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Nitrogen management, grain yield, and agronomic traits associated with linear relationships in wheat

Manejo do nitrogênio, produtividade de grãos e características agronômicas associadas a relações lineares em trigo

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Highlights

Wheat cultivars respond differently to nitrogen fertilization methods.
The maximum number of tillers reduces the hectoliter weight of wheat.
The maximum number of tillers has a direct effect on grain yield.

Abstract

Wheat is one of the most important cereal crops in the world, being the second most produced globally. It has the largest cultivation areas in the subtropical region of Brazil during the winter period. However, Brazilian wheat production is insufficient to meet domestic demand, requiring imports to adequately supply the demand. Thus, the objective of this study was to evaluate the effect of nitrogen splitting on wheat cultivars grown in a low-altitude subtropical environment. This study was conducted in a randomized block design distributed in strips, characterizing a three-factor experiment 4x6x2, (four cultivation environments, six wheat cultivars, and two nitrogen management regimes). It was possible to verify that the splitting or single application of nitrogen management as topdressing should be evaluated individually for each wheat cultivar, depending on the productive response of each cultivar.

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For wheat crops in different environments, and subjected to splitting or not of nitrogen fertilization as topdressing, the variable maximum number of tillers reduces the hectoliter weight of wheat when it is sown in July. The direct effects on the maximum number of tillers variable can be used to improve grain productivity for nitrogen management without split applications. For plant height, there are positive direct effects on grain productivity when sowing in June, with the effect enhanced by greater water availability.
Key words: Low-altitude subtropical environment. Path analysis. Pearson correlations. *Triticum aestivum* L. Yield components.

Resumo

O trigo é um dos cultivos de cereais mais importantes do mundo, sendo o segundo mais produzido a nível global. Aquele que apresenta maiores áreas de cultivo na região subtropical do Brasil no período hibernal. Embora, a produção brasileira de trigo seja insuficiente para suprir a demanda interna, necessitando de importação para suprimento adequado da demanda. Assim, o objetivo do estudo foi avaliar o efeito do parcelamento de nitrogênio em cultivares de trigo, cultivadas em ambiente subtropical de baixa altitude. Este estudo foi conduzido no delineamento experimental de blocos ao acaso distribuídos em faixas, caracterizando um experimento trifatorial (4x6x2), com quatro ambientes de cultivo, seis cultivares de trigo e dois manejos nitrogenados. Foi possível verificar que, o parcelamento ou aplicação única do manejo nitrogenado em cobertura deve ser avaliado individualmente para cada cultivar de trigo, em função da resposta produtiva de cada cultivar. Para cultivos de trigo em diferentes ambientes, e submetidos ao parcelamento ou não da adubação nitrogenada em cobertura a variável número de afilhos máximo reduz o peso hectolitro do trigo quando este é semeado no mês de julho. Os efeitos diretos para a variável número de afilhos máximo podem ser utilizados para a melhoria da produtividade de grãos para o manejo nitrogenado sem parcelamento. Para altura de plantas tem-se efeitos diretos positivos sobre a produtividade de grãos em datas de semeadura no mês de junho, com efeito potencializado por maior disponibilidade hídrica.
Palavras-chave: Ambiente subtropical de baixa altitude. Análise trilha. Componentes de rendimento. Correlações de Pearson. *Triticum aestivum* L.

Introduction

Wheat (*Triticum aestivum* L.) is one of the most important crops in the global food matrix, ranking as the second most-produced cereal (Food and Agriculture Organization of the United Nations [FAO], 2023). It holds a prominent position in Brazil's subtropical region during the winter, where it represents the crop with the largest cultivated area (Companhia Nacional de Abastecimento [CONAB], 2024). According to CONAB (2024), Brazil's wheat cultivation spanned 3.473 million hectares in the 2023 harvest, yielding 8.096 million tons of grain, with Rio Grande do Sul State (southern Brazil) alone accounting for 1.5 million hectares and 2.897 million tons of this production. However, with an annual domestic consumption approximating 12 million tons, Brazil remains reliant on grain imports to satisfy its domestic needs (Agricultural Market Information System [AMIS], 2020).

Southern Rio Grande do Sul has emerged as a promising region for wheat cultivation expansion. Between 2011 and 2015, soybean cultivation in this area expanded by one million hectares (Emygdio et al., 2017), highlighting the region's significant potential for winter wheat cultivation due to favorable yield and profitability outcomes. Nevertheless, challenges persist, primarily due to the hydromorphic nature of the soils, which suffer from imperfect drainage and are prone to prolonged periods of surface or subsurface waterlogging. These conditions complicate nitrogen application timing and limit mechanization, particularly for splitting (Emygdio et al., 2017).

Nitrogen management is a considerable expense in wheat production (Cui et al., 2014), making the adoption of agronomic practices that enhance productivity while minimizing costs essential for the crop's sustainability and economic feasibility (Kaneko et al., 2010). Nitrogen, an element surpassed in plant abundance only by carbon, oxygen, and hydrogen, plays a pivotal role in plant growth (Taiz et al., 2017). Demonstrating its essential role in physiological and biochemical processes, it is employed in leaf expansion, root growth, and gene expression, forming part of fundamental biomolecules such as amino acids, proteins, chlorophyll, membranes, and plant hormones (Fernandes et al., 2018).

