GMR
The Original by FUNPEC-RP

Simulation of wheat yield by nitrogen and ear components in harvest prediction analysis

O. Alessi[1], J.A.G. da Silva[1], V. Pansera[1], J.A. da Rosa[1], I.R. Carvalho[1], F. Lautenchleger[2], M.S. Jung[1], C. de F. Colet[1], C.A.M.B. Teixeira[1], N.C.F Basso[1], J.V. Tisott[1] and C.M. Babeski[1]

[1] Universidade Regional do Noroeste do Estado do Rio Grande do Sul, Ijuí, RS, Brasil
[2] Universidade Estadual do Centro-oeste, Guarapuava, PR, Brasil

Corresponding author: I.R. Carvalho
E-mail: carvalho.irc@gmail.com

Genet. Mol. Res. 20 (4): gmr18943
Received July 29, 2021
Accepted October 18, 2021
Published November 30, 2021
DOI http://dx.doi.org/10.4238/gmr18943

ABSTRACT. The application in a single or split dose of nitrogen in wheat affects the expression of ear components. Models that simulate these effects can help predict yield. Our objective was to identify wheat ear components that are responsive to the forms of nitrogen supply in a single versus split dose d. This was achieved by testing variables in the construction of a multiple linear regression model for grain yield simulation in harvest simulation analysis. The study was carried out in 2018 and 2019, in a randomized block design with four replications in a 3 x 3 factorial scheme, for three doses of nitrogen (30, 60, 120 kg ha^{-1}) and three forms of nutrient supply [single dose (100%) at phenological stage V_3 (third expanded leaf); split dose (70% and 30%) at phenological stage V_3/V_6 (third and sixth expanded leaf) and split dose (70% and 30%) at phenological stage V_3/R_1 (third expanded leaf and beginning of grain filling)] , respectively, in the soybean/wheat and corn/wheat succession systems. This form of fractionation of 70% and 30% is the form commonly used in commercial wheat crops. The wheat cultivar used was BRS Guamirim. Twenty ears of wheat per experimental unit were randomly collected, which were sent to the laboratory. Ear mass

(EM, g), ear grain mass (EGM, g), ear grain number (EGN, n), ear length (EL, cm) and ear harvest index (EHI), given by the ratio of ear grain mass to ear mass, dry weight were measured. Nitrogen supplied in single and split doses modifies with greater intensity the wheat ear components ear mass and ear grain mass. The nitrogen in a single dose supplied at stage V3 provides significant superior grain yield compared to split doses, regardless of nutrient dose, crop season and succession system.

Key words: *Triticum aestivum*; Nitrogen fertilizer; Agricultural security

INTRODUCTION

Wheat is a cereal grown on a large scale in several regions of the world, having great importance in the global economy (Trautmann et al., 2020; Moustafa et al., 2021). The yield and quality of wheat grains is directly linked to the performance of cultivars, management technologies, soil and climate (Silva et al., 2015; Costa et al., 2017).

Among the management technologies, nitrogen plays an important role in biochemical processes, being part of the constitution of proteins, enzymes, coenzymes, nucleic acids, phytochromes and chlorophyll, among others, with direct effects on grain yield and quality (Correa Filho et al., 2017; Brezolin et. al., 2017). Urea (soluble fertilizer) is the most used source of nitrogen in agriculture because of its high content of the nutrient (45%) and rapid availability to plants, in the form of broadcast application on the soil (Prando et al., 2013; Santos et al., 2020). The greater absorption of nitrogen by the urea source depends on soil moisture and adequate air temperature, conditions not always obtained at the time of fertilization, generating efficiency losses, increased production costs and environmental pollution (Mantai et al., 2015; De Mamann et al 2019). These facts have raised concern even in public health issues when it involves the contamination of groundwater and surface water (Fernandes et al., 2017; Peng et al., 2020). Difficulties encountered in nitrogen management suggest that application at different stages of development can be the solution for improving efficiency and reducing losses (Espindula et al., 2010; Brezolin et al., 2016).

In wheat, the components linked to the ear act directly on the expression of grain yield. These components, such as the number of spikelets per ear and the grain mass, are strongly influenced by the variation in the dose and timing of nitrogen supply (Silva et al., 2015; Batista et al., 2020). These conditions lead to the possibility of searching for the components of the ear and nitrogen simulation models that enable the prediction of productivity (Costa et al., 2018; Trautmann et al., 2020). The use of efficient models that integrate plant components and management can contribute to the predictability of crop seasons and crop planning, as well as a subsidy for the analysis of productivity in inspections of agricultural activity guarantee programs (Mantai et al., 2016; De Mamann et al., 2020).

Multiple linear regression is a model that enables the combination of controlled and uncontrolled variables to carry out simulations, explaining the effect of independent variables on a main variable (Trautmann et al., 2017; Marolli et al., 2017). The use of the Stepwise technique to identify potential variables for inclusion in multiple linear regression promotes the generation of a more robust and efficient model (Dalchiavon, Carvalho 2012; Mantai et al., 2016).

The objective of this work was to identify components of the wheat ear that are more responsive to the forms of nitrogen supply in a single versus split dose and the management of nitrogen that promotes greater productivity. This was done using a multiple linear regression model for grain yield simulation in crop prediction analysis.

