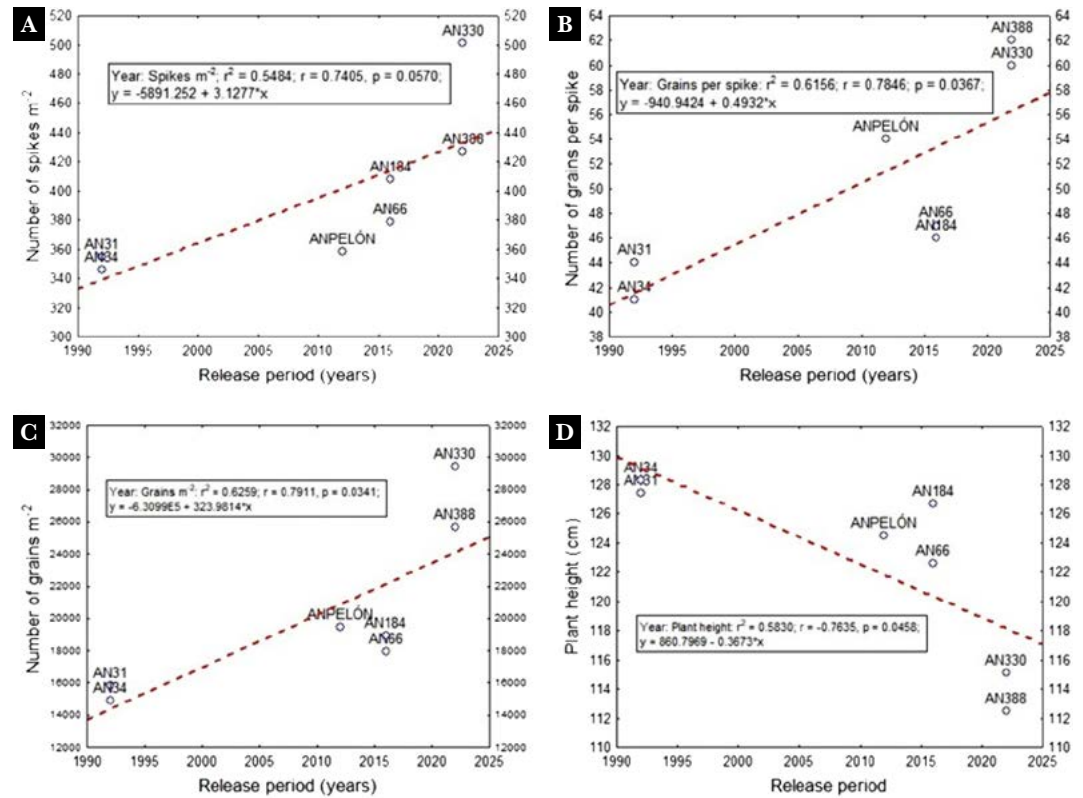


Figure 2. Relationships between the release period (1992-2022) of winter triticale cultivars developed by UAAAN and: A) number of spikes m^{-2} , B) number of grains per spike, C) number of grains m^{-2} , D) plant height.

Table 7. Absolute genetic gains per year for grain yield (GY) and its components of the cultivars under study according to their release period.

	GY ($kg\ ha^{-1}\ yr^{-1}$)	NSM2 (Spikes $m^{-2}\ yr^{-1}$)	NGPS (Grains spike $^{-1}\ yr^{-1}$)	NGM2 (Grains $m^{-2}\ yr^{-1}$)	PH ($cm\ yr^{-1}$)
M vs. O	70	3.80	0.60	499.60	-0.46
M vs. Int	236.20	10.10	1.50	1832.60	-1.36
Int vs. O	9.50	1.50	0.27	14.80	-0.14

M vs. O=Modern vs. Older; M vs. Int=Modern vs. Intermediate; Int vs. O=Intermediate vs. Older; NSM2=Number of spikes m^{-2} ; NGPS=Number of grains per spike; NGM2=Number of grains m^{-2} .

Table 8. Relative genetic gains (%) per year for grain yield (GY) and its components of the cultivars under study according to their release period.