The literature has yet to thoroughly investigate the responsiveness of modern wheat cultivars to nitrogen splitting. For cultivars with limited response to nitrogen splitting, employing a single application of nitrogen in top dressing could improve operational efficiency and decrease production costs in low-altitude subtropical environments. Thus, the objective of this study was to evaluate the effect of nitrogen splitting in wheat cultivars grown in a low-altitude subtropical environment.

Material and Methods

The experiment was conducted in Santa Maria, Rio Grande do Sul- Brasil. The climate in the region is classified as humid subtropical (Cfa) according to the Köppen classification, characterized by an absence of a distinct dry season and an average annual precipitation of 1.616 mm (Alvares et al., 2013); the soil is categorized as red dystrophic arenic ultisol (Santos et al., 2018).

The experiment followed a randomized block design in a trifactorial scheme (4×6×2), with four cultivation environments (Environment one with sowing in June 2021, environment two with sowing in July 2021, environment three with sowing in June 2022, and environment four with sowing in July 2022), six wheat cultivars ('Tbio Aton', 'Tbio Audaz', 'Tbio Ello, 'Tbio Ponteiro', 'Tbio Toruk', and 'Tbio Trunfo'), and two nitrogen management strategies (nitrogen management without splitting, and the splitting in two aplications nitrogen in two equal portions). In the nitrogen management without splitting, all nitrogen was applied as a top dressing at the tillering stage (V3/V4), with a dose of 75 kg ha^{-1} of N, derived from urea with 45% nitrogen. For the splitting, nitrogen was applied in two equal portions: 50% at the tillering stage (V3/V4) and 50% at the wheat elongation stage (V7/V8), with a total dose of 75 kg ha^{-1} of N, amounting to 37.5 kg ha^{-1} in each application, derived from urea with 45% nitrogen. The experimental design encompassed 12 treatments with three replications, resulting in 36 experimental units per growing environment and 144 experimental units across all environments. Each experimental unit consisted of 10 sowing rows, spaced at 0.20 m intervals and 2.5 m in length, yielding a total area of 5.0 m^2 per unit.

The selected cultivation environments were designed to align with the recommended wheat sowing periods for the region, as established by the crop's climate zoning. In the 2021 harvest season, sowing commenced in the first environment (EA) on June 16, 2021, and in the second (EB) on July 6, 2021. For the 2022 harvest, the sowing began in the third (EC) on June 14, 2022, and in the fourth environment (ED) on July 7, 2022. The seeding process utilized a density of 330 viable seeds/m2, establishing an initial plant population of 300 plants/m^2.

For wheat sowing, soil analysis was performed on the area designated for experimentation, where the following were verified for the year 2021: pH: 4.8; organic matter: 2.3%; clay: 32%; CEC pH7: 12.4; K: 48.0 mg dm^{-3}; P: 42.0 mg dm^{-3}. For 2022, the following were verified: pH: 5.2; organic matter: 2.4%; clay: 32%; CEC pH7: 13.6; K: 36.0 mg dm^{-3}; P: 11.0 mg dm^{-3}. For base fertilization, 400 kg ha^{-1} of the 05-20-20 NPK formulation was applied. During the crop cycle, pest, weed, and disease control management was applied, according to the technical recommendations for the crop (Joris et al., 2022).

Meteorological variables are important due to the impact they have on wheat cultivation (Figure 1), enhancing the wheat growing environment. For environment A (Figure 1A), during the experimental period, rainfall totaled 621.8 mm in the complete cycle, while it showed 271.6 mm between anthesis and harvest maturity of wheat, average air temperatures of 15.1ºC and incident radiation of 802.8 Mj m^{-2} between the anthesis and harvest maturity period of wheat. In relation to environment B (Figure 1B), rainfall totaled 519.4 mm in the complete cycle, with rainfall of 193.6 mm between anthesis and harvest maturity of wheat, average air temperatures of 16.6ºC and incident radiation of 855.6 Mj m^{-2} between the anthesis and harvest maturity period of wheat.

