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Sustainable nitrogen efficiency in wheat by the dose and mode of supply[1]

Eficiência sustentável do nitrogênio em trigo pela dose e forma de fornecimento

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HIGHLIGHTS:

Unfavorable years of wheat cultivation promote greater nitrogen losses.
Topdressing nitrogen fractionation does not increase productivity.
The technical efficiency of nitrogen is not suitable for cultivation recommendation.

ABSTRACT: The management of nitrogen by the assessment of agronomic and environmental indicators ensures satisfactory productivity with higher environmental quality. The objective of this study was to propose more sustainable management of nitrogen use in wheat, considering the supply of full and fractioned doses with an estimate of technical, economic efficiency, and expected productivity. Two experiments were conducted, one to quantify biomass productivity and the other to evaluate grain yield. The experimental design consisted of a randomized block with four repetitions in a 5 × 3 factorial, for N-fertilizer doses (0, 30, 60, 90, and 120 kg ha^{-1}) and nutrient supply form [full condition (100%) in the phenological stage V3 (the third leaf expanded); fractionated (70/30%) in the phenological stage V_3/V_6 (third and sixth leaf expanded) and; fractionated (70/30%) in the phenological stage V_3/R_1 (beginning of anthesis)], respectively. The most sustainable management of nitrogen in wheat was obtained with the expected yield rate of 3 t ha^{-1} by manual fertilization, with nitrogen supplied in full dose at the V_3 phenological stage.

Key words: *Triticum aestivum* L., full dose, fractionated dose, satisfactory productivity

RESUMO: O manejo do nitrogênio analisando indicadores agronômicos e ambientais garante produtividade satisfatória com maior qualidade ambiental. O objetivo neste estudo é propor um manejo mais sustentável de uso do nitrogênio em trigo, considerando o fornecimento em dose cheia e fracionada com estimativa da eficiência técnica, econômica e de expectativa de produtividade. Dois experimentos foram conduzidos, um para quantificar a produtividade de biomassa e outro, para avaliação do rendimento de grãos. O delineamento experimental foi o de blocos casualizados com quatro repetições em fatorial 5 × 3, para doses de N-fertilizante (0, 30, 60, 90 e 120 kg ha^{-1}) e forma de fornecimento do nutriente [condição cheia (100%) no estádio fenológico V_3 (terceira folha expandida); fracionada (70/30%) no estádio fenológico V_3/V_6 (terceira e sexta folha expandida) e; fracionada (70/30%) no estádio fenológico V_3/R_1 (início da antese)], respectivamente. O manejo mais sustentável do nitrogênio em trigo é obtido com a dose de expectativa de produtividade de 3 t ha^{-1} pela adubação manual, com o nutriente fornecido em dose cheia no estádio fenológico V_3.

Palavras-chave: *Triticum aestivum* L., dose cheia, dose fracionada, produtividade satisfatória

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Introduction

Nitrogen (N) is the nutrient most absorbed by the wheat crop and the most limiting to growth and productivity (Manschadi & Soltani, 2021). Soil nutrient availability is gradual, requiring annual cycle plants such as wheat, and supplementation in the form of soluble, rapidly available fertilizers (Kraisig et al., 2021). After fertilization, the high availability of these fertilizers promotes nitrogen leaching during rainfall (Wei et al., 2020) and volatilization occurs in soils with reduced humidity and high air temperature (Arenhardt et al., 2017). This reduces nitrogen transformation efficiency into straw and grain biomass with economic and environmental losses (Mamann et al., 2020).

One way of improving nitrogen uptake by plants is to apply an appropriate amount of fertilizer under conditions of air temperature, light, and soil moisture suitable to promote more assimilation by wheat (Tabak et al., 2020). Moreover, when supplied during the tillering and ear differentiation phase, it improves plant development, directly influencing the productive potential (Arenhardt et al., 2015). On the other hand, unfavorable years for wheat cultivation increase nitrogen losses and reduce the efficiency of N uptake by the plant, thereby generating instability in productivity (Silva et al., 2016).

Studies should be conducted that aim at the best application of dose and form of nutrient supplied to maximize the efficiency of nitrogen use, decisive condition in the search for more sustainable agriculture (Mamann et al., 2020). In this perspective, by estimating the ratio of input supplied and the product obtained by agronomic efficiency, the optimal dose by economic, technical efficiency, and the expected productivity dose of the fertilizer supplied in full or fractional doses, assists in decision making in the promotion of more sustainable processes in the management of nitrogen in wheat. The objective of this study was to propose more sustainable management of nitrogen use in wheat, considering the full and fractional doses supplied with estimates of economic and technical efficiency and expected productivity.

Materials and Methods

The research was conducted from 2012 to 2018 in the city of Augusto Pestana, state of Rio Grande do Sul, Brazil (28° 26'30" latitude S and 54° 00'58" longitude W and 298 m altitude). The soil of the experimental site is classified as Oxisols. According to Köppen's classification (Köppen & Geiger, 1928), the region has a humid subtropical climate. At 10 days before each sowing, a soil analysis was performed, to identify the average of the following chemical attributes: pH = 6.1, P = 49.1 mg dm^{-3}, K = 424 mg dm^{-3}, MO = 3.0%, Al = 0 cmolc dm^{-3}, Ca = 6.3 cmolc dm^{-3} and Mg = 2.5 cmolc dm^{-3}. Sowing was carried out with a seeder-fertilizer (Machines SB, model Semina 1400) in five 5 m length lines spaced 0.20 m apart, forming an experimental unit of 5 m^2. At sowing, 30 and 20 kg ha^{-1} of P_2O_5 and K_2O were applied, respectively, based on the levels of P and K in the soil for expected grain yields of 3 t ha^{-1} and N at the base with 10 kg ha^{-1}, with the remainder covering the proposed doses, with nitrogen provided in the form of urea. The seeds were submitted to germination and vigor tests to correct the desired density of 400 viable seeds m^{-2}. During the study, applications of 0.75 L ha^{-1} of tebuconazole fungicide were made. Weed control was achieved using metsulfuron-methyl herbicide at a dose of 4 g ha^{-1}. The cultivar used was TBIO Sinuelo, widely accepted for its resistance to leaf spot, leaf rust, and bacteriosis, and has a high yield potential.

