Diffuse system simulating wheat productivity by nitrogen and temperature in the use of biopolymers

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ABSTRACT: Fuzzy logic can simulate wheat yield by nitrogen and temperature nonlinearity, validating the use of hydrogel biopolymer. The objective of this study is to adapt the fuzzy logic model to the simulation of nitrogen biomass and wheat grain yield and non-linearity of the maximum air temperature, under the conditions of use of the hydrogel biopolymer, in high and low N-residual release systems. The study was conducted in 2014 and 2015, in Augusto Pestana, RS, Brazil (28° 26' 30'' latitude S and 54° 0' 58'' longitude W). The experimental design was a randomized block design with four replications in 5 x 5 factorial, for hydrogel doses (0, 30, 60, 90 and 120 kg ha\(^{-1}\)), added in the furrow next to the seed, and N-fertilizer doses (0, 30, 60, 90 and 120 kg ha\(^{-1}\)), applied at the phenological stage V\(_3\) (third expanded leaf) as top-dressing, respectively. The pertinence functions together with the quantitative and linguistic values for the input and output variables are suitable for the use of fuzzy logic in the wheat yield simulation. The fuzzy model made it possible to estimate the values of biomass and wheat grain yield by nitrogen and non-linearity of the maximum air temperature under the conditions of use of the hydrogel biopolymer in high and low N-residual release systems.

Key words: Triticum aestivum, water stress, hydrogel, fuzzy logic

Sistema difuso simulando a produtividade do trigo pelo nitrogênio e temperatura no uso de biopolímeros

RESUMO: A lógica fuzzy pode simular a produtividade do trigo pelo nitrogênio e não linearidade da temperatura, validando o uso do biopolímero hidrogel. O objetivo com o estudo é adequar o modelo de lógica fuzzy à simulação da produtividade de biomassa e grãos de trigo pelo nitrogênio e não linearidade da temperatura máxima do ar, nas condições de uso do biopolímero hidrogel, em sistemas de alta e reduzida liberação de N-residual. O estudo foi conduzido nos anos de 2014 e 2015, em Augusto Pestana, RS, Brasil (28° 26' 30'' latitude S e 54° 0' 58'' longitude W). O delineamento experimental foi o de blocos casualizados com quatro repetições em fatorial 5 x 5, para doses de hidrogel (0, 30, 60, 90 e 120 kg ha\(^{-1}\)), adicionado no sulco junto à semente, e doses de N-fertilizante (0, 30, 60, 90 e 120 kg ha\(^{-1}\)), aplicado em cobertura no estádio fenológico V\(_3\) (terceira folha expandida), respectivamente. As funções de pertinências junto aos valores quantitativos e linguísticos para as variáveis de entrada e de saída, se mostram adequados para o uso da lógica fuzzy na simulação da produtividade do trigo. O modelo fuzzy possibilitou estimar os valores de produtividade de biomassa e grãos de trigo pelo nitrogênio e não linearidade da temperatura máxima do ar, nas condições de uso do biopolímero hidrogel em sistemas de alta e reduzida liberação de N-residual.

Palavras-chave: Triticum aestivum, estresse hídrico, hidrogel, lógica fuzzy
**Introduction**

Among the meteorological elements, photoperiod, rainfall and air temperature are the most related to wheat productivity (Bischoff et al., 2015; Santi et al., 2018). High temperature rapidly reduces soil moisture, implying an increased ratio of plant respiration rate and decreased photosynthesis efficiency. In addition, it intensifies N-fertilizer losses by volatilization (Scremin et al., 2017; Trautmann et al., 2017). It is noteworthy that nitrogen is the main nutrient absorbed by plants, by acting on different metabolic routes linked to the development of productivity components. Therefore, the need for alternatives to improve its use by plants with reduced environmental impacts (Camponogara et al., 2016; Costa et al., 2018). One possibility of minimizing problems related to higher nitrogen efficiency is the use of biopolymers to maintain soil moisture (Fernandes et al., 2015; Scremin et al., 2017). Hydrogel biopolymers are biodegradable three-dimensional polymer networks, capable of retaining water in their gel-forming structure, able to hydrate and release water over a long period (Kaewpirom & Boonsang, 2006; Venturoli & Venturoli, 2011).