MATERIAL AND METHODS

The experiment was conducted in the field, in the seasons of 2018 and 2019, in the county of Augusto Pestana, RS, Brazil (28° 26’ 30’’ S latitude and 54° 00’ 58’’ W longitude). The soil of the experimental area is classified as a typical dystroferric red latosol (Oxysol) and the climate of the region, according to the Köeppen classification, of the Cfa type, with hot summer without a dry season. In the study, 10 days before sowing, soil analysis was performed and identified, over the years average, the following chemical characteristics of the site: i) corn/wheat system (pH= 6.5, P= 34.4 mg dm^{-3}, K= 262 mg dm^{-3}, OM= 3.5%, Al= 0.0 $cmol_c$ dm^{-3}, Ca= 6.6 $cmol_c$ dm^{-3} and Mg= 3.4 $cmol_c$ dm^{-3}) and; ii) soybean/wheat system (pH= 6.2, P= 33.9 mg dm^{-3}, K= 200 mg dm^{-3}, OM= 3.4%, Al= 0.0 $cmol_c$ dm^{-3}, Ca= 6.5 $cmol_c$ dm^{-3} and Mg= 2.5 $cmol_c$ dm^{-3}). The experimental design was a randomized block design with four replications, in a 3 x 3 factorial scheme for N-fertilizer doses (30, 60, 120 kg ha^{-1}) and forms of supply [single dose, with 100% nitrogen applied in the V_3 stage phenological (expanded third leaf); split dose, with 70% and 30% nitrogen applied in the phenological stages V_3 (expanded third leaf) and V_6 (expanded sixth leaf), respectively; and split dose, with 70% and 30% nitrogen applied in the phenological stages V_3 (expanded third leaf) and R_1 (beginning of grain filling), respectively]. This form of fractionation of 70 and 30% is the form commonly used in commercial wheat crops.

The sowing was carried out with a seeder-fertilizer for the composition of plots with 5 rows of 5 m in length and spaced 0.20 m apart, forming the experimental unit of 5 m^2. At sowing, 30 and 15 kg ha^{-1} of P_2O_5 and K_2O were applied, respectively, based on the P and K contents in the soil for expected grain yield of 3 t ha^{-1} and N in the base with 10 kg ha^{-1}, with the urea source, with the remainder to contemplate the doses proposed in the study. The experiment was carried out in two cropping systems, involving soil cover with high and low Carbon/Nitrogen vegetable residue, in a corn/wheat and soybean/wheat succession system, respectively. The seeds were submitted to a germination and vigor test in the laboratory, in order to correct the desired density of 400 viable seeds m^2. Applications of the fungicide tebuconazole at a dosage of 0.75 L ha^{-1} were carried out to control fungal diseases. For weed control, the herbicide metsulfuron-methyl was used at a dose of 4g ha^{-1}. The wheat cultivar used was BRS Guamirim, which is small in size, early cycle, resistant to lodging, commercial class "bread" type and with high productive potential, representing the standard biotype desired by wheat growers in southern Brazil. The harvest of the experiment to estimate the grain yield was done manually by cutting the three central lines of each plot, stage close to the harvest point (125 days), with grain moisture approximately 15%. The plots were tracked with a stationary harvester and sent to the laboratory for correction of grain moisture to 13%, after weighing and estimating grain yield (GY, kg ha^{-1}). In the analysis of ear components, 20 ears of wheat per experimental unit were randomly collected, which were sent to the laboratory for decomposition of the inflorescence components. Therefore, ear mass (EM, g), ear grain mass (EGM, g), ear grain number (EGN, n), ear length (EL, cm) and ear harvest index (EHI), given by the ratio of ear grain mass to ear mass, dry weight were measured.

In compliance with the assumptions of homogeneity and normality of the variables, analysis of variance of the main effects and interaction of doses and forms of nitrogen supply were performed (not shown). By Singh's method, contribution analysis of single and split nitrogen supply on wheat ear components at different nutrient doses. The Sing method is based on the $S_{.j}$, statistic, where:

$$D_{ii'}^{2} = \delta' \psi^{-1} \delta = \sum_{j=1}^{n} \sum_{j'=1}^{n} \omega_{jj'} d_j d_{j'} \qquad \text{(Eq. 1)}$$

where: $D_{ii'}^{2}$ is the Mahalanobis distance between treatments i and i', ψ is the matrix of residual variances and covariances, $\delta' = [\, d_1 \;\; d_2 \ldots d_n]$, where $d_j = Y_{ij} - Y_{i'j}$, Y_{ij} is the mean of the i-th dose in relation to the j-th character and ω is the element of the j-th row and j'-th column of the inverse of the matrix of residual variances and covariances. The total of distances involving all pairs of treatments is given by:

$$\sum_{i<} \sum_{i'} D_{ii'}^{2} = \sum_{m} D_{m}^{2} = \sum_{j=1} S_{.j} \qquad \text{(Eq. 2)}$$

The percentage values of $S_{.j}$ indicate the measure of the relative importance of variable j.

Linear regression analysis was performed to show the level of the relationship between grain yield and nitrogen dose in each nitrogen application condition (single and split), supporting the identification of the best way to supply the product and bases for simulation validation involving a multiple linear regression model.

The selection of potential variables for multiple linear regression was performed using the Stepwise technique. In this technique, a sequence of regression models in which variables are added and removed is iteratively constructed, selecting the regression that has the greatest relationship with the main variable. The addition and removal of variables is performed using partial F statistic, according to the model:

$$F_j = \frac{QS_R(\beta_j \mid \beta_1, \beta_0)}{QM_E(X_j, X_1)} \qquad \text{(Eq. 3)}$$

where: QS_R is the regression sum of squares and $QM_E(X_j, X_1)$ is the mean error square containing the variables X_j and X_1. Variables selected via Stepwise were used to compose the multiple linear regression equation to simulate wheat grain yield. This equation is composed of two or more variables in generating an equation as follows:

$$y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n + \varepsilon \qquad \text{(Eq. 4)}$$

described in matrix form as:

$$y = \begin{bmatrix} Y_1 \\ Y_2 \\ M \\ Y_n \end{bmatrix}; X = \begin{bmatrix} 1 & X_{11} & X_{12} & \ldots & X_{1p} \\ 1 & X_{21} & X_{22} & \ldots & X_{2p} \\ M & M & M & \ldots & M \\ 1 & X_{n1} & X_{n2} & \ldots & X_{np} \end{bmatrix}; b = \begin{bmatrix} b_1 \\ b_2 \\ M \\ b_3 \end{bmatrix}; \varepsilon = \begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ M \\ \varepsilon_3 \end{bmatrix}. \qquad \text{(Eq. 5)}$$