In this study, two experiments were conducted in the soybean/wheat succession system, one to quantify the biomass productivity (BP, kg ha^{-1}) (straw + grain) and another to estimate the grain yield (GY, kg ha^{-1}). In both experiments, the randomized block design was used with four repetitions in a 5 × 3 factorial treatment structure, for doses of N-fertilizer (0, 30, 60, 90, and 120 kg ha^{-1}) and forms of nutrient delivery: full dose (100%) in the phenological stage V_3 (third leaf set); fractional dose (70/30%) in the phenological stage V_3/V_6 (third and sixth leaf set) and fractional dose (70/30%) in the phenological stage V_3/R_1 (third leaf set and sprouting), respectively, totaling 120 experimental units constituted by five 5 m length lines spaced 0.20 m apart, forming an experimental unit of 5 m^2. According to the Feekes developmental scale, the wheat growth stages were defined (Large, 1954). The harvest of the experiments, to estimate the productivity of biomass and grain, was done manually by cutting the three central rows of each plot, stage close to the harvesting point (125 days), with grain moisture of 15%. The plots were harvested manually and threshed with a stationary harvester, sent to the laboratory to correct grain humidity to 13%, after weighing and estimating grain yield (GY, kg ha^{-1}). The plots for biomass productivity analysis (BP, kg ha^{-1}) were directed and kept in an oven with forced air circulation at a temperature of 65ºC until reaching constant weight and converted to kg ha^{-1}. The straw yield (SY, kg ha^{-1}) was obtained by the difference between biomass yield and grain yield (SY = BP - GY). The values of the general averages of grain yield, along with the information of temperature and rainfall, were used to classify the years as unfavorable, intermediate and favorable to the crop. The meteorological data of pluviometric precipitation and minimum and maximum temperature were obtained from a meteorological station located at about 500 m from the experiments.

After meeting the assumptions of homogeneity and normality of residuals via the Bartlett and Shapiro Wilk test, respectively, analysis of variance was performed. Based on this information, a linear function ($y = b_0 \pm b_1x$) was fitted to estimate the agronomic efficiency of grain, biomass, and straw yields. Under conditions where there was significant quadratic behavior ($GY = b_0 \pm b_1x \pm b_2x^2$) the estimation of maximum technical $MET = -[(b_1)/(2b_2)]$ and economic $MEE = [(t/w) - b_1]/(2b_2)$ efficiency of nitrogen use to grain yield was obtained. In order to estimate the maximum economic efficiency, the model includes the product's price (w) and the input price (t). The values used to represent the average prices charged in the northwestern region of Rio Grande do Sul, Brazil, included the input price (nitrogen) R$3.52 for each kg of nitrogen supplied and the wheat product price R$0.70 for each kg of wheat sold. Estimation of the nitrogen dose by the expected grain yield was according to the culture in succession to wheat, soybeans, and estimated harvest of 3,000 kg ha^{-1}, providing 60 kg ha^{-1} of the nutrient, according to technical recommendation for the culture (Brazilian Society of Soil Science, 2016). The mean test was performed by Scott & Knott (1974) in the comparison of agricultural years and the forms of nitrogen supply as well as the technical, economic efficiency and production expectations in nutrient use. The computer program Genes was used for these determinations.