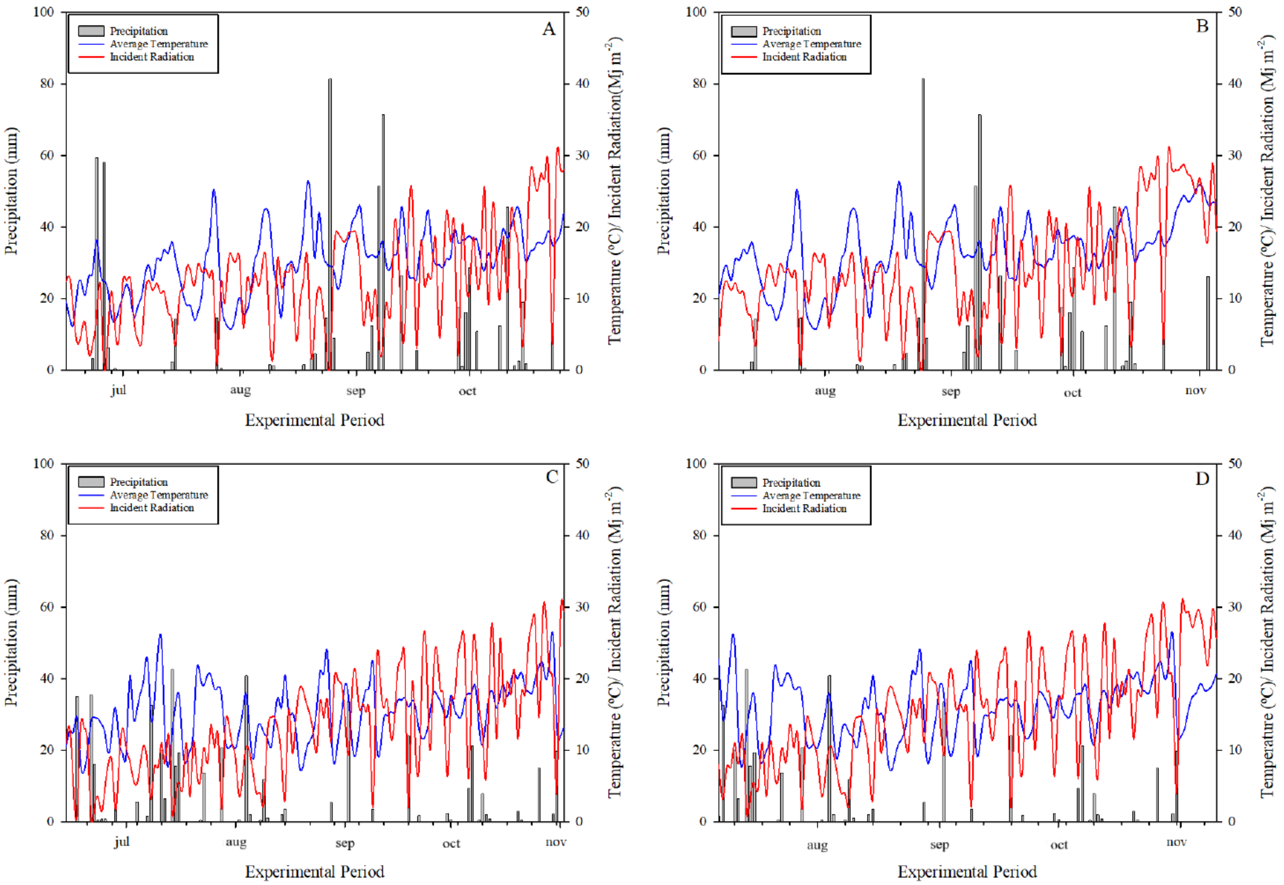

Figure 1. Climatic indicators for the different cultivation environments during the experimental period.
A) Environment A (June, 2021); B) Environment B (July, 2021); C) Environment C (June, 2022); and D) Environment D (July, 2022). The arrows indicate the onset of anthesis.

In comparison to environment C (Figure 1C), where 493.8 mm of accumulated rainfall was observed, with a volume of 111.4 mm distributed between anthesis and harvest maturity of wheat, average air temperatures of 15.3ºC and incident radiation of 926.2 Mj m^{-2} between anthesis and harvest maturity of wheat. In wheat cultivation environment D (Figure 1D), accumulated rainfall of 393.6 mm occurred, while 85.6 mm were distributed between anthesis and harvest maturity of wheat, average air temperatures of 15.9ºC and incident radiation of 910.8 Mj m^{-2} from anthesis to harvest maturity of wheat.

At the end of the crop cycle, 1,152 plants (8 plants per plot) were evaluated for agronomic traits and yield components, including plant height (PH), main spike length (MSL), tiller spike length (TSL), number of spikelets per main spike (NSS), number of spikelets per tiller spike (NST), number of grains per main spike (NGS), number of grains per tiller spike (NGT), thousand-grain weight (TGW), final number of tillers (FNT), maximum number of tillers (MNT), hectoliter weight (HW), and grain yield (GY).

The TGW was determined by weighing three samples of 100 grains each and adjusting the weight to a standard scale. For GY measurements, the grains from the productive area of the plot were weighed, with the productive area defined as the eight central rows, each two meters in length; moisture content was standardized to 13% for GY determination. The MNT was identified through weekly monitoring of the number of young plants in 12 previously marked samples within the experimental units. Meteorological data were obtained from the Brazilian National Institute of Meteorology, recorded at an automatic surface weather station, approximately 500 m from the experimental area.

We calculated the assumptions of error normality and homoscedasticity of variances using the Shapiro-Wilk and Bartlett tests, respectively. The variables GY, TGW, FNT, and PH underwent analysis of variance (ANOVA) to assess differences among treatments. The data were then grouped using the Scott-Knott test at a 5% probability level. Pearson's linear correlation and path analysis were conducted with the R software version 4.3.3 (R Core Team [R], 2024). Multicollinearity was evaluated using the condition number criterion and variance inflation factor before path analysis, which led to the exclusion of variables with high multicollinearity values.

Results and Discussion

For the characters subjected to analysis of variance in Table 1, the mean squares observed for each variable analyzed are presented. It is possible to denote the occurrence of significant individual effects for the cultivation environment factor, and the cultivar factor, as observed by Ahmed et al. (2023), for all variables analyzed. An interaction between the cultivation environment and cultivar factors is also observed for the variables FNT, HW, and GY. Similarly, an interaction between cultivars and nitrogen management is observed for the variables TGW and GY. And for the variables TGW and HW, an interaction between cultivation environments and nitrogen management is also observed.