From the perspective of understanding processes, modeling enables the simulation, optimization and validation of technologies, describing productivity behavior using controlled and uncontrolled variables (Barioni et al., 2011; Marolli et al., 2018). Fuzzy models are techniques that enable this description of complex systems (Silva et al., 2014; Wei et al., 2017), belonging to the smart controls class in the representation of uncertainties (Li et al., 2015; Mendel, 2017).

The aim of this study was to adapt the fuzzy logic model to the simulation of nitrogen biomass, wheat grain yield and non-linearity of the maximum air temperature, under the conditions of use of the hydrolpolymer in high succession and low N-residual release systems.

**Material and Methods**

The study was carried out in the field in 2014 and 2015, in the municipality of Augusto Pestana, RS, Brazil (28° 26' 30” latitude S and 54° 0' 58” longitude W). The soil of the experimental area is classified as Oxisol, and the climate of the region, according to Köppen classification, is the Cfa type, with hot summer without dry season. Ten days before sowing, soil analysis was performed and the following chemical characteristics were identified (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 dm⁻³, Ca = 6.3 cmol dm⁻³ e Mg = 2.5 cmol 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 dm⁻³, Ca = 6.8 cmol dm⁻³ and Mg = 3.1 cmol dm⁻³). Regardless of the agricultural year, sowing was carried out in the third week of June, according to crop recommendation, in high and low C/N residual cover, corn/wheat and soybean/wheat systems, respectively. In sowing, a seeder-fertilizer was used in the composition of the plot with 5 rows of 5 m long and 0.20 m line spacing, forming the experimental unit of 5 m². The seeds were submitted to germination and vigor test in the laboratory to correct the desired density of 400 viable seeds m⁻², using the TEC 10 wheat cultivar, commercial class type “bread” of high productive potential. During the study, tebuconazole fungicide was applied at a dose of 0.75 L ha⁻¹. Weed control was carried out with metsulfuron-methyl herbicide at a dose of 4 g ha⁻¹ and additional weeding whenever necessary. In the experiments, 45 and 30 kg ha⁻¹ of P₂O₅ and K₂O were applied at sowing, based on soil phosphorus (P) and potassium (K) contents, for grain yield expectation of 3 t ha⁻¹, respectively, and 10 kg ha⁻¹ of nitrogen (N) in the base (except in the standard experimental unit), with the remainder in top-dressing at phenological stage V₅ (expanded third leaf). These fertilizations took into consideration the recommendations of fertilization for the state of Rio Grande do Sul. The application of different doses of biopolymer hydrogel was next to the wheat seed, being at the same depth and cultivation line in the soil, approximately at three centimeters.

In each cultivation system two experiments were conducted, one to quantify biomass yield (PB, kg ha⁻¹), and another to estimate grain yield (PG, kg ha⁻¹). Therefore, in the four experiments, the experimental design consisted of randomized blocks with four replications, following a 5 x 5 factorial scheme, in the sources of variation, hydrogel doses at levels 0, 30, 60, 90 and 120 kg ha⁻¹ and doses of N-fertilizer (source urea) at levels 0, 30, 60, 90 and 120 kg ha⁻¹. Grain yield was obtained by cutting three central lines (rows) in each plot at the harvest maturity stage, with grain moisture around 20%. The plants were tracked with a stationary harvester and directed to the laboratory to correct grain moisture to 13% and weighed to estimate PG (kg ha⁻¹). In experiments to quantify biomass productivity, the plant material was harvested close to the soil, from the collection of one linear meter of the three central lines of each plot, at 120 days after emergence. The biomass samples were directed to a forced air oven at 65 ºC until reaching constant weight to the estimate productivity.

In the initial process of data analysis, the “data mining” technique was performed with the objective of forming association standards for the inferences of the rule base for the fuzzy model. From this knowledge, the rule base was elaborated in linguistic terms, with the help of an expert. The model input variables (independent variables) were the doses of N and the average maximum temperature (T_max). The maximum temperature values during the cycle were obtained by the Total Automatic Station, installed 500 m from the experiment. The output variables (dependent variables) were PG and PB. For the independent variable T_max (°C), the domain was considered in the range [21, 25], representing the ranges: < 22.5 ºC (Low Temperature) and > 22.5 ºC (High Temperature). For the independent variable N (kg ha⁻¹), the domain of the interval [0,120] was considered, representing the ranges: <15 = very low dose (MB); [15,45] = low dose (B); [45,75] = mean dose (M); [75,105] = high dose (A) and [105,120] = very high dose (MA). For the output variables, the image intervals were the maximum and minimum values of experimentally collected data on biomass and wheat grain yield, considering the cumulative effect of the years, in each condition of hydrogel use. Thus, 10 simulators were built, one for each condition of hydrogel use and cultivation system. The variable PG was divided into four equidistant intervals (Table 1): very low (MB), low (B), medium (M) and high (A). The variable PB was divided into five equidistant intervals (Table 2), four being used for the PG variable, plus the very high interval (MA).
Table 1. Fuzzy logic rule base for simulation of wheat grain yield in succession systems