Results and Discussion

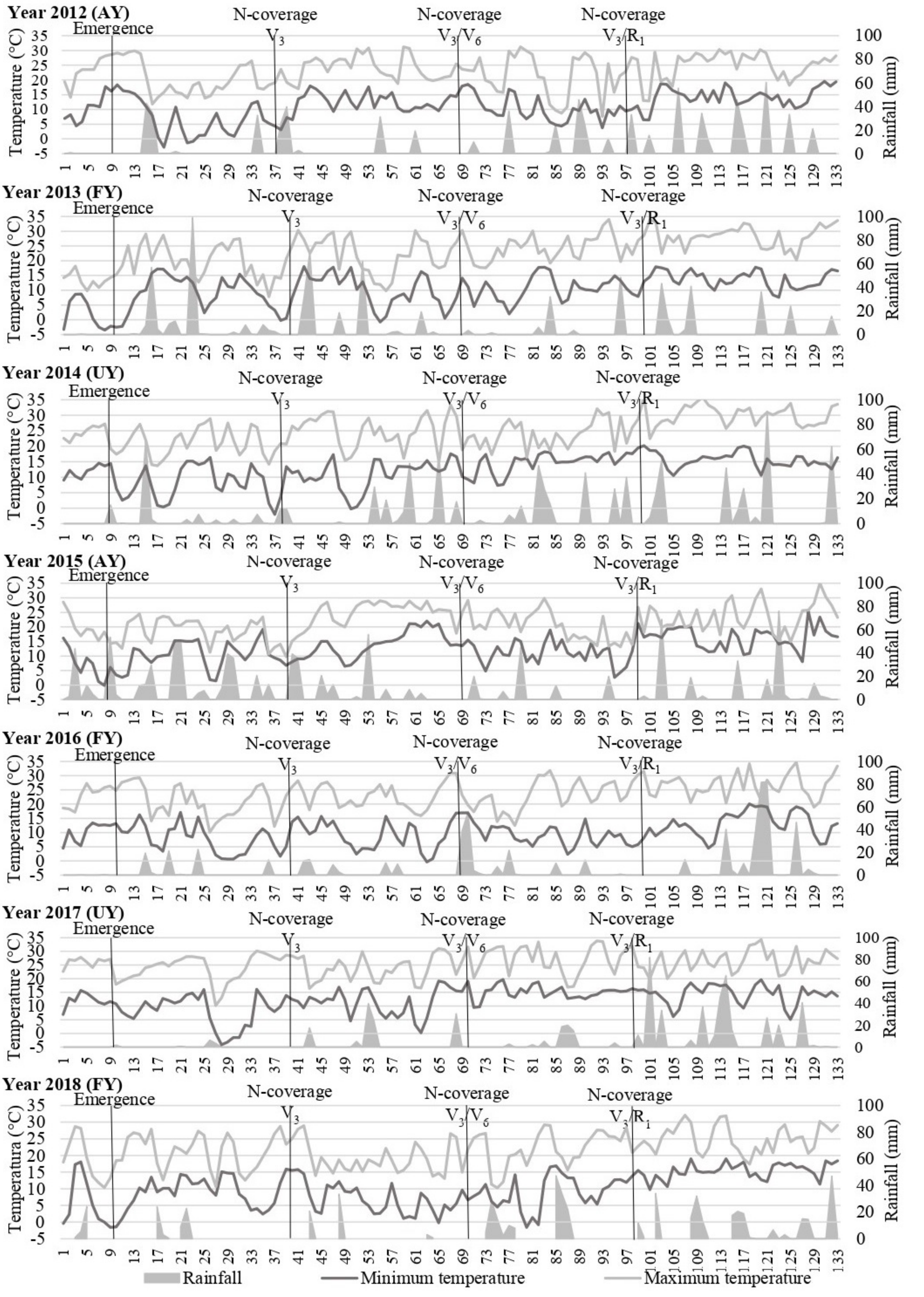
In the year 2012, at the beginning of the wheat development cycle, water restriction was verified with mild temperatures during nutrient supply (Table 1). At the end of the cycle, rainfall was frequent with high accumulated value, delaying the grain harvest (Figure 1). In 2015, rainfall before fertilization ensured soil moisture for nutrient management but was associated with a long water restriction period after fertilization. Furthermore, high temperatures were observed during anthesis, which could cause damage to reproductive system development. Meteorological information related to the productivity obtained in 2012 and 2015, with expectations around 2500 kg ha^{-1}, characterize acceptable years (AY) to the productivity obtained.

In 2014, high temperatures and a significant volume of rainfall were observed at the beginning of the crop development

Table 1. Temperature and rainfall during the months of growing and average yield of wheat grains

Year	Month	Temperature (°C)			Rainfall (mm)		GY_X (kg ha^{-1})	Class
		Min	Max	Med	Average of 25 years*	Occurred		
	May	10.4	26.6	18.5	149	18		
	June	8.8	22.0	15.4	163	57		
	July	6.4	19.7	13.0	135	181		
2012	August	12.9	23.4	18.1	138	61	2341 b	AY
	September	12.0	23.0	17.5	167	195		
	October	15.0	25.5	20.2	156	287		
	Total	-	-	-	908	799		
	May	10.0	22.6	16.3	149	108		
	June	8.9	20.0	14.5	163	74		
	July	7.0	20.6	13.8	135	103		
2013	August	6.6	19.8	13.2	138	169	3447 a	FY
	September	9.6	21.0	15.3	167	123		
	October	13.2	27.1	20.2	156	144		
	Total	-	-	-	908	721		
	May	10.8	23.6	17.2	149	382		
	June	9.2	20.7	16.1	163	412		
	July	9.7	21.8	15.7	135	144		
2014	August	8.8	23.7	16.2	138	78	1475 c	UY
	September	13.3	23.5	18.4	167	275		
	October	16.0	27.7	21.8	156	231		
	Total	-	-	-	908	1522		
	May	13.1	22.7	17.9	149	181		
	June	9.7	21.1	15.4	163	228		
	July	10.2	18.7	14.4	135	212		
2015	August	13.4	24.6	19.0	138	87	2455 b	AY
	September	12.4	19.6	16.0	167	127		
	October	16.1	24.8	20.4	156	162		
	Total	-	-	-	908	997		
	May	11.1	20.9	16.0	149	56		
	June	4.7	19.3	12.0	163	10		
	July	8.2	21.2	14.7	135	81		
2016	August	9.4	22.5	15.9	138	160	3210 a	FY
	September	8.4	23.8	16.1	167	56		
	October	13.2	26.8	20.0	156	326		
	Total	-	-	-	908	689		
	May	14.0	33.8	18.4	149	434		
	June	10.7	21.8	16.2	163	146		
	July	8.3	24.4	16.4	135	11		
2017	August	11.4	23.7	17.6	138	118	1749 c	UY
	September	15.36	27.1	21.2	167	162		
	October	14.1	26.8	20.5	156	304		
	Total	-	-	-	908	1175		
	May	13.2	25.8	19.5	149	63		
	June	7.4	19.4	13.4	163	104		
	July	9.2	20.1	14.6	135	80		
2018	August	6.2	20.0	13.1	138	120	3083 a	FY
	September	13.1	24.8	18.9	167	184		
	October	15.6	25.3	20.4	156	243		
	Total	-	-	-	908	794		

Min - Minimum; Max - Maximum; Med - Average; GY_X - Average grain yield; * - Average rainfall obtained from the months of May to October from 1993 to 2018; Averages followed by the same letter in the column do not differ at $p \leq 0.05$ by Scott-Knott test by Scott & Knott test; AY - Acceptable year; FY - Favorable year; UY - Unfavorable year



V_3 - Full condition (100%) of the nitrogen dose in the third leaf; V_3/V_6 - Fractional condition (70/30%) of the nitrogen dose at the third and sixth leaf expansion; V_3/R_1 - Fractional condition (70/30%) of the nitrogen dose at the third and differentiation of the ear; AY - Acceptable year; FY - Favorable year; UY - Unfavorable year

Figure 1. Rainfall, the maximum and minimum temperature during the wheat crop cycle, and the timing of nitrogen supply

cycle and near the grain harvest. The volume of rainfall was above the historical average, with irregular distribution throughout the cycle. In 2017, the volume of rainfall was higher than the historical average, with inadequate distribution throughout the cycle. During the development cycle, higher and more fluctuating temperatures were recorded. The high temperatures of 2014 and 2017 and irregular rainfall promoted yields of 1475 and 1749 kg ha^{-1}, respectively, much lower than the expected 3000 kg ha^{-1}, justifying the classification of unfavorable years (UY) of wheat cultivation (Figure 1, Table 1).