Table 1
Mean square of the ANOVA for the variables analyzed as a function of different nitrogen management, cultivation environments, and wheat cultivars

Variables	DF	FNT	TGW	PH	GY
Block	2	0.056	12.37	0.011	1023561
Nitrogen	1	0.047	17.46	9.379	25779
Block error	2	0.086	12.98	3.021	106676
Environment	3	5.285*	431.7**	97.39*	11260643*
Cultivar	5	2.003*	77.9*	147.84*	1257374*
Environment x cultivar	15	1.052*	8.90	26.91*	1110852*
Track error	46	0.106	8.00	3.670	223418
Environment x nitrogen	3	0.210	200.53*	17.061*	105207
Cultivar x nitrogen	5	0.076	57.33*	6.923	808688*
Environment x cultivar x nitrogen	15	0.089	34.92	2.068	333943
Error	46	0.126	20.34	3.956	208673

DF = Degrees of freedom; FNT = final number of tillers; TGW = thousand-grain weight; HW = hectoliter weight; GY = grain yield. *Statistically significant at a 5% probability level ($p \leq 0.05$).

An analysis of the characters, evaluated using the Scott-Knott test, revealed a FNT (Table 2), indicating differences due to the environmental factor. Environment B exhibited statistically significant superiority over the others. Furthermore, a statistical divergence was noted for the cultivar factor, corroborating the findings of Ahmed et al. (2023). 'Tbio Ello CL' exhibited an average of 1.41 final shoots, surpassing the performance of other materials assessed. This finding aligns with the observations of Fioreze et al. (2019), who reported that wheat demonstrates productive plasticity by emitting more spikes, a trait directly linked to FNT. However, no significant differences were observed between the nitrogen treatments, contrasting with the findings of Ferrari et al. (2016), where nitrogen splitting at the tillering and flowering stages resulted in a higher number of fertile tillers.

Table 2
Test of means for the variables analyzed as a function of different nitrogen management, cultivation environments, and wheat cultivars, subjected to the Scott-Knott grouping test

Cultivar	EA			EB			EC			ED			Avg. CxN	Avg. CxN	Avg. cultivars
	100%	50% +50%	Avg. CxEA	100%	50%+ 50%	Avg. CxEB	100%	50%+ 50%	Avg. CxEC	100%	50%+ 50%	Avg. CxED	100%	50% +50%	
Final tiller count															
'Tbio Aton'	0.67*	0.73	0.70^{cB}	1.33	1	1.16^{bA}	0.33	0.39	0.36^{cC}	0.92	1.19	1.05^{cA}	0.81^{ns}	0.83^{ns}	0.82^{c}
'Tbio Audaz'	0.53	0.53	0.53^{dC}	0.87	0.73	0.80^{cB}	0.11	0.22	0.16^{dD}	0.83	1.11	0.97^{cA}	0.59	0.65	0.61^{e}
'Tbio Ello CL'	0.8	0.93	0.87^{bC}	3.13	2.87	3.00^{aA}	0.59	0.94	0.77^{aC}	1.08	0.97	1.02^{cB}	1.4	1.43	1.41^{a}
'Tbio Ponteiro'	0.87	0.8	0.83^{bB}	1	1.2	1.10^{bA}	0.25	0.5	0.37^{cC}	1	0.67	0.83^{dB}	0.78	0.79	0.78^{d}
'Tbio Toruk'	1.33	1.4	1.37^{aB}	1.33	1	1.16^{bC}	0.42	0.53	0.47^{bD}	1.67	1.42	1.54^{aA}	1.19	1.09	1.13^{b}
'Tbio Trunfo'	1	0.73	0.87^{bB}	0.87	0.8	0.83^{cB}	0.44	0.58	0.51^{bC}	1.5	0.75	1.12^{bA}	0.95	0.72	0.83^{c}
Avg. NxE	0.87^{ns}	0.85		1.42	1.27		0.36	0.53		1.17	1.02				
Avg. N													0.95^{ns}	0.92	
Avg. env.			0.86^{c}			1.34^{a}			0.44^{d}			1.09^{b}			
Thousand-grain weight															
'Tbio Aton'	50.04	41.4	45.72^{ns}	44.19	48.98	46.59^{ns}	40.33	42.33	41.33^{ns}	34.67	36	35.34^{ns}	42.72^{cA}	42.51^{bA}	42.61^{b}
'Tbio Audaz'	41.24	48.68	44.96	33.84	48.11	40.98	38.67	40	39.34	36.33	37.33	36.83	37.10^{eB}	43.1 9^{aA}	40.15^{d}
'Tbio Ello CL'	43.68	43.41	43.55	36	42.7	39.35	38	38	38	34	36.67	35.34	37.91^{dB}	40.19^{dA}	39.05^{e}
'Tbio Ponteiro'	49.34	41.96	45.65	45.56	43.31	44.44	41.67	40.67	41.17	38.33	38	38.17	43.72^{bA}	40.98^{cB}	42.35^{c}
'Tbio Toruk'	48.24	44.05	46.15	43.06	46.3	44.68	40.33	39.33	39.83	38.67	38.67	38.67	42.57^{cA}	42.08^{bA}	42.33^{c}
'Tbio Trunfo'	53.64	37.21	45.43	39.76	52.86	46.31	43	44.67	43.84	41	39.67	40.34	44.35^{aA}	43.60^{aA}	43.97^{a}
Avg. NxE	47.69^{aA}	42.78^{bB}		40.40^{bB}	47.04^{aA}		40.33^{aB}	40.83^{aC}		37.16^{aC}	37.72^{aD}				
Avg. N													41.40^{ns}	42.09	
Avg. env.			45.24^{a}			43.72^{b}			40.58^{c}			37.44^{d}			