From these matrices, the values of the regression coefficients are obtained, as follows:

$$\hat{\beta} = (X'X)^{-1}X'Y \qquad \text{(Eq. 7)}$$

and the variance of these coefficients is obtained by the covariance matrix of the vector of the regression coefficients:

$$\boldsymbol{C\hat{o}v}\left(\boldsymbol{\hat{\beta}}\right) = (\boldsymbol{X'X})\,\boldsymbol{\hat{\sigma}}\ \text{e}\ \boldsymbol{\hat{\sigma}^2} = \frac{\left(\boldsymbol{Y-X\hat{\beta}}\right)'\left(\boldsymbol{Y-X\hat{\beta}}\right)}{\boldsymbol{n-p-1}} \qquad \text{(Eq. 8)}$$

where n is the number of equations p and is the number of parameters. The hypothesis test is verified: $H_0\!: \beta_i = 0; vs\ H_a\!: \beta_i \neq 0$, expressed by:

$$\boldsymbol{t} = \frac{\boldsymbol{\hat{\beta}_i - \beta_i}}{\sqrt{\hat{V}(\boldsymbol{\hat{\beta}_i})}} \qquad \text{(Eq. 9)}$$

The values of nitrogen doses together with the mean values of the wheat ear components validated by the Stepwise technique were used in the multiple linear regression models, regardless of the crop season. All analyzes were performed using the free Genes software (Cruz, 2013).

RESULTS AND DISCUSSION

In 2019 (Figure 1), high maximum temperatures were observed at the beginning of wheat development, with no rain in the days prior to fertilization at phenological stage V_3. This condition leads to a greater loss of nitrogen by volatilization and lower absorption efficiency due to the restriction of soil moisture to the plants, resulting in lesser development of tillers and ears per area. Fertilizer application in split condition at phenological stage V6 was followed by a high volume of rain, which favors the loss of nitrogen by leaching, due to the high solubility of urea. On the other hand, nutrient splitting at the flowering stage showed a more adequate condition for nitrogen management, with soil moisture caused by rains that occurred the day before fertilization. The meteorological conditions presented together with the reduced average grain yield obtained (Table 1) qualify the year 2019 as unfavorable (UY) for the growing of wheat. In 2018 (Figure 1), lower maximum temperatures were observed during nitrogen supply at the V_3 phenological stage, favoring tillering, a component directly linked to productivity. The occurrence of light rains before and after the application of nitrogen was also observed, ensuring soil moisture with great possibility of better use of nitrogen.

Similar moisture guarantee conditions were also observed in the phenological stages of nitrogen splitting in V_6 and R_1, but with higher temperatures in these periods compared to 2019. However, the average grain yield obtained in 2018 (Table 1), with difference of almost 1000 kg ha^{-1} in relation to 2019, qualifies the year as favorable (FY) for the growing of wheat.

The efficiency of the application of urea, the main source of nitrogen fertilization, depends on favorable weather conditions, especially adequate rainfall distribution and milder temperatures (Arenhardt et al., 2015; Costa et al., 2017). The milder air temperature in the vegetative cycle influences wheat development, with greater tiller production and distribution of photoassimilates for yield, while higher temperatures reduce root development and leaf area and the percentage of fertilized flowers (Ribeiro et al., 2012; Fioreze et al., 2019). Water stress, caused by the excess or shortage of rainfall, has negative effects on plant survival and growth, mainly harming grain yield (Santos et al., 2012). However, a favorable climate for wheat is described as one of milder temperatures and high solar radiation, without heavy rain and large volumes, with adequate distribution to maintain stored soil moisture (Silva et al., 2015; Trautmann et al., 2021).

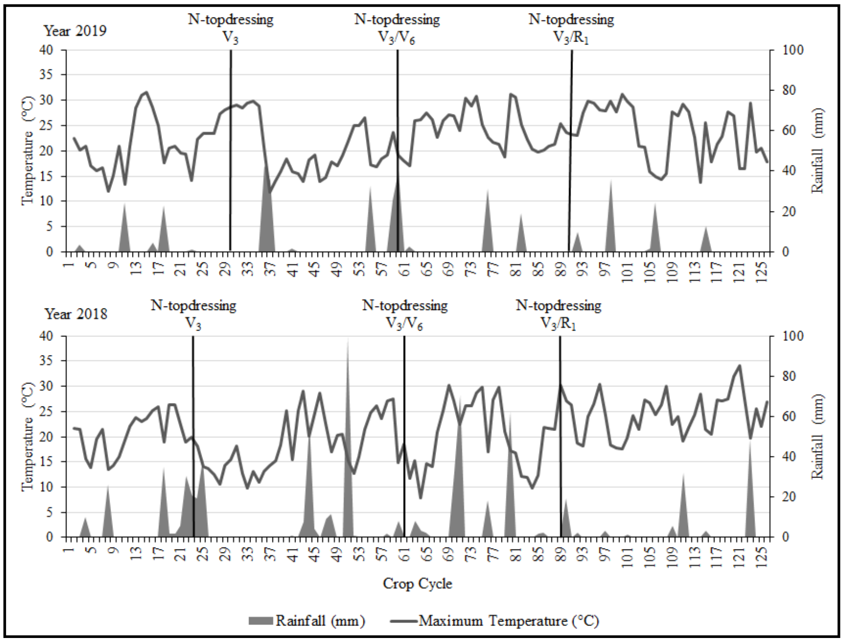

Figure 1. Rainfall and maximum temperatures along the wheat crop cycle and the times of nitrogen application in the years of growing. V_3 = Full condition (100%) of the nitrogen dose at the third expanded leaf stage. V_3/V_6 = Fractionated condition (70%/30%) of the nitrogen dose at the third and sixth expanded leaf stage, and V_3/R_1 = Fractionated condition (70%/30%) of the nitrogen dose at the third expanded leaf stage.