In wheat, a favorable climate is described as one with milder temperatures and adequate distribution of rainfall to maintain soil moisture (Silva et al., 2016). After fertilization, large and vigorous rainfall intensity result in nitrogen leaching, drastically reducing efficiency (Mandal et al., 2016). The high air temperatures associated with soil water restriction also cause significant nitrogen losses by volatilization (Liu et al., 2020). The lack of water and the presence of heat shortens the crop cycle, reduces the stature, leaf area, and the percentage of flower fertilization, thereby reducing productivity (Mamann et al., 2020).

Table 2 shows the agronomic efficiency results for the ratio of one kilogram of nitrogen supplied per kilogram of the product obtained for nitrogen supply condition and agricultural year. The highest agronomic efficiency of grain yield was obtained in a favorable crop year (2013), either in whole or fractional dose, with 23.9, 22.9, and 21.2 kg ha^{-1} of grain yield per kilogram of nitrogen in V_3, V_3/V_6, and V_3/R_1 conditions, respectively. The years 2016 and 2018 were also favorable for the crop, agronomic efficiency although lower, starting from higher intercept values, proved to be a more significant environmental stimulus for nitrogen use and increased grain yield. Regardless of the agricultural year and nutrient supply form, for each 1 kg of nitrogen, the return was 10 kg ha^{-1} of grain yield. The results demonstrated a slight to reduced agronomic efficiency and intercept values with fractionated doses at V_3/R_1.

For biomass and straw yields, the complexity of nutrient utilization is still higher and does not necessarily accompany the higher efficiency in grain yields. Generally, the most significant values were observed in the V_3/V_6 condition, showing that every 1 kg of nitrogen supplied returns 27 and 17 kg ha^{-1} of biomass and straw productivity, respectively. In the V_3/R_1 stages, there is also evidence of a tendency towards reduction of biomass and straw productivity, according to the verified values of intercept and angular coefficient.

The rapid release of N-residual by the lower C/N ratio of soybean straw on the soil improves wheat biomass and grain productivity, increasing agronomic efficiency, compared to the high C/N ratio in the corn/wheat system (Kraisig et al., 2021; Mantai et al., 2021). In addition, N-fertilizer, together with favorable weather conditions management, can increase agronomic efficiency in yield expression (Kraisig et al., 2021). In wheat, positive responses are obtained with high nitrogen doses on straw yields, unlike grain yields that reach stability with lower doses. In addition, the nutrient increase in the crop promotes plant lodging, depreciating the technological

Table 2. Agronomic efficiency of biological productivity, straw, and grain yields of wheat under nitrogen supply conditions in crop years

Years	V_3				V_3/V_6				V_3/R_1			
	y= a ± bx	R^2 (%)	AE (kg)	CV (%)	y= a ± bx	R^2 (%)	AE (kg)	CV (%)	y= a ± bx	R^2 (%)	AE (kg)	CV (%)
Grain yield (kg ha^{-1})												
2012 (AY)	1774 + 9.5*x	98	9.5	8	1743 + 9.9*x	82	9.9	17	1691 +10.7*x	93	10.7	11
2013 (FY)	2189 + 23.9*x	96	23.9	8	2102 + 22.9*x	97	22.9	10	1970 + 21.2*x	96	21.2	8
2014 (UY)	1292 + 4.1*x	72	4.1	19	1150 + 5.1*x	75	5.1	18	1111 + 5.4*x	80	5.4	14
2015 (AY)	1770 + 12.7*x	83	12.7	16	1619 + 13.8*x	92	13.8	12	1579 + 13.4*x	95	13.4	12
2016 (FY)	2859 + 7.3*x	65	7.3	20	2807 + 6.7*x	78	6.7	19	2621 + 8.3*x	81	8.3	13
2017 (UY)	1515 + 4.4*x	68	4.4	20	1613 + 4.5*x	75	4.5	18	1375 + 3.1*x	73	3.1	17
2018 (FY)	2465 + 9.1*x	80	9.1	15	2583 + 10.6*x	82	10.6	15	2567 + 7.5*x	75	7.5	16
General	1981 + 10.1*x	89	10.1	13	1945 + 10.5*x	90	10.5	10	1845 + 10.0*x	92	10.0	9
Biomass productivity (kg ha^{-1})												
2012 (AY)	5814 +17.5*x	92	17.5	9	5680 + 19.8*x	97	19.8	11	5444 + 20.1*x	98	20.1	7
2013 (FY)	6413 + 29.4*x	91	29.4	9	6345 + 31.5*x	99	31.5	9	5938 + 26.9*x	92	26.9	10
2014 (UY)	5081 + 20.1*x	94	20.1	8	4786 + 23.8*x	90	23.8	16	4797 + 21.9*x	92	21.9	10
2015 (AY)	5759 + 23.4*x	97	23.4	8	5772 + 24.4*x	95	24.4	12	5354 + 22.0*x	97	22.0	9
2016 (FY)	7575 + 28.4*x	93	28.4	11	7353 + 30.5*x	98	30.5	8	7317 + 25.4*x	97	25.4	8
2017 (UY)	4757 + 26.2*x	95	26.2	13	5199 + 22.8*x	86	22.8	19	4694 + 18.7*x	91	18.7	9
2018 (FY)	8104 + 35.6*x	95	35.6	9	8287 + 37.5*x	92	37.5	15	8013 + 33.2*x	94	33.2	11
General	6215 + 25.8*x	97	25.8	10	6203 + 27.1*x	97	27.1	10	5936 + 24.1*x	98	24.1	10
Straw yield (kg ha^{-1})												
2012 (AY)	4040 + 7.9*x	76	7.9	17	3937 + 9.8*x	96	9.8	10	3753 + 10.2*x	85	10.2	15
2013 (FY)	4073 + 10.5*x	90	10.5	12	4243 + 8.5*x	91	8.5	13	3968 + 7.5*x	71	7.5	17
2014 (UY)	3789 + 15.9*x	95	15.9	9	3635 + 18.7*x	92	18.7	13	3686 + 16.4*x	92	16.4	11
2015 (AY)	3990 + 10.7*x	97	10.7	8	4153 + 10.6*x	96	10.6	9	3774 + 8.7*x	90	8.7	13
2016 (FY)	4716 + 21.4*x	92	21.4	12	4547 + 23.7*x	98	23.7	12	4695 + 17.1*x	95	17.1	9
2017 (UY)	3242 + 21.8*x	97	21.8	10	3186 + 21.6*x	91	21.6	13	3318 + 15.6*x	88	15.6	20
2018 (FY)	5639 + 26.4*x	97	26.4	10	5704 + 26.9*x	90	26.9	18	5446 + 25.7*x	96	25.7	12
General	4212 + 16.4*x	99	16.4	8	4200 + 17.1*x	99	17.1	9	4091 + 14.4*x	97	14.4	14

