Simulation of wheat yield by nitrogen and nonlinearity of environmental conditions

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ABSTRACT: Fuzzy logic can simulate wheat productivity by assisting crop predictability. The objective of the study is the use of fuzzy logic to simulate wheat yield in the conditions of nitrogen use, together with the effects of air temperature and rainfall, in the main cereal succession systems in Southern Brazil. The study was conducted in the years 2014, 2015 and 2016, in Augusto Pestana, RS, Brazil. The experimental design was a randomized block design with four repetitions in a 4 x 3 factorial scheme for N-fertilizer doses (0, 30, 60, 120 kg ha^{-1}) and nutrient supply forms [100% in phenological stage V_3 (third expanded leaf); (70%/30%) in the phenological stage V_3/V_6 (third and sixth expanded leaf) and; fractionated (70%/30%) at the phenological stage V_3/E (third expanded leaf and beginning of grain filling)], respectively, in the soybean/wheat and corn/wheat systems. The pertinence functions and the linguistic values established for the input and output variables are adequate for the use of fuzzy logic. Fuzzy logic simulates wheat grain yield efficiently in the conditions of nitrogen use with air temperature and rainfall in crop systems.

Key words: *Triticum aestivum*, temperature, precipitation, fuzzy logic, modeling

Simulação da produtividade do trigo pelo nitrogênio e não linearidade das condições ambientais

RESUMO: A lógica fuzzy pode simular a produtividade do trigo auxiliando na previsibilidade de safras. Objetivou-se no estudo o uso de lógica fuzzy para simulação da produtividade do trigo nas condições de uso do nitrogênio junto aos efeitos de temperatura do ar e precipitação pluviométrica, nos principais sistemas de sucessão do cereal no sul do Brasil. O estudo foi conduzido nos anos de 2014, 2015 e 2016, em Augusto Pestana, RS, Brasil. O delineamento experimental foi o de blocos casualizados com quatro repetições em fatorial 4 x 3, para doses de N-fertilizante (0, 30, 60, 120 kg ha^{-1}) e formas de fornecimento do nutriente [condição única (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/E (terceira folha expandida e início do enchimento de grãos)], respectivamente, no sistema soja/trigo e milho/trigo. As funções de pertinências e os valores linguísticos estabelecidos para as variáveis de entrada e de saída se mostram adequados para o uso da lógica fuzzy. A lógica fuzzy simula com eficiência a produtividade de grãos de trigo nas condições de uso do nitrogênio com temperatura do ar e precipitação pluviométrica nos sistemas de cultivo.

Palavras-chave: *Triticum aestivum*, temperatura, precipitação, lógica fuzzy, modelagem

Introduction

The prior and precise knowledge of agricultural harvests is a strategic issue in world agriculture (Gomes et al., 2014; Marolli et al., 2018). Predicting with efficiency has been a complex activity, due to the different managements, types of soils and climates (Crusiol et al., 2016; Marolli et al., 2017). Mathematical models that seek efficient simulations, describing complex interactions with the nonlinear effects of agroecosystems are nincreasingly being sought (Rosa et al., 2015; Mantai et al., 2017). In this perspective, fuzzy models are techniques that allow the description of complex systems, produced from rules elaborated by specialists, providing their experience to the elaboration of an inference system of the type "If <condition> Then <result>" (Barros & Bassanezi, 2010; Silva et al., 2014).

Wheat is a cereal of great importance in the global economy (Santos et al., 2016; Goergen et al., 2017), but it is strongly dependent on nitrogen in the expression of productivity (Camponogara et al., 2016; Costa et al., 2018). The efficiency of nitrogen to production elaboration is dependent on the non-linearity of environmental conditions, mainly rainfall and air temperature (Acosta et al., 2014; Mantai et al., 2016). Under real conditions, the proper timing of nitrogen supply does not always coincide with adjusted conditions of soil moisture and air temperature, changing the efficiency of nutrient utilization and, consequently, the expected productivity (Acosta et al., 2014; Arenhardt et al., 2015).

The use of fuzzy logic can represent an efficient tool for the simulation of productivity, involving the nonlinear relationships of environmental conditions in nitrogen supply in real agricultural systems. Therefore, the objective of this study is to use fuzzy logic to simulate wheat grain yield under nitrogen use conditions along with the effects of air temperature and rainfall, considering the main systems of cereal succession in southern Brazil.