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							Hectoliter weight								
'Tbio Aton'	77.4	78.13	77.76^{cB}	77.4	72.9	75.15^{cC}	76.2	74.4	75.30^{cC}	78.57	78.88	78.72^{bA}	77.39^{ns}	76.08^{ns}	76.73^{c}
'Tbio Audaz'	77.38	77.4	77.39^{cB}	79.62	78.13	78.87^{bA}	74.7	75	74.85^{cC}	78.6	79.47	79.03^{bA}	77.58	77.5	77.53^{b}
'Tbio Ello CL'	78.13	79.62	78.87^{bA}	73.65	71.4	72.52^{dC}	74.4	75.9	76.65^{bB}	79.45	78.28	78.86^{bA}	76.41	76.3	76.72^{c}
'Tbio Ponteiro'	77.38	80.38	78.88^{bA}	70.65	68.4	69.52^{eD}	73.2	73.8	73.50^{dB}	71.4	69.9	70.65^{dC}	73.16	73.12	73.13^{e}
'Tbio Toruk'	75.15	78.13	76.64^{dB}	74.4	75.15	74.77^{cC}	75	75.75	75.37^{cC}	78.28	78.28	78.28^{cA}	75.71	76.83	76.26^{d}
'Tbio Trunfo'	84.18	82.65	83.41^{aA}	81.92	78.13	80.02^{aB}	80.85	79.47	80.15^{aB}	80.35	79.45	79.90^{aB}	81.83	79.93	80.87^{a}
Avg. NxE	78.27^{bA}	78.38^{aA}		76.27^{aC}	74.01^{bD}		76.22^{aC}	75.71^{bC}		77.77^{aB}	77.37^{bB}				
Avg. N													77.01^{ns}	76.63	
Avg. env.			78.92^{a}			75.14^{d}			75.97^{c}			77.57^{b}			
							Grain yield								
'Tbio Aton'	2661.12	3185.49	2923.30^{cC}	3552.97	4111.57	3832.27^{aB}	4495.12	4732.34	4613.73^{aA}	2391.7	2692.13	2541.91^{aD}	3275.22^{cB}	3680.38^{aA}	3477.80^{a}
'Tbio Audaz'	3060.03	2904.56	2982.29^{cC}	3639.53	3353.72	3496.62^{bB}	4053.11	5213.38	4633.24^{aA}	2478.67	3011.02	2744.84^{cD}	3307.83^{bB}	3620.67^{aA}	3464.25^{a}
'Tbio Ello CL'	2979.48	2802.55	2891.01^{eD}	3616.43	3160.76	3388.59^{bC}	4492.77	3963.14	4227.95^{bA}	3722.78	3391.83	3557.30^{aB}	3702.86^{aA}	3329.57^{bB}	3516.21^{a}
'Tbio Ponteiro'	3324.57	3809.78	3567.17^{aA}	3133.09	3144.37	3138.73^{cB}	3301.68	2796.01	3048.84^{dB}	2756.44	1742.19	2249.31^{eC}	3128.94^{dA}	2873.08^{dB}	3001.01^{c}
'Tbio Toruk'	2702.63	2321.91	2512.26^{dD}	3353.82	2760.27	3057.04^{cB}	4127.85	3777.56	3952.70^{cA}	2782.28	2957.84	2870.06^{bC}	3241.64^{cA}	2954.39^{cB}	3098.01^{b}
'Tbio Trunfo'	2873.3	3573.34	3223.32^{bC}	3497.04	4121.69	3809.36^{aB}	3855.86	4143.28	3999.56^{cA}	3022.74	2846.51	2934.62^{bD}	3312.23^{bB}	3671.20^{aA}	3491.72^{a}
Avg. NxE	2933.52^{ns}	3099.61		3465.48	3442.06		4054.4	4104.29		2859.1	2773.59				
Avg. N													3328.12^{ns}	3354.88	
Avg. env.			3016.56^{C}			3453.77^{B}			4079.34^{A}			2816.34^{D}			

E = Environment; N = nitrogen; ns = non-significant difference. *Means followed by the same superscript lowercase letter in a column and the same superscript uppercase letter in a row do not differ statistically according to the Scott Knott test at a 5% probability level ($p < 0.05$). For the interaction between nitrogen management and environments, lowercase superscript letters compare nitrogen management within each environment, while uppercase superscript letters compare environments within each nitrogen management (mean N x E).