AY - Acceptable year; FY - Favorable year; UY - Unfavorable year; y – variable of interest; a – linear coefficient; bx – slope; V_3 - Full condition (100%) of the nitrogen dose in the third leaf expanded; V_3/V_6- Fractionated condition (70/30%) of the nitrogen dose in the third and sixth leaf expanded; V_3/R_1- Fractional condition (70/30%) of the nitrogen dose in the third and differentiation of the ear; R^2 - Coefficient of determination; AE - Agronomic efficiency; CV - Coefficient of variation; * - Significant at $p \leq 0.05$ by F test quality of wheat grains for marketing (Arenhardt et al., 2017). Agronomic nitrogen use efficiency is species-dependent and does not always exhibit a positive angular coefficient trend. In this perspective, Sant'ana et al. (2011) verified in beans that the agronomic efficiency of nitrogen decreases with increasing dose, showing reduction in grain yield with the increase of nutrient accumulated in its biomass.

Table 3 presents the estimates of technical and economic efficiency, considering the supply of nitrogen in full dose. For the years 2012 (AY) and 2013 (FY), only significant linear behavior was verified, not allowing the establishment of an ideal dose for technical and economic efficiency. Thus, a grain yield ratio of 9.5 and 23.9 kg ha^{-1} per kilogram of nitrogen supplied was obtained in 2012 and 2013, respectively. In contrast, a significant quadratic trend was verified for the other crop years, with estimated technical efficiency in favorable crop years (2016 and 2018) around 87 and 93 kg ha^{-1} of N, and estimated grain yield of 3671 and 3365 kg ha^{-1}, respectively. In the years unfavorable to cultivation (2014 and 2017), the technical efficiency doses were 88 kg ha^{-1}, maintaining similarity yields of 1704 and 1927 kg ha^{-1}, respectively.

The expected estimate of grain yield with a dose of 88 kg ha^{-1} of N, considering the fertilization manual for wheat culture, would be over 4000 kg ha^{-1}, very different from the actual value obtained, indicating the need to develop more solid criteria for fertilization definition, considering the economic, meteorological and environmental aspects. By assessing the results obtained when supplying nitrogen in full dose at the V_3 stage, there was a significant reduction in the amount of N supplied, for an expected grain yield of 3 t ha^{-1} (60 kg ha^{-1}) compared to the technical and economic efficiency of nutrient use, with minimal grain yield reduction.

For the condition of the fractional supply of the nutrient in V_3/V_6, linearity was observed for the conditions of favorable years (2013 and 2018) and acceptable years (2015), making it impossible to estimate the optimal technical and economical dose by regression. This indicates increasing nutrient absorption with increasing doses.

In the fractional supply condition of nitrogen in V_3/V_6, there was also a significant reduction in the amount of nutrient used when comparing the doses of maximum technical and economic efficiency with the expected yield of 3 t ha^{-1}, with reduced change in grain yield.

In the fractionated nitrogen supply condition at V_3/R_1, linearity was also observed in acceptable (2012 and 2015) and favorable (2013) yield years. The nitrogen dose recommendation considering yield expectation of 3 t ha^{-1} was more advantageous in this fraction condition than in a full dose. Moreover, considering the full and fractionated doses, similar productivity was obtained in V_3 and V_3/V_6, but with a decreased productivity in V_3/R_1. The results also showed that the fractionated conditions of nitrogen, even when not promoting efficiency, increased productivity, but resulted in higher costs due to the need for a second operation at the beginning of the crop, confirming that the full dose application at the V_3 stage was more advantageous.