Materials and Methods

The study was carried out in 2014, 2015 and 2016, in the municipality of Augusto Pestana, RS, Brazil (28° 26' 30" S, 54° 0' 58" W and altitude of 400 m). The soil of the experimental area is classified as an Oxisol and the climate of the region, according to the Köeppen classification, is of the CFA type, having hot summer without dry season. Ten days before sowing, soil analysis was performed and the following chemical characteristics were identified in the averages of the years (Tedesco et al.,1995): i) soybean/wheat system (pH = 6,1, P= 49,1 mg dm^{-3}, K = 424 mg dm^{-3}, MO = 3,0%, Al = 0 cmol$_c$ dm^{-3}, Ca = 6,3 cmol$_c$ dm^{-3} and Mg = 2,5 cmol$_c$ dm^{-3}) and; ii) corn/wheat system (pH = 6,5, P = 23,6 mg dm^{-3}, K = 295 mg dm^{-3}, MO = 2,9%, Al = 0 cmol$_c$ dm^{-3}, Ca = 6,8 cmol$_c$ dm^{-3} and Mg = 3,1 cmol$_c$ dm^{-3}). Independent of agricultural year, sowing was performed based on the technical indications of the species, with a seeder-fertilizer for composition of plots with 5 rows of 5 m long and spaced 0.20 m, forming an experimental unit of 5 m^2. During sowing, 30 and 20 kg ha^{-1} of P$_2$O$_5$ and K$_2$O were applied, respectively, based on soil P and K concentrations for

grain yield expectation of 3 t ha^{-1} and N in the base with 10 kg ha^{-1}, with nitrogen available in the form of urea. The seeds were subjected to germination test and vigor in a laboratory, in order to correct the desired density of 400 viable seeds m^{-2}. During the execution of the study, applications of Tebuconazole fungicide were performed at the dose of 0.75 L ha^{-1}. Weed control was performed with a metsulfuron-methyl herbicide at a dose of 4 g ha^{-1}. In the study, the wheat cultivar used was BRS Guamirim of low-size, early cycle, resistant to lodging, of commercial class type "bread" of high productive potential. This cultivar represents the standard biotype commonly desired by the growers in Southern Brazil.

In each cultivation system (soybean/wheat, corn/wheat system), the experimental design was a randomized block design with four repetitions in a 4 x 3 factorial scheme for N-fertilizer doses (0, 30, 60, 120 kg ha^{-1}) and forms of nutrient supply [single condition (100%) at phenological stage V$_3$ (expanded third leaf); fractionated (70%/30%) at the phenological stage V$_3$/V$_6$ (third and sixth expanded leaf) and fractionated (70%/30%) in the phenological stage V$_3$/E (third expanded leaf and initiation of grain filling)], respectively, totaling 96 experimental units. In all years of cultivation, N-fertilizer application at V$_3$, V$_6$ and E stages were at 30, 60 and 90 days after wheat emergence, respectively. The experiments were harvested to estimate grain yield manually by cutting the three central lines of each plot, near the harvest point (135 days), with grain moisture around 15%. After harvest, the grains were tracked with a stationary harvester and sent to the laboratory to correct grain moisture to 13%, after weighing and yield estimation.

The values of productivity with the information of air temperature and rainfall were used to classify the agricultural years as unfavorable, reasonable and favorable to the cultivation of wheat. The maximum and minimum temperature information for the calculation of the thermal sum and rainfall were obtained by the Automatic Total Station installed at 500 m from the experiment. Thermal sum (TS) was obtained from the emergence of plants by the model:

$$TS = \sum_{i=1}^{n} \left(\frac{T_{max} + T_{min}}{2} \right) - Tb \qquad (1)$$

where:

T$_{max}$ - maximum temperature;
T$_{min}$ - minimum temperature;
n   - number of days from emergence period to harvest; and,
Tb   - base temperature. The wheat base temperature used in the study was 4 °C (Pedro Júnior et al., 2004).