	GY	NSM2	NGPS	NGM2	PH
M vs. O	2.10	2.50	2.30	1.60	-3.70
M vs. Int	8.50	10.30	9.90	6.30	-13.60
Int vs. O	4.30	4.10	3.90	4.40	-4.60

M vs. O=Modern vs. Older; M vs. Int=Modern vs. Intermediate; Int vs. O=Intermediate vs. Older; NSM2=Number of spikes m^{-2} ; NGPS=Number of grains per spike; NGM2=Number of grains m^{-2} .

The comparison between modern and old cultivars (M *vs.* O) showed an increase in AGG of $70 \text{ kg ha}^{-1} \text{ yr}^{-1}$ in GY (Table 7), with an increase in RGG of $2.10\% \text{ yr}^{-1}$ (Table 8). These values are similar to those reported by Ferrante *et al.*, (2017) in wheat, who observed annual genetic improvements in yield between 1.80% and 2.50% under Mediterranean climate conditions. Furthermore, the increase in NSM2 with $3.80 \text{ spikes m}^{-2} \text{ yr}^{-1}$ of AGG and 2.50% of RGG; as well as NGPS with $0.60 \text{ grains spike}^{-1} \text{ yr}^{-1}$ of AGG and 2.30% of RGG suggests that the improvement has been effective in both the formation of reproductive structures and fertility.

The comparison between modern and intermediate cultivars (M *vs.* Int) revealed even higher gains, with a GY increase of $236.2 \text{ kg ha}^{-1} \text{ yr}^{-1}$ of AGG and a relative increase of $8.5\% \text{ yr}^{-1}$ of RGG (Tables 7 and 8), indicating that recent generations of cultivars have incorporated significant genetic advances. This observation is consistent with that reported by Velasco-López *et al.* (2025) in Mexico, who report that new triticale cultivars show significant improvements in phenotypic and genetic parameters associated with yield, thanks to assisted selection and the incorporation of materials adapted to specific environments. On the other hand, plant height showed an AGG and RGG decrease in all comparisons, with a reduction of up to $-13.6\% \text{ yr}^{-1}$ in the case of modern versus intermediate cultivars. This reduction in height is desirable from an agronomic viewpoint, since shorter plants tend to be more resistant to lodging problems and promote better resource utilization, as recent studies by Paccapelo *et al.* (2015) in triticale indicate.

Finally, genetic gains between intermediate and old cultivars (Int *vs.* O) were moderate but positive, reflecting continued progress in genetic improvement over the years, supported by the use of modern statistical and phenotypic tools to evaluate and select superior genotypes (Fischer *et al.*, 2014).

The above findings are consistent with those reported by Perry & D'Antuono (1989), Royo *et al.*, (2007) and Valvo *et al.*, (2018) in wheat and Stoyanov & Baychev, (2023) in triticale, who recorded linear increases in yield in response to genetic improvement over time. Genetic gains in yield were also related to progress in yield components, such as NGPS and NGM2 (Tables 7 and 8). This positive relationship between the aforementioned traits explains the trend observed in Figure 1, given that yield is a complex and multigenic trait, highly dependent on the components that affect it (Slafer *et al.*, 2015).

The above results confirm that the implemented strategies have been effective in increasing and improving yield potential by strengthening precision in the selection stage (Reynolds *et al.*, 2009; Rodríguez-Pérez *et al.*, 2023).

The analysis of the historical series of winter-habit triticale forage cultivars released by the UAAAN between 1992 and 2022 showed significant genetic progress in grain yield, primarily associated with an increase in the number of grains per square meter and grains per spike. The modern cultivars outperformed the older and intermediate cultivars by more than 2 t ha^{-1} , with estimated annual genetic gains of up to 70 kg ha^{-1} , reflecting the effectiveness of the breeding program in optimizing yield without compromising forage production. The progressive reduction in plant height helped minimize the risk of lodging and improve the efficiency of biomass partitioning toward the grain, while maintaining adequate forage production potential.

CONCLUSIONS

Overall, these results demonstrate that the UAAAN triticale breeding program has achieved significant advances in yield and stability, prioritizing key traits such as grain density and height reduction, while maintaining its value as a forage crop. These results confirm that the breeding applied at UAAAN has allowed the development of triticale cultivars that are more productive, stable, and adapted to the conditions of northern Mexico, strengthening its role as a strategic crop in dual-purpose production systems.

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