Table 3. Technical, economic, and expected efficiency of 3 t ha^{-1} under nitrogen use conditions in wheat with estimated grain yield (GY)

Year	Model	R^2	CV	N (kg ha^{-1})			GY (kg ha^{-1})		
	$GY = b_0 \pm b_1x + b_2x^2$	(%)	(%)	MET	MEE	3 t ha^{-1}	MET	MEE	3 t ha^{-1}
				Full dose (V_3)					
2012 (AY)	$1773 + 9.5^*x$	90	12	-	-		-	-	2343
2013 (FY)	$2188 + 23.9^*x$	95	9	-	-		-	-	3622
2014 (UY)	$1140 + 14.2^*x - 0.08^*x^2$	70	14	88	67		1770	1689	1704
2015 (AY)	$1548 + 27.5^*x - 0.12^*x^2$	94	10	114	93	60	3123	3067	2766
2016 (FY)	$2600 + 24.5^*x - 0.14^*x^2$	76	18	87	79		3671	3623	3566
2017 (UY)	$1369 + 14.1^*x - 0.08^*x^2$	79	16	88	66		1990	1907	1927
2018 (FY)	$2239 + 24.2^*x - 0.13^*x^2$	95	10	93	83		3365	3320	3223
General	$1809 + 21.5^*x - 0.09^*x^2$	99	8	119	91	60	3093 aA	3020 aA	2775 aB
				Fractional dose (V_3/V_6)					
2012 (AY)	$1583 + 20.6^*x - 0.09^*x^2$	89	13	114	86		2762	2689	2495
2013 (FY)	$2101 + 22.9^*x$	95	14	-	-		-	-	3475
2014 (UY)	$937 + 19.3^*x - 0.12^*x^2$	87	18	80	69		1713	1658	1663
2015 (AY)	$1618 + 13.8^*x$	92	12	-	-	60	-	-	2446
2016 (FY)	$2636 + 18.1^*x - 0.09^*x^2$	86	18	100	72		3546	3473	3398
2017 (UY)	$1445 + 15.5^*x - 0.09^*x^2$	80	15	86	68		2112	2041	2051
2018 (FY)	$2582 + 10.6^*x$	80	17	-	-		-	-	3218
General	$1777 + 21.7^*x - 0.09^*x^2$	99	10	120	93	60	3085 aA	3017 aA	2755 aB
				Fractional dose (V_3/R_1)					
2012 (AY)	$1691 + 10.7^*x$	88	15	-	-		-	-	2333
2013 (FY)	$1970 + 21.2^*x$	93	16	-	-		-	-	3242
2014 (UY)	$995 + 13.1^*x - 0.06^*x^2$	80	18	109	77		1710	1603	1565
2015 (AY)	$1579 + 13.4^*x$	93	10	-	-	60	-	-	2383
2016 (FY)	$2463 + 18.9^*x - 0.09^*x^2$	85	11	105	77		3455	3384	3273
2017 (UY)	$1306 + 7.7^*x - 0.04^*x^2$	50	22	96	63		1676	1516	1624
2018 (FY)	$2383 + 19.7^*x - 0.10^*x^2$	81	16	98	83		3353	3288	3205
General	$1845 + 9.9^*x$	92	11	-	-	60	-	-	2439 b

AY- Acceptable year; FY - Favorable year; UY - Unfavorable year; b_0 - linear coefficient; b_1x - degree 1 slope; b_2x^2–degree 2 slope; V_3 - Full condition (100%) of the nitrogen dose in the third leaf expanded; V_3/V_6- Fractionated condition (70/30%) of the nitrogen dose in the third and sixth leaf expanded; V_3/R_1- Fractionated condition (70/30%) of the nitrogen dose in the third and differentiation of the ear; N -Nitrogen doses; GY - Grain yield (kg ha^{-1}); R^2 -Coefficient of determination; CV - Coefficient of variation; * -Significant at $p \leq 0.05$ by F test; MET - Maximum technical efficiency; MEE - Maximum economic efficiency; Means followed by the same small letter in the column compare the forms of nitrogen supply and capital letters in the row with the types of efficiency (MET, MEE and expectation of 3 t ha^{-1}), constitute statistically homogeneous group at $p \leq 0.05$ by Scott-Knott test

Research has shown that the favorability of the crop year is decisive on productivity potentials due to rainfall volume and distribution, air temperature, and solar radiation (Marolli et al., 2018). Nitrogen deficiency reduces solar radiation uptake by wheat, reduces vegetative and root growth, reflecting on nutrient uptake and yield elaboration (Carciochi et al., 2020). The definition of the N-fertilizer dose in wheat by the fertilization manual is defined as a function of the soil organic matter content, the previous crop, and the expected productivity (Brazilian Society of Soil Science, 2016). Trautmann et al. (2017) stated that the use of a fractional dose of nitrogen is recommended for providing greater efficiency in nitrogen assimilation, especially when weather conditions are not suitable for the application. Costa et al. (2017) observed that providing nitrogen in a single dose increases grain yield in a favorable year for the crop, in unfavorable years, fractionated doses at the V_3/V_6 stages are the most indicated.

Table 4 shows functions describing the behavior of biomass productivity by the supply of nitrogen in full and fractional doses in different conditions of the crop year. The doses used for the simulations were defined from the functions of grain yield by the maximum technical efficiency, economic, and expectation of 3 t ha^{-1} (Table 3). Therefore, the biological interpretation of nitrogen use is desired, considering the optimal dose of productivity independent of the agricultural year. In this perspective, regardless of the nitrogen supply condition, the behavior of biomass productivity showed a linear trend. Furthermore, the simulation of nitrogen dose by grain yield via maximum technical, economic, and 3 t ha^{-1} efficiency showed a reduction of biomass productivity. Although biomass yield decreased, grain yield showed little change (Table 3). Full and fractional nitrogen supply conditions showed similar expression of biomass productivity, with a significant reduction at V_3/R_1. Therefore, the biomass yield decreased significantly with the delay of N supply, since in comparison with the other conditions at the expectation of 3 t ha^{-1} at V_3/R_1, the decrease was linear due to the delay in releasing nutrient to the plants.