In fuzzy modeling, the input variables (independent) were nitrogen doses (N, kg ha^{-1}), thermal sum (TS, degrees d^{-1}) and rainfall (PP, mm), with variable output (dependent) grain yield (PG, kg ha^{-1}). The information obtained was organized and classified in linguistic terms for the composition of the rules base by the help of a specialist, considering the set of results from three agricultural seasons. For the thermal sum (degrees d^{-1}), the interval domain [1370, 1803] was considered, representing the ranges: <1575 [Low (B)] and > 1575 [High

(A)]. In the supply of nitrogen (kg ha⁻¹), the interval domain [0, 120] was considered, representing the ranges: <30 [low dose (B)]; 30-90 [intermediate dose (I)] and > 90 [high dose (A)]. For rainfall (mm), the interval domain [777, 1009] was defined, representing the ranges: <893 [Low (B)] and > 893 [High (A)]. In the output variable [grain yield (kg ha⁻¹)], the image intervals represent the maximum and minimum values of experimentally collected data, considering the averages of the different years of evaluation. Six simulators were built for the conditions of nitrogen use in each succession system. The grain yield variable was divided into four equidistant intervals (Table 1): very low (MB), low (B), mean (M) and high (A). Although the construction of the rule base is the same in both systems, the lower and upper limits of grain yield were changed according to expected productivity in each system of high succession (soybean/wheat) and reduced (corn/wheat) N-residual release.

In the elaboration of the model, the Fuzzy Rule Based System (SBRF) was used, implemented by the Fuzzy Logic Toolbox of the Matlab software. In the prediction applications, the Mamdani fuzzy model was used, which includes interface modules in the transformation of input variables into diffuse sets and, later outputs in proportional numerical quantities (Cecconello et al., 2010). The fuzzification process occurred by 4 successive modules. In module 1 (fuzzification), the input variable information was mathematically modeled using fuzzy sets. From the specialist, each input variable was assigned linguistic terms representing the states of this

variable and, each linguistic term is associated with a fuzzy set by a function of pertinence. In Module 2 (rule base), the variables were adjusted in their linguistic classifications, where each rule base satisfied the following structure:

$$\text{If A is in } A_i \text{ then B is in } B_i$$

A_i and B_i being the fuzzy sets. The expression A is in A_i means that $\mu_{A_i}(a) \in [0, 1]$. Both the A_i and B_i sets are the Cartesian product of fuzzy sets, that is, $A_i = A_{i1} \times A_{i2} \times ... \times A_{im}$ and $B_i = B_{i1} \times B_{i2} \times ... \times B_{in}$. In this case, each fuzzy set A_{ij} and B_{ik} represented a linguistic term for the J-th input variable and k-th output variable, and expression A is in A_i which means:

$$\mu_{A_i}(a) = \min\left\{\mu_{A_{i1(a)}}, \mu_{A_{i2(a)}}, ..., \mu_{A_{im(a)}}\right\} \in [0,1] \quad (2)$$

In module 3 (inference), the logical connectors used to establish the fuzzy relationship for rule base modeling were defined. The relationship between linguistic variables was characterized by the fuzzy system operator (MIN). In each rule a fuzzy relation R_i was considered where the degree of relevance/pertinence for each pair (a, b) is:

$$\mu_{R_i}(a,b) = \min\{\mu_{A_i}(a), \mu_{B_i}(b)\} \quad (3)$$

The relationship between each rule is characterized by the operator (MAX), of the fuzzy R relationship that represents the

Table 1. Fuzzy rule base for wheat grain yield simulation

N (kg ha⁻¹)		TS (degree d⁻¹)		PP (mm)		PG (kg ha⁻¹)		
V_L	V_Q	V_L	V_Q	V_L	V_Q	V_3	V_3/V_6	V_3/E
Soy/wheat system (2014 + 2015 + 2016)								
B	[0, 30[	B	1575	B	893	MB	MB	MB
				A	893	B	B	B
		A	1575	B	893	MB	MB	MB
				A	893	MB	MB	MB
I	[30, 90[	B	1575	B	893	M	M	M
				A	893	M	M	M
		A	1575	B	893	M	M	M
				A	893	M	M	M
A	[90, 120]	B	1575	B	893	M	M	M
				A	893	A	A	A
		A	1575	B	893	M	M	M
				A	893	A	A	A
Real value	Minimum	-	-	-	-	1056	891	897
	Maximum	-	-	-	-	4000	4076	4000
Corn/wheat system (2014 + 2015 + 2016)								
B	[0, 30[	B	1575	B	893	MB	MB	MB
				A	893	B	B	B
		A	1575	B	893	MB	MB	MB
				A	893	MB	MB	MB
I	[30, 90[	B	1575	B	893	M	M	M
				A	893	M	M	M
		A	1575	B	893	M	M	M
				A	893	M	M	M
A	[90, 120]	B	1575	B	893	M	M	M
				A	893	A	A	A
		A	1575	B	893	M	M	M
				A	893	A	A	A
Real value	Minimum	-	-	-	-	648	518	411
	Maximum	-	-	-	-	3500	3600	3000