| V<sub>n</sub> | V<sub>e</sub> | Year | T<sub>max</sub> (°C) | Output Linguistic variables | N (kg ha<sup>-1</sup>) | T<sub>max</sub> (°C) | DPB<sub>10</sub> | DPB<sub>50</sub> | DPB<sub>90</sub> | DPB<sub>100</sub> | DPB<sub>120</sub> |
|-------------|-------------|------|----------------------|-----------------------------|------------------------|----------------------|------------------|------------------|------------------|------------------|------------------|
| MB | [0, 15] | 2015 | B < 22.5 | MB | MB | MB | B | B | B | B | B |
| B | [15, 45] | 2015 | B < 22.5 | M | M | M | M | M | M |
| M | [45, 75] | 2015 | B < 22.5 | M | M | M | M | M | M | M |
| A | [75, 105] | 2015 | A > 22.5 | A | A | A | A | A | A |
| MA | [105, 120] | 2015 | B < 22.5 | M | M | M | M | M | M | B |

Soybean/wheat system

| Real value | Minimum | Maximum |
|------------|---------|---------|
| 2014-2015 | 1214 | 3189 |
| 2014-2015 | 1257 | 3395 |
| 2014-2015 | 1265 | 3487 |
| 2014-2015 | 1266 | 3222 |
| 2014-2015 | 1151 | 3165 |

Table 2. Fuzzy logic rule base for simulating wheat biomass productivity in succession systems

| V<sub>n</sub> | V<sub>e</sub> | Year | T<sub>max</sub> (°C) | Output Linguistic variables | N (kg ha<sup>-1</sup>) | T<sub>max</sub> (°C) | PB<sub>10</sub> | PB<sub>50</sub> | PB<sub>90</sub> | PB<sub>100</sub> | PB<sub>120</sub> |
|-------------|-------------|------|----------------------|-----------------------------|------------------------|----------------------|------------------|------------------|------------------|------------------|------------------|
| MB | [0, 15] | 2015 | B < 22.5 | B | B | B | B | B | B | B | B |
| B | [15, 45] | 2015 | B < 22.5 | M | M | M | M | M | M | M | M |
| M | [45, 75] | 2015 | B < 22.5 | M | M | M | M | M | M | M | M |
| A | [75, 105] | 2015 | A > 22.5 | A | A | A | A | A | A | A | A |
| MA | [105, 120] | 2015 | B < 22.5 | M | M | M | M | M | M | M | M |

Corn/wheat system

| Real value | Minimum | Maximum |
|------------|---------|---------|
| 2014-2015 | 487 | 2678 |
| 2014-2015 | 609 | 2779 |
| 2014-2015 | 616 | 2657 |
| 2014-2015 | 653 | 2556 |
| 2014-2015 | 682 | 2450 |

N - Nitrogen; T<sub>max</sub> - Maximum average temperature; V<sub>n</sub> - Linguistic variables; V<sub>e</sub> - Quantitative variables; PB - Biomass productivity; MB - Very low; B - Low; M - Medium; A - High; MA - Very High; H - Hydrogel (kg ha<sup>-1</sup>)

Tables 1 and 2 present the fuzzy logic rule base, considering the variables of nitrogen input and maximum temperature to the simulation of biomass and wheat grain yield, respectively.