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

Year	Month	Temperature °C			Rainfall mm		GY	Class
		Min	Max	Mean	Average*	Actual	Kg	
2019	May	11.1	24.5	17.8	149.7	20.3	2436b	UY
	June	9.3	20.7	14.5	162.5	59.4		
	July	7.4	17.5	12.4	135.1	176.6		
	August	12.9	23.4	18.1	138.2	61.4		
	September	12.0	23.0	17.5	167.4	194.6		
	October	15.0	25.5	20.2	156.5	286.6		
	Total				909.4	798.9		
2018	May	10.5	22.7	16.6	149.7	100.5	3421 a	FY
	June	7.9	18.4	13.15	162.5	191.0		
	July	8.3	19.2	13.75	135.1	200.8		
	August	9.3	20.4	14.85	138.2	223.8		
	September	9.5	23.7	16.6	167.4	46.5		
	October	12.2	25.1	18.65	156.5	211.3		
	Total				909.4	973.9		

*Average rainfall obtained in the last 25 years; means followed by the same letter in the column do not differ at $p \leq 0.05$ by the Scott & Knott test; Min: Minimum; Max: Maximum; Mean: average temperature; FY: Favorable year; UY: unfavorable year; GY: Average grain yield.

In Table 2, the general averages of grain yield and wheat ear components show a tendency to reduction in most variables with nitrogen splitting, regardless of the cropping system. This behavior possibly shows that the dose splitting of the nutrient in stages close to the grain filling does not contribute to the maximization of components related to yield.

Table 2. Mean values and relative contribution of wheat yield and ear components by the forms of nitrogen supply in each dose of the nutrient.

Characters	Splitting Average			RC (Singh, %) Nitrogen doses (Kg ha^{-1})		
	V_3	V_3/V_6	V_3/R_1	30	60	120
			(2018+2019) Soybean/wheat system			
GY	3278	3226	3065	21.53	23.69	10.0
EM	1.45	1.39	1.5	14.96	24.69	14.1
EGM	1.06	1.05	1.01	35.90	39.25	38.8
EGN	27.88	27.92	27.96	0.80	1.72	9.0
EL	7.25	6.72	7.15	0.42	5.83	15.6
EHI	0.72	0.75	0.74	26.39	4.81	12.5
			Corn/wheat system			
GY	2752	2762	2546	31.05	55.88	70.47
EM	1.35	1.28	1.28	19.31	9.32	5.17
EGM	0.97	0.92	0.94	34.14	14.92	10.54
EGN	27.29	27.22	25.74	0.31	10.03	5.10
EL	6.98	6.48	6.51	2.36	4.05	0.96
EHI	0.72	0.72	0.73	12.82	5.80	7.76

V_3 = collar formed on the 3rd leaf of the main stem; V_3/V_6= Collar formed on the 6th leaf of the main stem and V_3/R_1= Differentiation of the ear; RC=Relative contribution by Singh's method; GY= grain yield (kg ha^{-1}); EM= ear mass (g); EGM= ear grain mass (g); EGN= ear grain number (n); EL= ear length (cm); EHI= Ear Harvest Index (EGM/EM).

In the analysis of the relative contribution in the soybean/wheat system (Table 2), the variables grain yield, ear mass, ear grain mass and ear harvest index show effective changes due to the single and split form of nitrogen supply in different doses of the nutrient, with the exception of the ear harvest index with 60 kg ha-1, which showed a reduced contribution. Regardless of nutrient dose, ear grain mass was the most effective component of change due to single and split nitrogen availability. In the corn/wheat system (Table 2), regardless of the nitrogen dose, a high change by the single and split dose of the nutrient was observed for grain yield, ear mass and ear grain mass. In this condition, the greater sensitivity for the single and split supply of nitrogen is directly linked to yield, unlike the soybean/wheat system, due to the greater contribution of the ear grain mass. This fact justifies that the greater availability of residual-N in the soybean/oat system enhances the expression of fertile tillers, generating a greater influence of nitrogen on the inflorescence components. On the other hand, the restriction of residual-N imposed by the corn/wheat system hinders greater expression of tillering, generating a greater need for the use of fertilizer nitrogen in the maintenance of this component, therefore, the effects observed on the inflorescence components are smaller. It is noteworthy that the number and mass of ear grains and the number of fertile tillers per plant or area are components directly linked to yield and with greater contribution from tillering in altering grain yield (Valério et al., 2009; Silva et al., 2015).

Relative contribution analysis allows knowing the characteristics or components that have the greatest contribution to genetic and environmental effects (Mantai et al., 2016b). They observed the influence of succession systems on grain yield and oat panicle components, with greater change by the analysis of relative contribution of grain and panicle mass by different doses of nitrogen supply. Kurek et al. (2002), studying oats, found the greatest contribution in the identification of plants with higher grain yield in panicle mass. According to these authors, panicle grain number and panicle grain mass were also effective in differentiating more desirable genotypes. Silva et al. (2007) in wheat observed in the ear mass and the number of grains per ear the greatest sensitivity of alteration due to genetic and environmental effects, with direct effects on yield.