N - Nitrogen; TS - Thermal sum; PP - Rainfall V_L - Linguistic variables; V_Q - Quantitative variables; PG - Grain yield; MB - Very low; B - Low; M - Mean; A - high; I - Intermediate; V_3 - Full condition (100%) of nitrogen dose in the third expanded leaf; V_3/V_6 - Fractionated condition (70%/30%) of nitrogen dose in the third and sixth expanded leaf; V_3/E - Fractionated condition (70%/30%) of the nitrogen dose in the third expanded leaf and initiation of grain filling

model determined by a rule base obtained by the MAX Union of each individual rule, so that for each pair (a, b) is obtained:

$$\mu_R(a,b) = \max_{1 \le i \le n}\left\{\mu_{A_i}(a) \wedge \mu_{B_i}(b)\right\} \qquad (4)$$

where $\wedge$ represents the MIN operator.

By the Mamdani method the pertinence function of B is given by:

$$\mu_B(b) = \max_{1 \le i \le n}\left\{\max_a\{\mu_A(a) \wedge \mu_{Ai}(a)\} \wedge \mu_{Bi}(b)\right\} \qquad (5)$$

If the input is a classic unitary set, then $\mu_A(a) = 1$ and $\mu_{Ai}(a) \le 1$. Therefore, the above expression results in:

$$\mu_B(b) = \max_{1 \le i \le n}\left\{\mu_{Ai}(a)\right\} \wedge \mu_{Bi}(b)\} \qquad (6)$$

Therefore, the fuzzy set B represents the action for each input A. In Module 4 (defuzzification), the state of the fuzzy output variable provides the numerical value. One of the main methods of defuzzification is the center of mass which for continuous variables is given by the expression:

$$m(B) = \frac{\int b_{\mu B}(b)db}{\int \mu_B(b)db} \qquad (7)$$

and discrete variables by the expression:

$$m(B) = \frac{\sum_b b_{\mu B}(b)db}{\sum_b b_{\mu B}(b)b} \qquad (8)$$

The fuzzy controller is described as a function f: $R_n \to R_m$, since given an input value, there is a single corresponding output value.

To validate the rule base and simulated values of grain yield by fuzzy logic, the behavior and regression parameters obtained by the observed points and simulation, and the lower and upper limits of the confidence interval of the real values of the average of three agricultural harvests were considered at 0.05 level of probability of error. For the determination of regression models, confidence interval and mean comparison test of Scott & Knott, the computational program Genes was utilized.

Results and Discussion

In the agricultural year 2016 (Figure 1A), the maximum temperature observed at the time and after application of N-fertilizer was not high (± 15°C) and had favorable soil moisture conditions due to the rainfall that occurred in the days prior to fertilization. In addition, adequate rainfall
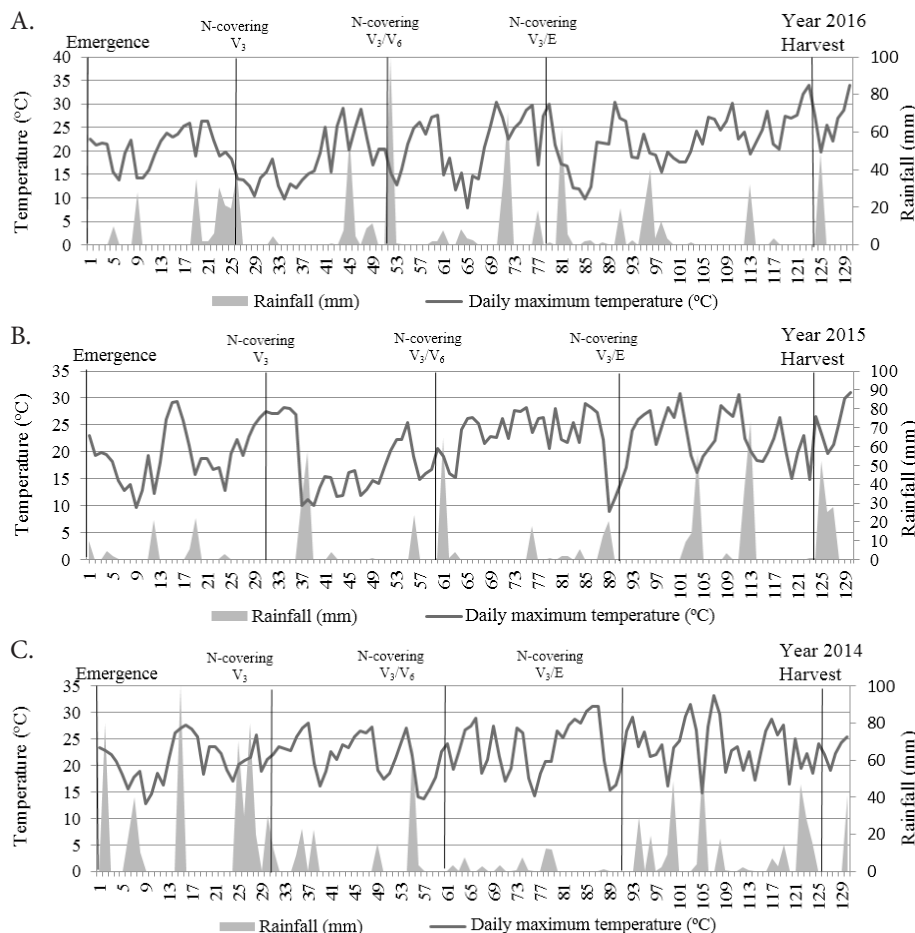
V_3 - Full condition (100%) of the nitrogen dose in the third expanded leaf. V_3/V_6 - Fractionated condition (70%/30%) of the nitrogen dose in the third and sixth expanded leaf; V_3/E - Fractionated condition (70%/30%) of the nitrogen dose in the third expanded leaf and initiation of grain filling