In Table 5, the nitrogen doses by maximum technical and economic efficiency and expectation of 3 t ha^{-1} grain yield (Table 3) established by supply condition and crop year, were used to estimate the expression of straw productivity from the functions that explain their behavior. The linear trend of straw productivity was obtained, with a ratio of 17.1 kg ha^{-1} of straw productivity per kilogram of nitrogen supplied in the fractional condition V_3/V_6, of best response for this variable. Furthermore, the simulation of nitrogen dose by straw productivity via technical, economic, and 3 t ha^{-1} efficiency showed a decline of straw productivity in V_3/R_1, regardless of the nutrient supply condition. The results presented suggest that using optimal doses for the expression of biomass and straw productivity should consider the soil and climatic conditions and the time of nutrient application during the wheat crop cycle, considering a satisfactory grain yield with economic return and cost reduction.

Table 4. Simulation of biological productivity by maximum economical and technical efficiency, and expected yield of wheat grains of 3 t ha^{-1} in nitrogen use

Year	Model	R^2	CV	N (kg ha^{-1})			BP(kg ha^{-1})		
	$BP = b_0 \pm b_1x \pm b_2x^2$	(%)		GYMET	GYMEE	GY3t ha^{-1}	GYMET	GYMEE	GY3t ha^{-1}
				Full dose (V_3)					
2012 (AY)	$5814 + 17.4^*x$	92	10	-	-		-	-	6858
2013 (FY)	$5988 + 57.7x^* - 0.23^*x^2$	98	9	-	-		-	-	8622
2014 (UY)	$5081 + 20.1^*x$	94	15	88	67		6850	6227	6287
2015 (AY)	$5759 + 23.4^*x$	97	14	114	93	60	8426	7935	7163
2016 (FY)	$7575 + 28.4^*x$	93	14	87	79		10046	9534	9279
2017 (UY)	$4477 + 44.9^*x - 0.15^*x^2$	99	11	88	66		7266	6521	6631
2018 (FY)	$8104 + 35.6^*x$	95	13	93	83		11415	10703	10240
General	$6215 + 25.8^*x$	97	16	119	91	60	9285 aA	8563 aB	7763 aC
				Fractional dose (V_3/V_6)					
2012 (AY)	$5680 + 19.8^*x$	97	8	114	86		7937	7383	6868
2013 (FY)	$6345 + 31.5^*x$	99	8	-	-		-	-	8235
2014 (UY)	$4786 + 23.8^*x$	90	12	80	69		6690	6190	6214
2015 (AY)	$5772 + 24.4^*x$	95	14	-	-	60	-	-	7236
2016 (FY)	$7353 + 30.5^*x$	98	9	100	82		10393	9542	9183
2017 (UY)	$5199 + 22.8^*x$	86	17	86	68		7160	6521	6567
2018 (FY)	$8287 + 37.5^*x$	92	12	-	-		-	-	10537
General	$6203 + 27.1^*x$	97	11	120	93	60	9455 aA	8723 aB	7829 aC
				Fractional dose (V_3/R_1)					
2012 (AY)	$5444 + 20.1^*x$	98	12	-	-		-	-	6650
2013 (FY)	$5938 + 26.9^*x$	92	13	-	-		-	-	7552
2014 (UY)	$4797 + 21{,}9^*x$	92	12	109	67		7184	6264	6111
2015 (AY)	$5354 + 22.0^*x$	97	11	-	-	60	-	-	6674
2016 (FY)	$7317 + 25.4^*x$	97	8	105	77		9984	9273	8841
2017 (UY)	$4694 + 18.7^*x$	91	14	96	73		6489	5311	5816
2018 (FY)	$8013 + 33.2^*x$	94	17	98	73		11266	10436	10005
General	$5936 + 24.1^*x$	98	15	-	-	60	-	-	7382 b

AY - Acceptable year; FY -Favorable year; UY - Unfavorable year; b_0 - linear coefficient; b_1x - degree 1 slope; b_2x^2 – degree 2 slope; V_3 - Full condition (100%) of the nitrogen dose in the third leaf expanded; V_3/V_6 - Fractionated condition (70/30%) of the nitrogen dose in the third and sixth leaf expanded; V_3/R_1 - Fractional condition (70/30%) of the nitrogen dose at the third and ear differentiation; N -Nitrogen doses; BP - Biological productivity (kg ha^{-1}); R^2 - Coefficient of determination; CV - Coefficient of variation;* - Significant at $p \leq 0.05$ by F test;PGMET -Nitrogen dose by maximum technical efficiency of grain yield (kg ha^{-1}); PGMEE -Nitrogen dose by maximum economic efficiency of grain yield (kg ha^{-1}); PG3t ha^{-1}-Nitrogen dose by the expectation of 3 t ha^{-1} of grain yield (kg ha^{-1}); Means followed by the same small letter in the column compare the forms of nitrogen supply and capital letters in the row with the types of efficiency (PGMET, PGMEE and PG3 t ha^{-1}), constitute statistically homogeneous group at $p \leq 0.05$ by Scott-Knott test

Table 5. Wheat straw yield simulation for maximum economical and technical efficiency and expected 3 t ha^{-1} grain yield using nitrogen