Regarding HW, no statistically significant differences were found among the environments, with EA showing a higher average. Cultivars displayed differences, with ‘Tbio Trunfo’ achieving the best result. However, no significant difference was detected between nitrogen management practices for HW, in line with Jadoski et al. (2024), who found that different nitrogen management strategies did not affect HW averages. Additionally, interactions between environments and cultivars, and environments and nitrogen management were identified. ‘Tbio Trunfo’ consistently showed superiority across all environments when analyzing the effects of cultivars within cultivation environments.

Moreover, EA and ED exhibited superior results within each cultivar, although ED was superior for four of the six cultivars tested, suggesting its suitability for cultivating these cultivars. The interaction between the environments and nitrogen management was analyzed in more detail, revealing that, for the different managed environments, the approach without nitrogen splitting showed superior results in all environments, except for the EA where nitrogen management with splitting was superior. Nevertheless, EA displayed superior averages for both nitrogen management practices when evaluating the effect of environments within nitrogen management.

Among the variables assessed individually, GY exhibited statistical differences across environments. Environment C produced the highest yields, while EA experienced higher precipitation. Conversely, ED, with the lowest precipitation, resulted in lower GY. Intermediate precipitation levels in EB and EC (519.4 and 493.8 mm, respectively) were associated with higher GY. These findings are consistent with those of Nehbandani et al. (2023), who observed that reduced precipitation in southern Brazil could enhance wheat production, provided extreme events such as droughts do not occur.

The cultivar factor revealed that ‘Tbio Aton’, ‘Tbio Audaz’, ‘Tbio Ello CL’, and ‘Tbio Trunfo’ achieved higher average GYs, exceeding 3000 kg ha^{-1}. These averages surpassed those reported by Martin et al. (2021), who examined the impact of nitrogen fertilization in similar environments. Furthermore, interactions between factors were noted, particularly between environments and cultivars and between cultivars and nitrogen management. The analysis identified five cultivars with the highest GY in EC. An evaluation of cultivars within each environment revealed varied responses: ‘Tbio Ponteiro’ performed best in EA ‘Tbio Trunfo’ and ‘Tbio Aton’ excelled in EB ‘Tbio Aton’ and ‘Tbio Audaz’ yielded the most in EC and ‘Tbio Ello CL’ led in ED. These results underscore the variable adaptive capacities of cultivars to different environments, with only ‘Tbio Aton’ consistently excelling in more than one environment for GY.

The interaction between different wheat cultivars and nitrogen management strategies indicated that the cultivar ‘Tbio Ello CL’ outperformed other cultivars under single-dose nitrogen management strategies. Conversely, the cultivars ‘Tbio Aton’, ‘Tbio Audaz’, and ‘Tbio Trunfo’ showed superior performance with nitrogen management that involved splitting the application into multiple doses. These findings are in line with the research conducted by Marinho et al. (2020), which concluded that the impact of nitrogen fertilization on seed yield varies depending on the cultivar. Similarly, Costa et al. (2013) underscored the variability in productive responses across different genotypes, noting that certain genotypes did not exhibit increased GY when nitrogen was applied in split applications.

Further examination of nitrogen management practices within each cultivar revealed two distinct clusters of three cultivars each. Applying nitrogen in a single dose yielded the highest mean performance for ‘Tbio Ello CL’, ‘Tbio Ponteiro’, and ‘Tbio Toruk’. In contrast, applying nitrogen in split doses was more beneficial for ‘Tbio Aton’, ‘Tbio Audaz’, and ‘Tbio Trunfo’. However, research by Batista et al. (2020), focusing on nitrogen splitting in Paraná State (southern Brazil), showed similar grain yields for both split and single-dose nitrogen applications.

The relationship between various traits also played a crucial role, as indicated by Pearson’s linear correlations (Figure 2) and path analysis (Figure 3), which elucidated the direct and indirect effects of each trait on grain yield. A significant number of Pearson correlations demonstrated meaningful coefficients across different environments and nitrogen management scenarios for wheat cultivars. For instance, the correlation between NST and NGT showed positive and significant indices in all scenarios, ranging from 0.71 in EB with split-dose nitrogen management to 0.97 under single-dose nitrogen management in EC.

Although not universally significant across all combinations of environments and nitrogen management strategies, several other correlations, notably TSL × NST, TSL × NGT, NSS × NGS, and MSL × NGS, were positively significant in seven of the eight possible scenarios (Figure 2). For example, the correlation between TSL and NGT varied at 0.53–0.94, yet it was not significant in EB under nitrogen management without splitting. A similar pattern was observed for TSL × NST, which was not significant in EB under a single-dose nitrogen management strategy but ranged at 0.64–0.99 across all other environment and management combinations.