Figure 1. Rainfall and maximum temperature in the wheat growing cycle and the moment of nitrogen supply. Emergence: 2016 (17/06) (A); 2015 (27/06) (B) and 2014 (25/06) (C)

distribution was observed throughout the cycle. These conditions were decisive in the higher efficiency of nitrogen use to the expression of high productivity, characterizing the year 2016 as favorable (AF) to the cultivation of wheat (Table 2). In 2015 (Figure 1B), the maximum temperatures at the beginning of wheat development were high (≈ 27 °C). This condition favors faster elongation with reduced yield of new tillers, a component directly linked to grain yield. The high temperatures and no rainfall caused reduced soil moisture at the time of nitrogen fertilization, conditions that favor nutrient losses by volatilization. The meteorological information along with the productivity obtained, characterized 2015, as a reasonable year (AR) for the cultivation (Table 2; Figure 1B). In the year 2014 (Figure 1C), although at the time of nitrogen supply, the maximum temperature was intermediate (≈ 23 °C), the nutrient application was followed by a significant volume of rainfall (≈ 30 mm), favoring leaching. In addition, the large rainfall period and volume affected radiation quality during the grain filling phase and grain harvest. These facts justify the low grain yield obtained in 2014 (Table 2; Figure 1C), characterized as an unfavorable year (AD) for wheat cultivation.

In wheat crop, although the management of agricultural practices is decisive for higher yields, the rainfall and air temperature are meteorological variables that determine the success of agricultural harvests (Arenhardt et al., 2015; Salton et al., 2016). Rain is directly linked to nutrient utilization efficiency such as nitrogen, because the correct absorption is a function of adequate soil moisture. High temperatures promote reduced productivity and reduced biomass accumulation due to the lower net photosynthesis obtained due to increased respiration rate, reducing the efficiency of nitrogen utilization (Arenhardt et al., 2015; Mantai et al., 2016). The supply of nitrogen followed by excessive rainfall promotes losses by leaching, and when supplied with reduced soil moisture and high air temperature, cause volatilization losses, therefore reducing productivity, generating environmental contamination and collaborating on events related to global warming (Mandal et al., 2016; Arenhardt et al., 2017).

Figure 2 shows the behavior and parameters of the equation for biological interpretation of nitrogen utilization to grain yield, considering in each model the starting point of performance, given by the linear coefficient (a) and the slope of the line by the angular coefficient (b_x) in the comparison between the real data and those simulated by fuzzification. It is noteworthy that the parameter b_x of the linear equation provides the agronomic efficiency, indicating the relationship between the productivity obtained per unit of nitrogen supplied. In this perspective, the behavior and values of the linear coefficients of observed and simulated productivity were similar. In addition, the tendency and slope values in the estimation of the behavior and agronomic efficiency were also close to the real and simulated values. It stands out as an example, the supply of nitrogen in full dose in the phenological stage V_3 in the soybean/wheat system, showing that for every 1 kg ha^{-1} of nitrogen provided there is an increment of 11 kg ha^{-1} of grain yield in the real condition of cultivation, with return of 10 kg ha^{-1} productivity considering the simulation results (Figure 2).