Table 3 shows the linear regression analysis to estimate the agronomic efficiency of wheat grain yield as a function of nitrogen doses provided in single (V_3) and split (V_3/V_6 and V_3/R_1) doses in a soybean/wheat and corn/wheat systems, in the joint analysis of the crop seasons. It is noteworthy that the agronomic efficiency is obtained by the angular coefficient (b_ix) of the linear equation (Arenhardt et al., 2017; Mantai et al., 2021), indicating in this research the relation of yield increment per kilogram of nitrogen supplied. In soybean/wheat system, the greatest agronomic efficiency was obtained with the nutrient supplied in a single dose, in the ratio 1: 66, therefore, an increase of 66 kg ha^{-1} of grains for each kilogram supplied of the nutrient. A reduction in efficiency is also observed when splitting takes place in V_3/V_6 and advances to V_3/R_1, with 60 and 52 kg of grains for each kilogram of nitrogen added, respectively. In corn/wheat system, the most effective agronomic efficiency was observed equally when the nutrient was directed in a single dose (V_3) and split in V_3/V_6, with a return of 51 kg ha^{-1} of grains per kilogram of nitrogen. In this condition, there is also a strong reduction in efficiency with the splitting in V_3/R_1, with a return of 39 kg ha^{-1} of grains per kilogram of nitrogen supplied.

Table 3. Linear regression in the estimation of agronomic efficiency as a function of nitrogen doses in a single and split supply with simulation of wheat grain yield.

N Supply	$GY=b_o \pm b_ix$	P (b_ix)	R² (%)	N-fertilizer dose GY_E (3000 kg ha^{-1})	GYs (kg ha^{-1})
(2018 + 2019)					
Soybean/wheat system					
V_3	107+66x	*	99	60	4067
V_3/V_6	243+60x	*	94	60	3843
V_3/R_1	237+52x	*	93	60	3357
Corn/wheat system					
V_3	67+51x	*	99	90	4657
V_3/V_6	124+51x	*	98	90	4714
V_3/R_1	189+39x	*	93	90	3699

V_3=third leaf expanded stage; V_3/V_6=third and sixth leaf expanded stage; V_3/R_1= third leaf expanded stage and ear differentiation; GY=grain yield; P(b_ix)=parameter that measures the significance of the line; R²=coefficient of determination; GY_E=expected grain yield as recommended in the Lime and Fertilizer Manual for the States of Rio Grande do Sul and Santa Catarina, 2016; GYs=simulated grain productivity.

In table 3, from the parameters of the linear equation, the simulated grain yield (SGY) was also obtained considering the nitrogen dose of 60 and 90 kg ha^{-1} for the soybean/wheat and corn/wheat succession system, respectively, in the grain yield expectation of 3000 kg ha^{-1}, according to the Lime and Fertilizer Manual for the states of

Rio Grande do Sul and Santa Catarina, Brazil. Thus, the replacement of the expectation dose to the regression models shows that the highest grain yield estimated in the soybean/wheat system was obtained in the single dose application at V_3 stage (4067 kg ha^{-1}), with reduced yield under the conditions of splitting, mainly in V_3/R_1. In the corn/wheat system, the expectation dose of 3000 kg ha^{-1} shows greater magnitude of yield simulated in stages V_3 and V_3/V_6, with 4657 and 4714 kg ha^{-1} of grains, respectively, and with a strong reduction in yield with the splitting in V_3/R_1. Therefore, the obtained results qualify the nitrogen management in a single application at stage V_3, avoiding the expense of a second management operation in the crop by splitting in V_3/V_6, and especially in V_3/R_1, with a strong reduction in yield, regardless of the succession system.

Nitrogen fertilization is one of the most important management techniques in cereal growing due to its great effect on grain yield (De Mamann et al., 2019). In wheat, the timing and form of nitrogen supply modify ear components directly linked to yield (Silva et al., 2015). Pietro-Souza et. al (2013) mention the importance of nitrogen supply in the initial stages of growing to increase the number of spikelets and grains per ear. However, the greatest efficiency of the nutrient depends on adequate conditions of soil moisture and air temperature, a condition not always obtained at the time of fertilization (Costa et al., 2018). According to Brezolin et al. (2016), the fractional supply of nitrogen at different times of wheat development can be an alternative to reducing nutrient losses. The results obtained here show that a single supply in V_3 is more efficient on the expression of yield compared to splitting. Therefore, management in a single application of fertilizer under more favorable conditions of soil moisture and air temperature ensure greater efficiency in the elaboration of grain yield.

The complex relationships between the plant and nitrogen management reinforce the search for more adjusted simulation models that allow for qualifying the crop forecast estimate. These models can potentially be constructed taking into account plant inflorescence components and nitrogen rates (Mantai et al., 2016). In this perspective, in Table 4, the significance by the Stepwise technique is presented, in the indication of potential variables for inclusion in a multiple simulation model. In the soybean/wheat system, the application of nitrogen in a single dose in V_3 qualifies the number of grains per ear, the ear harvest index and the nitrogen dose as potential variables. In the V_3/V_6 phenological stage, ear mass and nitrogen dose indicated more significant effects. In the application at the V_3/R_1 stage, both ear length and nitrogen dose were the most promising variables. In the corn/wheat system (Table 4), in the single dose application in V_3, the ear grain mass, ear length and nitrogen dose were effective. In stage V_3/V_6, ear harvest index and nitrogen dose were classified, and in stage V_3/R_1, only nitrogen dose shows contribution for inclusion in the multiple linear regression model.

The results presented in Table 4 show that the forms of nitrogen supply act differently on the components of the wheat ear, modifying the magnitude of importance for inclusion in the multiple model. On the other hand, the nitrogen dose proved to be effective regardless of the form of supply, being potentially necessary in the simulation. Studies analyzing plant variables and nitrogen management support the importance of the nutrient on the development of different crops (Pietro-Souza et. al 2013; De Mamann et al., 2017). Mantai et al. (2016), for the oat crop, using the Stepwise technique, defined the panicle harvest index and the nitrogen dose as efficient to compose the multiple linear regression model in a soybean/oat system. In corn/oat system, panicle harvest index, number of grains per panicle and number of spikelets per panicle were selected, showing that the succession system interferes with the classification and magnitude of importance of the variables, meeting the results of this study. Marolli et al. (2017) used the grain mass per panicle and the oat panicle harvest index to compose the multiple linear regression models, with high reliability of grain yield simulation along with the management of the growth regulator and nitrogen. Trautmann et al. (2017) selected rainfall, crop cycle days and nitrogen rates in development in the simulation of wheat biomass yield, with results close to those observed. Marolli et al. (2018) identified the thermal sum, rainfall, solar radiation, growth regulator dose and biomass cut-off moment, qualifying the composition of the multiple linear regression model, in the simulation of oat biomass yield. In the cited works, the high reliability of the multiple linear regression models in the simulation of yield in different scenarios, based on the variables selected by the Stepwise technique, is highlighted.