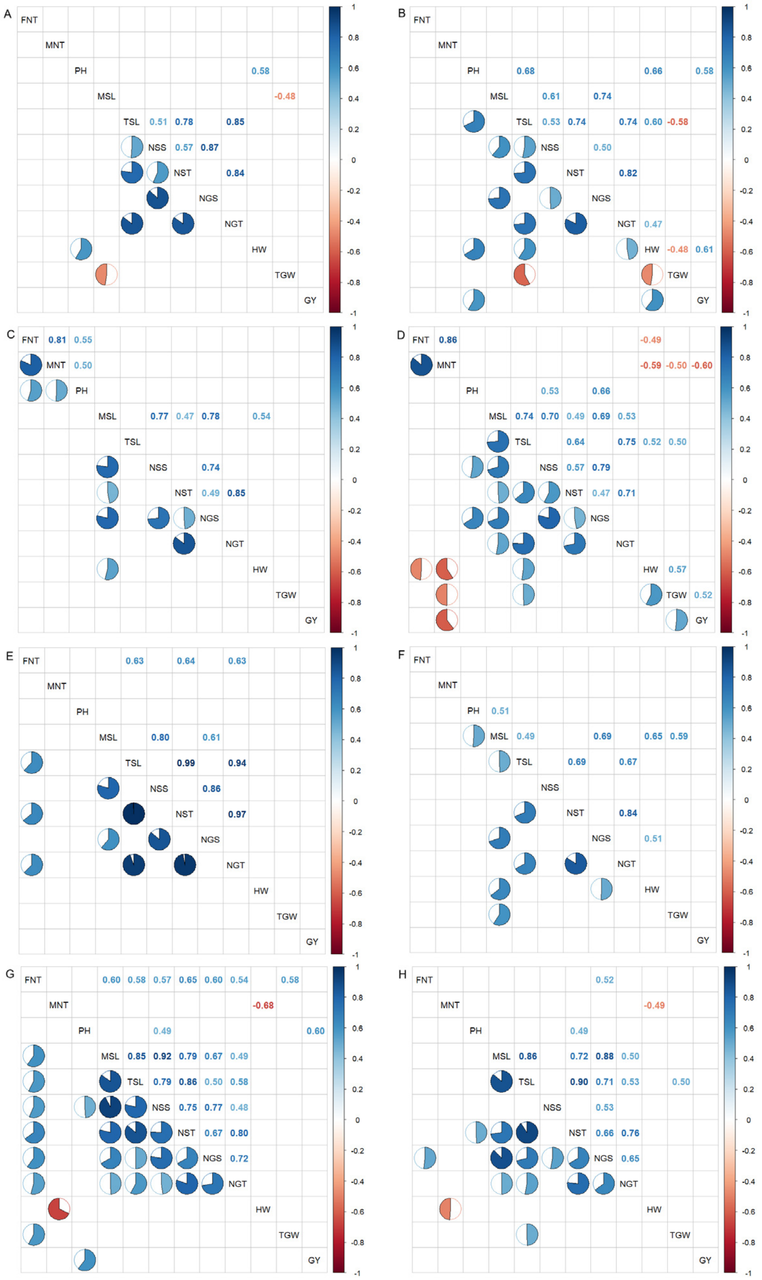

Figure 2. Pearson linear correlation between wheat characteristics for nitrogen topdressing treatments with and without split applications. Treatments with nitrogen application without splitting are shown in figures A: Environment A; C: Environment B; E: Environment C; G: Environment D, and treatments with split nitrogen application in figures B: Environment A; D: Environment B; F: Environment C; H: Environment D.
PH = Plant height; MSL = main spike length; TSL = tiller spike length; NSS = number of spikelets per main spike; NST = number of spikelets per tiller spike; NGS = number of grains per main spike; NGT = number of grains per tiller spike; TGW = thousand-grain weight; FNT = final number of tillers; MNT = maximum number of tillers; HW = hectoliter weight; and GY = grain yield. Significant correlations are represented in blue (positive) and red (negative) according to the Student's t-test (p ≤0.05).

Comparable to these findings, the positive correlation between NGS and NSS produced coefficients varied at 0.50–0.87, corroborating Ojha et al. (2018). Nonetheless, this particular correlation was not significant in EC when nitrogen was managed with splitting, contrasting with the outcomes reported by Buratto et al. (2020), who found no significant correlation between these variables in their study of triticale. Furthermore, the relationship between NGS and MSL demonstrated correlation coefficients between 0.61 and 0.88, yet it was not significant in EA under nitrogen management without splitting. In comparison, NGT and NGS exhibited a significant correlation, which diverges from the findings of Nakachew et al. (2024), where no significant correlations were noted for the NGS.

In a different analytical approach, path analysis unveiled coefficients of determination ranging from 0.44 to 0.83 (Figure 3), indicating variability in response across different environmental and nitrogen management combinations. The inclusion of variables in the path analysis for each environment was determined by multicollinearity diagnoses, necessitating the exclusion of certain variables under specific conditions. Notably, PH, TGW, FNT, MNT, and HW consistently established the direct and indirect effects on GY across all tested combinations. This finding contrasts with Oliveira et al. (2020), who highlighted the number of grains per spike as the most significant trait for identifying high-yielding wheat cultivars. Conversely, selecting NGS or NGT did not elicit consistent responses across different environments and nitrogen management strategies.