In Tables 3 and 4 of the soybean/wheat and corn/wheat system, respectively, the increase of nitrogen doses in the real cultivation conditions showed increase of grain yield, independent of the supply (full or fractionated) and succession system (soybean/wheat; corn/wheat). In the soybean/wheat system, the application of nitrogen in full and fractionated doses showed no change in wheat yield (Table 3). On the other hand, in the corn/wheat system, the more restrictive N-residual condition showed higher fertilization dependence in the early stages of development in V_3 and V_3/V_6 fractionated conditions, with reduced grain yield fractionation (Table 4).

Tables 3 and 4 also show a trend of higher wheat yield due to the increase of N-fertilizer obtained by the simulation

Table 2. Temperature and precipitation in the months of cultivation and average productivity

| Year | Month | Temperature (ºC) | | | Precipitation (mm) | | PG$_x$ (kg ha^{-1}) | Class |
		Minimum	Maximum	Mean	Mean of 26 years*	Occurrence		
2014	May	10.8	23.6	17.2	149.7	412	1441 c	AD
	June	8.6	19	13.8	162.5	412		
	July	9.7	21.82	15.76	135.1	144		
	August	8.8	23.66	16.23	138.2	77.8		
	September	13.33	23.58	18.46	167.4	274.8		
	October	16.02	27.49	21.76	156.5	230.8		
	Total	-	-	-	909.4	1551.4		
2015	May	11.1	24.5	17.8	149.7	20.3	2441 b	AR
	June	9.3	19.7	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	23	17.5	167.4	194.6		
	October	15	25.5	20.2	156.5	286.6		
	Total	-	-	-	909.4	798.9		
2016	May	10.5	22.7	16.6	149.7	100.5	3357 a	AF
	June	7.9	18.4	13.15	162.5	191		
	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		

*Mean rainfall obtained from May to October 1990 to 2016; Means followed by the same letter in the column do not differ from each other at p ≤ 0.05 by the Scott & Knott test; AR - Reasonable year; AF - Favorable year; AD - Unfavorable year; PG$_x$ - Mean grain yield
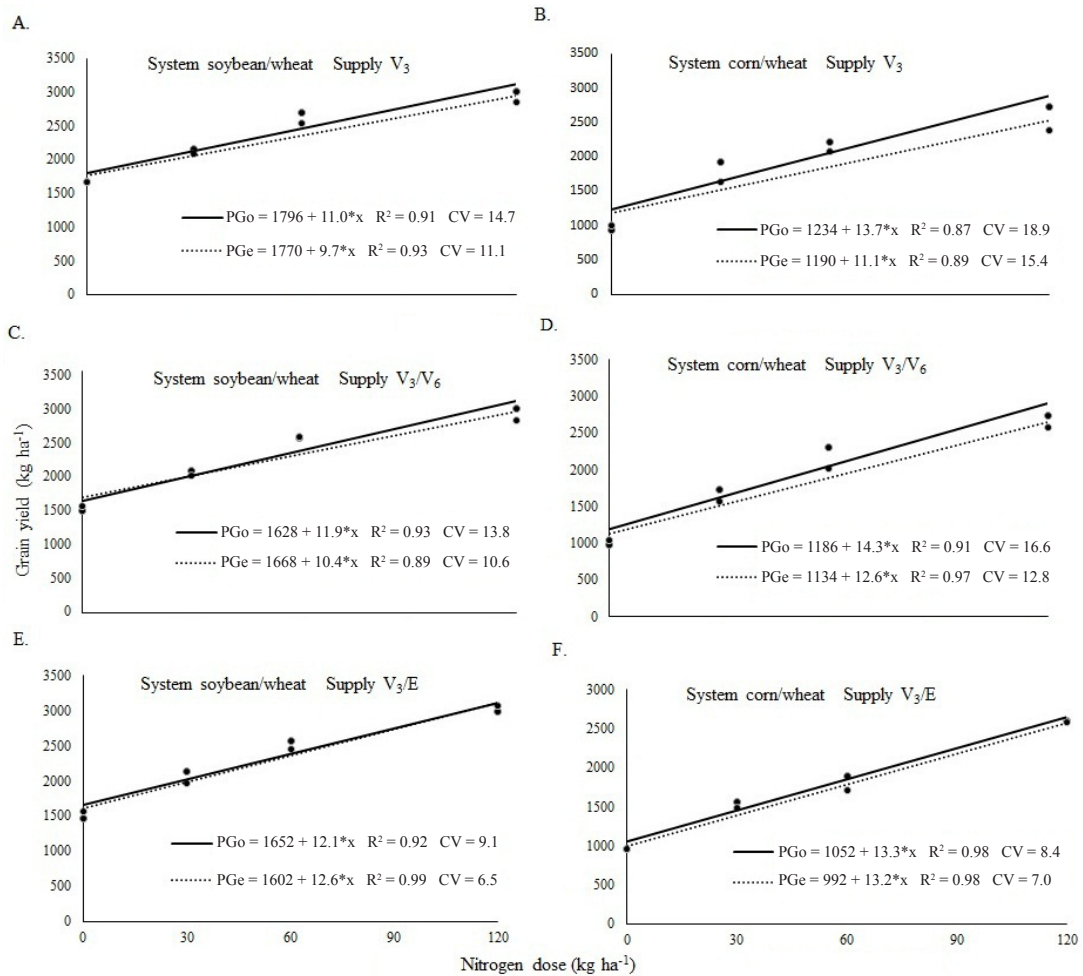
* Significant of p ≤ 0.05 by F test