Year	Model	R^2	CV	N (kg ha^{-1})			SY (kg ha^{-1})		
	$SY = b_0 \pm b_1x \pm b_2x^2$	(%)		PGMET	PGMEE	PG3t ha^{-1}	PGMET	PGMEE	PG3t ha^{-1}
				Full dose (V_3)					
2012 (AY)	4040 + 7.9*x	76	18	-	-		-	-	4514
2013 (FY)	4074 + 10.5*x	90	15	-	-		-	-	4704
2014 (UY)	3789 + 15.9*x	95	13	88	57		5188	4695	4743
2015 (AY)	3990 + 10.7*x	97	9	114	93	60	5210	4985	4632
2016 (FY)	4716 + 21.4*x	92	14	87	69		6579	6193	6000
2017 (UY)	3242 + 21.8*x	97	10	88	56		5160	4463	4550
2018 (FY)	5638 + 26.4*x	97	10	93	73		8093	7565	7222
General	4212 + 16.4*x	99	12	119	91	60	6163 aA	5704 aA	5196 aB
				Fractional dose (V_3/V_6)					
2012 (AY)	3937 + 9.8*x	96	9	114	86		5054	4878	4525
2013 (FY)	4243 + 8.5*x	91	14	-	-		-	-	4753
2014 (UY)	3635 + 18.7*x	92	13	80	59		5131	4738	4757
2015 (AY)	4153 + 10.6*x	96	9	-	-	60	-	-	4790
2016 (FY)	4547 + 23.7*x	98	9	100	72		6917	6253	5969
2017 (UY)	3186 + 21.6*x	91	12	86	58		5035	4433	4482
2018 (FY)	5704 + 26.9*x	90	12	-	-		-	-	7318
General	4200 + 17.1*x	99	8	120	93	60	6252 aA	5790 aA	5226 aB
				Fractional dose (V_3/R_1)					
2012 (AY)	3753 + 10.2*x	85	13	-	-		-	-	4365
2013 (FY)	3968 + 7.5*x	80	20	-	-		-	-	4418
2014 (UY)	3686 + 16.4*x	92	15	109	67		5473	4785	4670
2015 (AY)	3774 + 8.7*x	90	15	-	-	60	-	-	4296
2016 (FY)	4695 + 17.1*x	95	12	105	77		6490	6012	5721
2017 (UY)	3318 + 15.6*x	88	18	96	33		4815	3832	4254
2018 (FY)	5446 + 25.7*x	96	13	98	73		7964	7322	6988
General	4091 + 14.4*x	97	16	-	-	60	-	-	4955 a

AY - Acceptable year; FY - Favorable year; UY - Unfavorable year; b_0 - linear coefficient; b_1x - degree 1 slope; b_2x^2 – degree 2 slope; V_3 - Full condition (100%) of the nitrogen dose in the third leaf expanded; V_3/V_6- Fractionated condition (70/30%) of the nitrogen dose in the third and sixth leaf expanded; V_3/R_1- Fractional condition (70/30%) of the nitrogen dose at the third and differentiation of the ear; N -Nitrogen doses; SY - Straw yield (kg ha^{-1}); R^2 -Coefficient of determination; CV - Coefficient of variation; * -Significant at $p \leq 0.05$ by F test; PGMET -Nitrogen dose by maximum technical efficiency of grain yield (kg ha^{-1}); PGMEE -Nitrogen dose by maximum economic efficiency of grain yield (kg ha^{-1}); PG3t ha^{-1} -Nitrogen dose by the expectation of 3 t ha^{-1} of grain yield (kg ha^{-1}); Means followed by the same small letter in the column compare the forms of nitrogen supply and capital letters in the row with the types of efficiency (PGMET, PGMEE and PG3 t ha^{-1}), constitute statistically homogeneous group at $p \leq 0.05$ by Scott-Knott test

Wendling et al. (2007) concluded that the wheat crop responded economically to a dose of 35 kg ha^{-1} of nitrogen after soybean, for productivity of around 3,100 kg ha^{-1}, after corn crop responded economically until the dose of 30 kg ha^{-1}, reaching productivity of around 2,100 kg ha^{-1}. In corn, the maximum grain yield was obtained with the application of 283 to 289 kg ha^{-1} of nitrogen, but maximum economic efficiency occurred with 156 to 158 kg ha^{-1} of nitrogen, showing that, in many situations, nitrogen fertilizers are used more than necessary (Pavinato et al., 2008). After studying the efficiency of nitrogen use in corn cultivars, with doses of 0 to 180 kg ha^{-1} of nitrogen, a contradictory answer was provided by the research of Fernandes et al. (2005). They reported that the utilization of nitrogen decreased with the application of increasing doses because the nutrient supply exceeded the crop's needs. This decrease is generally due to probable ammonium and nitrate losses by leaching after the nitrification process, which increased with the applied dose, increasing linearly or exponentially (Farinelli & Lemos, 2010). The use efficiency of nitrogen fertilization at levels higher than 120 kg ha^{-1} did not influence wheat grain and straw yield parameters, but for the qualitative aspects, there were no significant changes, except for the increase in grain protein (Wrobel et al., 2016). These results are similar to the one found in this work, corroborating that the range of productivity is associated with high variability in growing conditions and nutrient management.

In recent decades, institutions such as the FAO [Food and Agriculture Organization of the United Nations] have justified the practice of agriculture as a fundamental activity to overcome hunger and poverty (Daufenback et al., 2019). This reinforces the importance of investments and public policies that integrate nutrition, food, and agriculture, thereby strengthening food production and processing (Bocchi et al., 2019). In this sense, the importance of efficient agricultural practices necessary to promote food security is fundamental, with agriculture being the leading supplier of products considered essential for human nutrition (Nkomoki et al., 2018) and fulfilling a decisive role in the production of food for supply (CAISAN, 2011) with socio-environmental sustainability (Silva et al., 2020). The results obtained in favorable, acceptable, and unfavorable years for the crop define the management that ensures satisfactory productivity with lower environmental impacts. It is noteworthy that this research is convergent with goal 2 of the United Nations for Sustainable Development (Agenda 2030), called Zero Hunger and Sustainable Agriculture, in the search for more sustainable production systems with low carbon emissions and low use of external inputs.

Conclusion

The most sustainable management of nitrogen in wheat was obtained with the expected yield rate of 3 t ha^{-1} by manual fertilization, with nitrogen supplied in full dose at the V_3 phenological stage.

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