In the development of fuzzy logic programming, the FuzzyLogic Toolbox module from MATLAB<sup>®</sup> software was used. In forecasting applications the fuzzy Mamdani model was used, which includes interface modules for transforming input variables into fuzzy sets and later outputs into proportional numerical quantities (Cecconello et al., 2010). The fuzzification process took place by 4 successive modules. In module 1 (fuzzification), the input variable information was mathematically modeled using fuzzy sets. From the expert,
each input variable was assigned linguistic terms representing the states of this variable and each linguistic term was associated with a fuzzy set by a pertinence function. In module 2 (rule base), the variables in their linguistic classifications were adjusted, where each rule base satisfied the following structure:

If $A$ is in $A_i$, 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, $A_i = A_{i_1} \times A_{i_2} \times \ldots \times A_{i_m}$ and $B_i = B_{i_1} \times B_{i_2} \times \ldots \times B_{i_n}$. In this case, each fuzzy set $A_{i_k}$ and $B_{i_k}$ represented a linguistic term for the $j$th input variable and $k$th output variable, and the expression $A$ is in $A_i$ which means:

$$\mu_{A_i}(a) = \min \left( \mu_{A_{i_1}}(a_1), \mu_{A_{i_2}}(a_2), \ldots, \mu_{A_{i_m}}(a_m) \right) \in [0, 1] \tag{1}$$

In module 3 (inference), the logical connectives used to establish the fuzzy relationship were defined for rule base modeling. The relationship between linguistic variables was characterized by the fuzzy system operator (MIN). In each rule, a fuzzy $R$ relationship with degree of relevance for each pair $(a, b)$ was considered:

$$\mu_{R_i}(a, b) = \min \{\mu_{A_i}(a), \mu_{B_i}(b)\} \tag{2}$$

The relationship between each rule is characterized by the operator (MAX), of the fuzzy $R$ relationship that represents the model determined by a rule base obtained by the MAX union of each individual rule, so that for each pair $(a, b)$ it is obtained:

$$\mu_R(a, b) = \max \left\{ \mu_{A_i}(a)^{\land} \mu_{B_i}(b) \right\} \tag{3}$$

where $^{\land}$ represents the MIN operator.

By Mamdani’s method, the pertinence function of $B$ is given by:

$$\mu_B(b) = \max_{1 \leq a \leq n} \left\{ \max_{a \leq b} \mu_A(a)^{\land} \mu_B(b) \right\} \tag{4}$$

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

$$\mu_B(b) = \max_{1 \leq a \leq n} \left\{ \mu_{A_i}(a)^{\land} \mu_{B_i}(b) \right\} \tag{5}$$

Therefore, the fuzzy set $B$ represents the action for each input $A$.

In module 4 (defuzzification), the state of the fuzzy output variable gives the numeric value. One of the main defuzzification methods is the center of mass for continuous variables, given by the expression:

$$m(B) = \frac{\int_{\mu_B(b)} b \mu_B(b) \, db}{\int_{\mu_B(b)} \mu_B(b) \, db} \tag{6}$$

and discrete variables by the expression:

$$m(B) = \sum_{\mu_B(b)} \frac{b \mu_B(b)}{\sum_{\mu_B(b)}}$$

The fuzzy controller is described as a function $f: \mathbb{R}^n \rightarrow \mathbb{R}^n$, since given an input value, there is a single corresponding output value.

To validate the rule base and simulated values of biomass and grain yield by fuzzy logic, the behavior and parameters of polynomial regression were considered. These were obtained from the real value of the variables in the different doses of $N$ use and the lower and upper limits from the confidence interval of the real values of the mean of two agricultural harvests, at a level of 0.05 probability of error. For confidence intervals and regression models we used the computer program Genes.

**Results and Discussion**

In Figure 1, during the wheat crop cycle, accumulated rainfall of 952 mm in 2014 (Figure 1A) and 817 mm in 2015 (Figure 1B) were observed. The observed values are similar to the historical average of the last 20 years, which is 900 mm, but with different distribution of rainfall between years during cultivation (Figure 1). In 2014, there were shorter periods of rain at the beginning of the cycle, with higher maximum temperatures. A condition that favors nitrogen loss through volatilization during fertilization.

The highest rainfall in 2014 occurred between the half of the wheat cycle until near maturity (Figure 1A), which favored periods of lower insolation, indicating a reduction in photosynthesis efficiency. In addition, excess rainfall was observed near grain maturation. In 2015, the highest rainfall was recorded between emergence until around 36 days of wheat development and with maximum temperatures lower than those recorded in 2014. Precipitation was regular, with lower intensity and better distribution from the beginning of the reproductive phase to maturity (Figure 1B), facts report the higher productivity obtained in 2015 compared to 2014.