V_3-Full condition (100%) of the nitrogen dose in the third expanded leaf; V_3/V_6-Fractional condition (70%/30%) of the nitrogen dose in the third and sixth expanded leaf; V_3/E - Fractionated condition (70%/30%) of nitrogen dose in the third expanded leaf and initiation of grain filling; PGo - Observed grain yield (kg ha^{-1}); PGe - Estimated grain yield (kg ha^{-1}); *Significant at p ≤ 0.05 by the F test; R^2 - Coefficient of determination; CV - Coefficient of variation

Figure 2. Condition of nitrogen use: A – Supply in V_3 (soybean/wheat); B – Supply in V_3 (corn/wheat); C – Supply in V_3/V_6 (soybean/wheat); D – Supply in V_3/V_6 (corn/wheat); E – Supply in V_3/E (soybean/wheat); F – Supply in V_3/E (corn/wheat)

Table 3. Fuzzy logic in the simulation of wheat yield by nitrogen doses, thermal sum and temperature under nitrogen use conditions in the soybean/wheat system

Phenological stage	N (kg ha^{-1})	PGo (kg ha^{-1}) L_i	X	L_S	PGe (kg ha^{-1}) Fuzzy model	Absolute error
			(2014 + 2015 +2016)			
	0	1446	1659	1880	1670	11
	30	1456	2154	2842	2080	74
V_3	60	1897	2694	3598	2530	164
	120	1928	2997	4624	2850	147
Mean V_3		1682	2376 Aa	3236	2283 Aa	93
	0	1291	1479	1697	1540	61
	30	1734	2058	2698	1980	78
V_3/V_6	60	1775	2540	3422	2550	10
	120	1816	2950	4535	2790	160
Mean V_3/V_6		1654	2332 Aa	3088	2215 Aa	117
	0	1297	1469	1779	1570	101
	30	1421	2138	2637	1960	178
V_3/E	60	1476	2562	3373	2450	112
	120	1986	2984	4273	3070	86
Mean V_3/E		1545	2288 Aa	3016	2263 Aa	25

V_3 - Full (100%) nitrogen dose condition in the expanded third leaf; V_3/V_6 - Fractional condition (70%/30%) of nitrogen dose in the third and sixth expanded leaf; V_3/E - Fractional condition (70%/30%) of nitrogen dose in the third expanded leaf and initiation of grain filling; N-nitrogen; L_i and L_s-Lower and upper limit of the confidence interval to p ≤ 0.05 by the Scott & Knott test; X-mean; PG$_O$- observed grain yield; PG$_e$-Estimated grain yield. Means followed by the same uppercase letter in the row and lowercase in the column do not differ statistically from each other, at p ≤ 0.05 level by the Scott & Knott test

Table 4. Fuzzy logic in the simulation of wheat yield by nitrogen doses, thermal sum and temperature in the conditions of nitrogen use in the corn/wheat system