Table 4. Significance by the Stepwise technique of potential wheat variables for use in the multiple linear regression model, with mean values of the classified variables.

Source of variation	**Mean square/Stepwise**			**Mean square/Stepwise**		
	Soybean/wheat system			**Corn/wheat system**		
	V_3	**V_3/V_6**	**V_3/R_1**	**V_3**	**V_3/V_6**	**V_3/R_1**
	2018+2019					
Regression	6508728*	7030946*	4940923*	2597993*	4329377*	7547405*
EM	ns	*	ns	ns	ns	ns
EGM	ns	ns	ns	*	ns	ns
EGN	*	ns	ns	ns	ns	ns
EL	ns	ns	*	*	ns	ns
EHI	*	ns	ns	ns	*	ns
N Dose	*	*	*	*	*	*
Error	99659	145805	192093	159756	100438	65295
Selected variables	Soybean/wheat system means			Corn/wheat system means		
	V_3	V_3/V_6	V_3/R_1	V_3	V_3/V_6	V_3/R_1
EM	-	1.39	-	-	-	-
EGM	-	-	-	0.97	-	-
EGN	27.88	-	-	-	-	-
EL	-	-	7.15	6.98	-	-
EHI	0.72	-	-	-	0.72	-
N Dose	60	60	60	90	90	90

V_3 = collar formed on the 3rd leaf of the main stem, V_3/V_6= Collar formed on the 6th leaf of the main stem and V_3/R_1= Differentiation of the ear; EM= ear mass (g); EGM= ear grain mass (g); EGN= ear grain number (n); EL= ear length (cm); EHI= ear harvest index (EGM/EM); N Dose = Dose of Nitrogen; * = Significant at 5% error probability, respectively, by the F test; ns= Not significant by the F test at 5% probability of error.

From the selected variables in each of the scenarios, Table 5 presents the multiple linear regression equations for the simulation of wheat grain yield by the dose of nitrogen and ear components in the doses in single and split nitrogen supply. The simulations considered the nitrogen dose for the expected yield of 3000 kg ha^{-1}, in a soybean/oat (60 kg ha^{-1}) and corn/oat (90 kg ha^{-1}) system, together with the average values of the components of ear obtained in the joint analysis of the studied crop seasons (Table 4). For both succession systems, the grain yield values simulated at stages V_3, V_3/V_6 and V_3/R_1 were similar to the mean values observed under field conditions, with the results contained in the mean confidence interval (Table 5). Also noteworthy are the different multiple regressions found for the same fertilization conditions. That confirms the dynamics of the carbon/nitrogen ratio of succession systems in influencing plant variables and interaction with fertilizer nitrogen. This dynamic is, for example, observed with the number of grains per ear, which was significant in the phenological stage V_3 only in the soybean/wheat system. Due to the greater release of residual-N in this system, the maximization of expression of the number of grains is favored, a phase that initiates the cellular differentiation processes of spikelets of the ear (Kuhnem et al 2020).

Table 5. Multiple linear regression to simulate wheat grain yield by ear components and nitrogen rates in the forms of supply in growing systems.

N supplied (stage)	Equation $GY=f(x_i)$	GYo (kg ha^{-1})	GYs (kg ha^{-1})	CI LL-UL
Soybean/wheat system				
V_3	$GY=-4547+70.99_{EGN}+6947_{EHI}+11.48_{N}$	3277	3122	2860-3494
V_3/V_6	$GY=-1782+3097.92_{EM}+9.38_{N}$	3226	3086	2864-3487
V_3/R_1	$GY=-6457+1156_{EL}+17.98_{N}$	3065	2887	2649-3281
Corn/wheat system				
V_3	$GY=6212+2007.84_{EGM}-904.38_{EL}+12.99_{N}$	2752	3016	2482-3121
V_3/V_6	$GY=-4618+9134_{EHI}+11.57_{N}$	2762	2999	2496-3128
V_3/R_1	$GY=1497+14.98_{N}$	2546	2845	2312-2980

V_3 = collar formed on the 3rd leaf of the main stem, V_3/V_6= Collar formed on the 6th leaf of the main stem and V_3/R_1= Ear differentiation; GYo= Observed grain yield; GYs= simulated grain yield; EM= ear mass (g); EGM= ear grain mass (g); EGN= ear grain number (n); EL= ear length (cm); EHI= ear harvest index (EGM/EM); N= nitrogen dose; CI = confidence interval; LL= lower limit of the confidence interval; UL= upper limit of the confidence interval.

In the supply at later stages, little influence is given on the ear components. In the V_3/R_1 condition, only in the soybean/wheat system there is inclusion of the ear length, however, it has no direct influence on yield. Similar results in later fertilization were also observed by Costa et. al (2018). Multiple linear regressions are of great importance in the study of systems where there is a need to understand the influence of multiple factors on a main variable. Dalchiavon et al. (2012), simulated with high quality by multiple linear regression the rice yield by the number of panicles, weight and number of spikelets per panicle and thousand grain mass. Marolli et. al (2018) efficiently developed a multiple linear regression model, considering plant variables, climate and management of growth regulator and nitrogen to simulate the yield of oat biomass for silage throughout the cycle. Liu et al (2020) used multiple linear regression to quantify the importance of ear components for determining wheat grain yield per plant under low air temperature conditions, finding that the reduction in grain yield is attributed to the decrease in number of ears per plant and number of grains per ear.