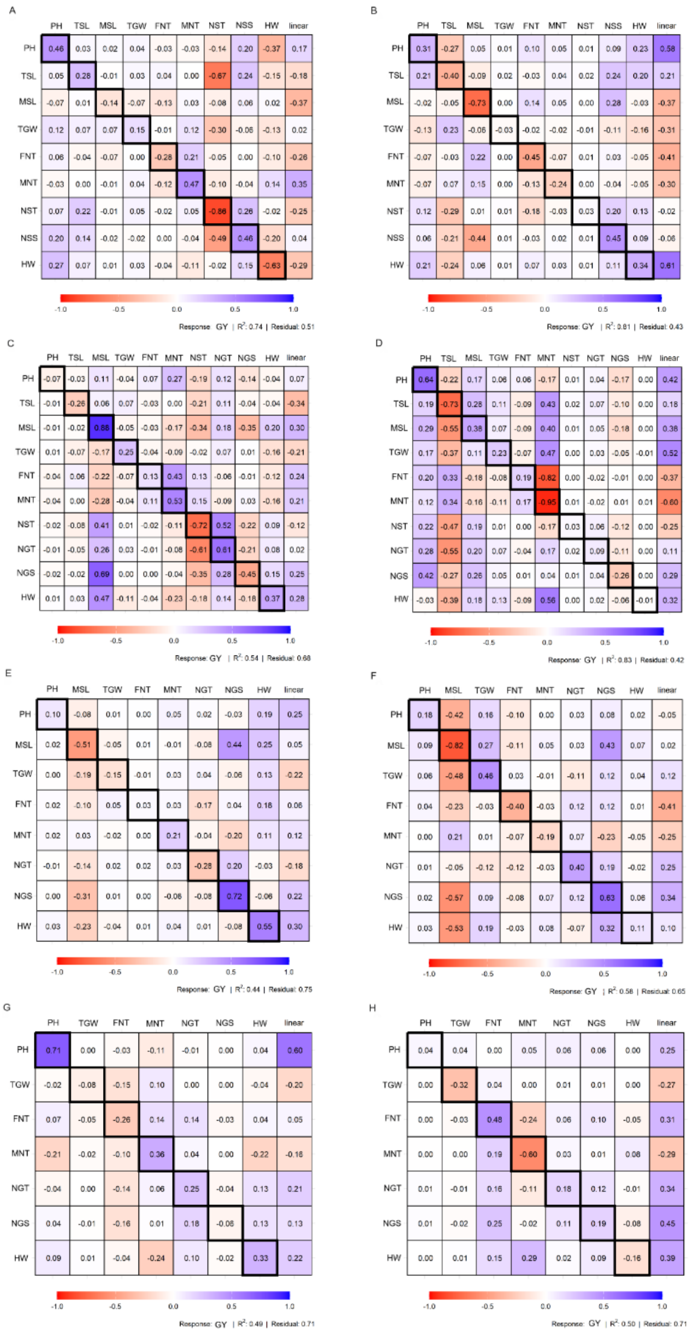

Figure 3. Estimating direct effects, indirect effects, and linear correlations from path analysis for nitrogen topdressing treatments with and without split applications. Treatments with nitrogen application without splitting are shown in figures A: Environment A; C: Environment B; E: Environment C; G: Environment D, and treatments with split nitrogen application in figures B: Environment A; D: Environment B; F: Environment C; H: Environment D.
PH = Plant height; MSL = main spike length; TSL = tiller spike length; NSS = number of spikelets per main spike; NST = number of spikelets per main spike; NGS = number of grains per main spike; NGT = number of grains per tiller spike; TGW = thousand-grain weight; FNT = final number of tillers; MNT = maximum number of tillers; HW = hectoliter weight; GY = grain yield.

The direct effects revealed through path analysis indicated that the efficient utilization of specific traits results in positive outcomes for crop yield enhancement (Kavalco et al., 2014). Across all environmental conditions, positive effects were observed for single-application nitrogen management strategies. In contrast, nitrogen management involving splitting applications demonstrated adverse effects on the MNT in all environments. These findings contrast with the research of Farid et al. (2020), which highlighted the number of fertile shoots as a critical variable for enhancing wheat productivity in lowland regions. For PH, direct effects were positive for June sowing dates, particularly in environments with greater levels of precipitation, which contributed to an increase in GY.

Regarding indirect effects, the interaction between FNT and MNT yielded positive outcomes for single nitrogen applications, whereas splitting nitrogen applications resulted in adverse effects. Similarly, the interaction between HW and PH demonstrated positive indirect effects on GY in conditions with higher precipitation during crop development. Nonetheless, these findings are in contrast to those of Vesohoski et al. (2011), which suggested that indirect selection for GY, based on the number of grains per spike and the TGW, represents the most effective strategy for identifying superior wheat genotypes.

This study underscores the varying responses of different wheat cultivars to diverse environmental conditions and nitrogen fertilization strategies, whether applied partially or in a single dose. It emphasizes the significance of the interactions among multiple factors in determining linear relationships, agronomic traits, and yield components in low-altitude subtropical environments. Lastly, the results provide practical management strategies tailored to farmers' objectives, offering valuable insights for the optimization of wheat production in the southern region of the state of Rio Grande do Sul.

Conclusions

The Tbio Aton, Tbio Audaz, and Tbio Trunfo cultivars achieved higher grain yields when subjected to split nitrogen topdressing, and the Tbio Ello CL, Tbio Ponteiro, and Tbio Toruk cultivars were more responsive when subjected to nitrogen management in a single application at the beginning of tillering. Splitting or single application of nitrogen topdressing should be evaluated for each wheat cultivar.

The maximum number of tillers reduces the hectoliter weight of wheat when sown in later environments such as EB and ED. The maximum number of tillers has a direct effect on grain yield for nitrogen management in a single application. Plant height has a direct positive effect on grain yield in sowings in June, with the effect potentiated by greater water availability.

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