Phenological stage	N (kg ha^{-1})	PG$_o$ (kg ha^{-1}) L_i	X	L_S	PG$_S$ (kg ha^{-1}) Fuzzy model	Absolute error
			(2014 + 2015 +2016)			
	0	748	943	1111	997	54
	30	1393	1924	2582	1640	284
V_3	60	1550	2222	2841	2070	152
	120	1945	2728	3589	2390	338
Mean V_3		1459	1954 Aa	2531	1838 Aa	116
	0	718	971	1155	1040	69
	30	1351	1728	2021	1560	168
V_3/V_6	60	1799	2304	2812	2010	294
	120	1714	2739	3681	2580	159
Mean V_3/V_6		1396	1926 Aa	2417	1823 Aa	103
	0	811	954	1031	954	0
	30	1256	1558	1912	1490	68
V_3/E	60	1313	1789	2272	1710	79
	120	1734	2479	3372	2590	11
Mean V_3/E		1279	1695 Ab	2147	1524 Ab	171

V_3-Full condition (100%) of the nitrogen dose in the third expanded leaf; V_3/V_6-Fractional condition (70%/30%) of nitrogen dose in the third and sixth expanded leaf; V_3/E-Fractional condition (70%/30%) of the nitrogen dose in the third expanded leaf and the initiation of grain filling; N-nitrogen; L_i and L_s - Lower and upper confidence interval limit at p ≤ 0.05 by the Scott & Knott test; X - Mean; PG$_O$ - Estimated grain yield; PG$_e$ - Estimated grain yield. Means followed by the same uppercase letter in the row and lowercase in the column do not differ statistically from each other, at p ≤ 0.05 level by the Scott & Knott test

result. The conditions mentioned for the absence of differences in the conditions of fertilization in the soybean/wheat system (Table 3) and reduction of productivity in the fractionation in V_3/V_6 were also recognized by the fuzzification process (Tables 3 and 4). Fuzzy rule-based simulation identified simulated productivity values in succession systems very close to the real results obtained by experimentation, all within the confidence interval of the average in each treatment. A surprising result that shows reduced absolute error between the real and simulated value of grain yield.

The functions of pertinence and linguistic values for simulation in this research were adequate for the fuzzification process, indicating the ability to recognize biological processes by set theory via fuzzy logic. Thus, indicating the obtaining of reliable data by integrating information between the plant, nitrogen management and weather conditions in the simulation. In this perspective, new opportunities open up given these characteristics in the development of more efficient models in areas where it is necessary to deal with uncertainty and subjectivity, a common condition in agriculture where the predictability of crops is sought.

Silva et al. (2014) used fuzzy logic to estimate wheat grain yield, showing that the model allowed an adequate estimation of wheat grain yield by nitrogen use, not taking into account the non-linear conditions of meteorological elements. Francisco et al. (2007), developed a fuzzy model to estimate the soybean sowing area from vegetation image indexes, showing to be highly correlated with the official estimates. Campos et al. (2013) developed a fuzzy model to predict the occupancy rate of stalls in free-stall dairy cattle installations, assisting in optimizing project sizing. Through fuzzy logic, Ponciano et al. (2011) exemplified successful situations in predicting the variables that affect thermal comfort for broilers, supporting decision making in controlling the climate of poultry houses. Cavalcanti et al. (2013) used fuzzy logic to evaluate the sensory acceptance of bread enriched with seeds of 'faveleira' (*Cnidoscolus quercifolius*), plant originating from the Brazilian Northeast with high quality omega-6 fatty acids. Khatchatourian & Treter (2010) developed a methodology based on fuzzy logic for evaluation and classification of economic and financial performance of agricultural cooperatives. Maranduba et al. (2016) used fuzzy logic to evaluate the viability of the life cycle of biodiesel produced in Brazil, considering two mixing scenarios: B7 (7% Biodiesel and 93% fossil diesel) and B10 (10% biodiesel and 90% of fossil diesel). Cardoso et al. (2018), through Fuzzy logic, was able to characterize and successfully map the uncertainties of both rainfall and erosivity to the state of Bahia, Brazil.

Conclusions

1. The pertinence functions and linguistic values established for the input and output variables are adequate for the use of fuzzy logic.

2. Fuzzy logic efficiently simulates wheat grain yield under conditions of nitrogen use with air temperature and rainfall in the cultivation systems.

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