CONCLUSIONS

Nitrogen supplied in single and split doses modifies the wheat ear components ear mass and ear grain mass at different nitrogen doses and succession systems.

The nitrogen in a single dose supplied at stage V3 provides significantly superior grain yield compared to a split dosabe, regardless of nutrient dose, crop season and succession system.

The multiple linear regression model efficiently simulates wheat grain yield by inflorescence and nitrogen components, ensuring crop predictability.

ACKNOWLEDGMENTS

We would like to thank CAPES, CNPq, FAPERGS and UNIJUI for the financial support and for the Scientific and Technological Initiation Scholarship, Graduate Scholarship and Research Productivity Scholarship. We would also like to thank the Graduate Program in Mathematical and Computational Modeling at UNIJUÍ for the resources made available in the development of this research.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

REFERENCES

Arenhardt EG, Silva JAG, Gewehr E, Oliveira AC, et al. (2015). The nitrogen supply in wheat cultivation dependent on weather conditions and succession system in southern Brazil. *Afr. J. Agric Res.* 10: 4322-4330. https://doi.org/10.5897/AJAR2015.10038.

Arenhardt EG, Silva JAG, Arenhardt LG, Silva DR, et al. (2017). Technical and agronomic efficiency of oat cultivars as a function of nitrogen availability. *Científica*. 45: 257-270. http://dx.doi.org/10.15361/1984-5529.2017v45n3p257-270.

Batista VV, Salapata MC, Oligini KF, Camana D, et al. (2020). Componentes de Rendimento e Produtividade de Cultivares de Trigo submetidas ao Parcelamento ou não de Nitrogênio. *Rev. Cienc. Agri. 18*: 1-7. https://doi.org/10.28998/rca.v18i3.9024.

Brezolin AP, Silva JAG, Frantz FCR, Binelo MO, et al. (2016). The efficiency of wheat yields by nitrogen dose and fractionation. *Afr. J. Agric Res.* 11: 3440-3449. https://doi.org/10.5897/AJAR2016.11249.

Brezolin AP, Silva JAG, Roos-Frantz F, Binelo MO, et al. (2017). Wheat yield obtained from nitrogen dose and fractionation. *Afr. J. Agric Res.* 12: 566-576. https://doi.org/10.5897/AJAR2016.11929.

Correa Filho DVB, Correia ECSS, Neto FJD, Santos DV, et al. (2017). Crescimento e desenvolvimento de aveia preta em resposta à inoculação com *Azospirillum* brasilense e adubação nitrogenada. *Colloq. Agrar*. 13: 1-08.

Costa JSP, Mantai RD, Silva JAG, Scremin AH, et al. (2017). Single and fractioned supply of nitrogen in wheat productivity. *Int. J. Dev. Res.* 7: 13055-13061.

Costa JSP, Mantai RD, Silva JAG, Scremin OB, et al. (2018). Single and split nitrogen dose in wheat yield indicators. *Rev. Bras. Eng. Agrí. Ambiental.* 22: 16-21. https://doi.org/10.1590/1807-1929/agriambi.v22n1p16-21.

Cruz CD (2013) Genes: A Software Package for Analysis in Experimental Statistics and Quantitative Genetics. *Acta Scientiarum. Agronomy*. 35: 271-276. http://dx.doi.org/10.4025/actasciagron.v35i3.21251.

Dalchiavon FC and Carvalho MP (2012). Correlação linear e espacial dos componentes de produção e produtividade da soja. *Semin. Cienc. Agrar*. 33: 541-552. doi: 10.5433/1679-0359.2012v33n2p541.

De Mamann ATW, Silva JAG, Scremin OB, Mantai RD, et al. (2017). Nitrogen efficiency in wheat yield through the biopolymer hydrogel. *Rev. Bras. Eng. Agrí. Ambiental.* 21: 697-702. https://doi.org/10.1590/1807-1929/agriambi.v21n10p697-702.

De Mamann ATW, Silva JAG, Binelo MO, Scremin OB, et al. (2019). Artificial intelligence simulating grain productivity during the wheat development considering biological and environmental indicators. *J. Agric. Stud.* 7: 197-212. doi: 10.5296/jas.v7i3.15153.

De Mamann TWA, Silva JAG, Scremin OB, Trautmann APB, et al. (2020). Diffuse system simulating wheat productivity by nitrogen and temperature in the use of biopolymers. *Rev. Bras. Eng. Agrí. Ambiental.* 24: 289-297. https://doi.org/10.1590/1807-1929/agriambi.v24n5p289-297.

Espindula MC, Rocha VS, Souza MA, Grossi JAS, et al. (2010) Nitrogen application methods and doses in the development and yield of wheat. *Cienc. Agrotec*. 34: 1404-1411. https://doi.org/10.1590/S1413-70542010000600007.

Fernandes G, Tiecher T, Piton R, Pellegrini A, et al. (2017). Impacto da fertilização nitrogenada em pastagens perenes na contaminação dos recursos naturais. *Rev. Bras. Tecnol. Agropec*. 1: 03-14.

Fioreze SL, Vacari J, Turek TL, Michelon LH, et al. (2019). Componentes produtivos do trigo em função da temperatura no período de diferenciação de espiguetas. *Rev. Cienc. Agrovet*. 18: 24-32. doi: 10.5965/223811711812019024.

Kuhnem P, Rosa AC, Wagner F and da Rosa AT (2020). Informações técnicas para trigo e triticale: safra 2020. *Biotrigo Genética*. Passo Fundo.

Kurek AJ, Carvalho FIF, Cruz PJ, Lorencetti C, et al. (2002). Variabilidade em genótipos fixos de aveia branca estimada através de caracteres morfológicos. *Rev. Bras. Agrocienc*. 8: 13-17.

Liu L, Xia Y, Liu B, Chang C, et al. (2020). Individual and combined effects of jointing and booting low-temperature stress on wheat yield. *Eur. J. Agron*. 113: 125989. https://doi.org/10.1016/j.eja.2019.125989.

Mantai RD, Silva JAG, Arenhardt EG, Heck TG, et al. (2015). The effect of nitrogen dose on the yield indicators of oats. *Afr. J. Agric Res.* 10: 3773-3781. https://doi.org/10.5897/AJAR2015.9845.

Mantai RD, Silva JAG, Arenhardt EG, Scremin OB, et al. (2016). Simulation of oat grain (*Avena sativa*) using its panicle components and nitrogen fertilizer. *Afr. J. Agric. Res.* 11: 3975-3983. doi:10.5897/AJAR2016.10943.

Mantai RD, Silva JAG, Arenhardt EG, Sausen ATZR, et al. (2016b). The dynamics of relation oat panicle with grain yield by nitrogen. *Am. J. Plant Sci*. 7: 17-27. doi: 10.4236/ajps.2016.71003.

Mantai RD, Silva JAG, Carbonera R, Carvalho IR, et al. (2021). Technical and agronomic efficiency of nitrogen use on the yield and quality of oat grains. *Rev. Bras. Eng. Agrí. Ambiental*. 25: 529-537. https://doi.org/10.1590/1807-1929/agriambi.v25n8p529-537.

Marolli A, Silva JAG, Mantai RD, Brezolin AP, et al. (2017). Oat yield through panicle components and growth regulator. *Rev. Bras. Eng. Agrí. Ambiental.* 21: 261-266. https://doi.org/10.1590/1807-1929/agriambi.v21n4p261-266.

Marolli A, Silva JAG, Sawicki S, Binelo MO, et al. (2018). A simulação da biomassa de aveia por elementos climáticos, nitrogênio e regulador de crescimento. *Arq. Bras. Med. Vet. Zootec*. 70: 535-544. https://doi.org/10.1590/1678-4162-9504.

Moustafa ES, Ali M, Kamara MM, Awad MF, et al. (2021). Field screening of wheat advanced lines for salinity tolerance. *Agronomy*. 11: 281. https://doi.org/10.3390/agronomy11020281.

Peng J, Xu Y, Shang B, Qu L, et al. (2020). Impact of ozone pollution on nitrogen fertilization management during maize (*Zea mays L.*) production. *Environ. Pollut*. 266: 115158. https://doi.org/10.1016/j.envpol.2020.115158.

Pietro-Souza W, Bonfim-Silva EM, Schlichting AF and Silva M de C (2013). Desenvolvimento inicial do trigo sob doses de nitrogênio em latossolo vermelho de cerrado. *Rev. Bras. Eng. Agrí. Ambiental.* 17: 575-580. https://doi.org/10.1590/S1415-43662013000600001.

Prando AM, Zucareli C, Fronza V, Oliveira FAD, et al. (2013). Características produtivas do trigo em função de fontes e doses de nitrogênio. *Pesq Agropec Trop*. 43: 34-41.

Ribeiro G, Pimente AJB, Souza MA, Rocha JRASC, et al. (2012). Estresse por altas temperaturas em trigo: impacto no desenvolvimento e mecanismos de tolerâncias. *Rev. Bras. Agrociênc*. 18: 133-142. https://doi.org/: 10.18539/cast.v18i2.2502.

Santos D, Guimarães VF, Klein J, Fioreze SL, et al. (2012). Cultivares de trigo submetidas a déficit hídrico no início do florescimento, em casa de vegetação. *Rev. Bras. Eng. Agrí. Ambiental.* 6: 836-842. https://doi.org/10.1590/S1415-43662012000800004.

Santos JB, Silva AN, Cruz JO, Santos RB, et al. (2020). Características agronômicas e avaliação econômica do milho sob diferentes doses de nitrogênio na forma de ureia comum e peletizada. *AGRIES*. 6: 1-9. https://doi.org/10.36725/agries.v6i0.3561.

Silva JAG, Carvalho FIF, Hartwig I, Caetano FR, et al. (2017). Distância morfológica entre genótipos de trigo com ausência e presença do caráter "stay-green". *Cienc. Rural.* 37: 1261-1267. https://doi.org/10.1590/S0103-84782007000500007.

Silva JAG, Arenhardt EG, Kruger CAMB, Lucchese AO, et al. (2015) A expressão dos componentes de produtividade do trigo pela classe tecnológica e aproveitamento do nitrogênio. *Rev. Bras. Eng. Agrí. Ambiental.* 19: 27-33. https://doi.org/10.1590/1807-1929/agriambi.v19n1p27-33.

Trautmann APB, Silva JAG, Scremin OB, Marolli A, et al. (2017). A proposal of simulation of wheat grain productivity by nitrogen and meteorological elements. *Int. J. Dev. Res.* 7: 13985-13992.

Trautmann APB, Silva JAG, Binelo MO, Valdiero AC, et al. (2020). Simulation of wheat yield by nitrogen and nonlinearity of environmental conditions. *Rev. Bras. Eng. Agr. Ambiental.* 24: 44-51. https://doi.org/10.1590/1807-1929/agriambi.v24n1p44-51.

Trautmann APB, Silva JAG, Rosa JA, Carvalho IR, et al. (2021). The supply of nitrogen fertilizer in wheat to the highest environmental quality with satisfactory yield. *Genet. Mol. Res*. 20: 1-16. https://doi.org/10.4238/gmr18903.

Valério IP, Carvalho FIF, Oliveira AC, Benin G, et al. (2009). Fatores relacionados à produção e desenvolvimento de afilhos em trigo. *Semin. Cienc. Agrar*. 30: 1207-1218. http://dx.doi.org/10.5433/1679-0359.2009v30n4Sup1p1207.