In cereals such as wheat, a favorable year for cultivation meets the minimum rainfall requirement for the crop, with

![Figure 1. Rainfall and maximum temperature in the wheat cycle. (A) agricultural year 2014 and (B) agricultural year 2015](image-url)
adequate distribution of milder temperatures (Arenhardt et al., 2015). Water deficit corroborates N-fertilizer volatilization, increasing nutrient losses to the environment and increasing production costs, not to mention lower productivity by reducing photosynthesis efficiency (Minuzzi & Lopes, 2015). On the other hand, high rainfall causes nitrogen loss by leaching, favoring the incidence of leaf and root diseases (Souza et al., 2013). Thermal conditions influence the most diverse vital processes of plants, from germination to phenological development (Minuzzi & Lopes, 2015). In addition, temperature is decisive for productivity, acting as a catalyst for biological processes, which is why plants require a minimum and maximum temperature for normal physiological activities (Tonin et al., 2014).

Figures 2 and 3 show the behavior and parameters of the equation \( y = a + bx \) regarding the biological interpretation of

![Figure 2](image)

**Figure 2.** Behavior of grain yield observed and simulated by fuzzy logic. (A) Soybean/wheat system and (B) Corn/wheat system - 0 kg ha\(^{-1}\) of hydrogel; (C) Soybean/wheat system and (D) Corn/wheat system - 30 kg ha\(^{-1}\) of hydrogel; (E) Soybean/wheat system and (F) Corn/wheat system - 60 kg ha\(^{-1}\) of hydrogel; (G) Soybean/wheat system and (H) Corn/wheat system - 90 kg ha\(^{-1}\) of hydrogel; (I) Soybean/wheat system and (J) Corn/wheat system - 120 kg ha\(^{-1}\) of hydrogel.
Figure 3. Behavior of biomass productivity observed and simulated by fuzzy logic. (A) Soybean/wheat system and (B) Corn/wheat system - 0 kg ha\(^{-1}\) hydrogel; (C) Soybean/wheat system and (D) Corn/wheat system - 30 kg ha\(^{-1}\) hydrogel; (E) Soybean/wheat system and (F) Corn/wheat system - 60 kg ha\(^{-1}\) hydrogel; (G) Soybean/wheat system and (H) Corn/wheat system - 90 kg ha\(^{-1}\) hydrogel; (I) Soybean/wheat system and (J) Corn/wheat system - 120 kg ha\(^{-1}\) hydrogel

in nitrogen utilization for grain and biomass yield, respectively, considering the starting point of performance, given by the linear coefficient (a) and slope of the line by the angular coefficient (b), in the comparison between the real data and those simulated by fuzzy logic. Parameter “a” of the linear equation provides the agronomic efficiency, indicating the relationship between the yield obtained per unit of nitrogen supplied.

In Figure 2, regardless of the cultivation system (soybean/wheat and corn/wheat), the behavior and values of the linear coefficients of observed and simulated grain yield were similar. The trend and slope values in estimating agronomic efficiency were also approximate. For the validation of fuzzy logic in the simulation of grain yield, Figure 2C stands out, showing that for every 1 kg of nitrogen supplied per hectare there is an increase of 11 kg of grain yield in the real cultivation condition. In the regression obtained by the simulation points, each 1 kg of nitrogen supplied per hectare increases the grain yield by 10 kg. Therefore, the equations show the same behavior and approximate coefficients between the real and simulated values.

In Figure 3, regardless of the succession system, the linear and angular behavior and coefficients of observed and simulated biomass yield were similar. This fact reports the validation of fuzzy logic in the simulation of biomass
productivity. In view of this, we highlight in Figure 3E, that for every 1 kg of nitrogen supplied per hectare there is an increase of 30 kg of biomass productivity in the real cultivation condition. In the regression obtained by the simulation points, each 1 kg of nitrogen supplied per hectare increases the biomass productivity by 31 kg.

Figures 2 and 3 indicate that the simulation of wheat grain yield by fuzzy logic is qualified in each hydrogel use condition when compared to the real results obtained by bioexperimentation. Other researchers have also reported the potential of using nebulous logic in simulation studies involving the linear and nonlinear effects of environmental conditions, such as Castro et al. (2019) who used fuzzy to estimate feed consumption by Japanese quails. Ramos et al. (2015), using fuzzy logic, classified lambs for slaughter. Campos et al. (2013) used fuzzy logic to predict the occupancy rate of stalls in dairy cattle facilities under a free-stall system.

In Tables 3 and 4 of the soybean/wheat and corn/wheat system, respectively, the increase of nitrogen doses under real cultivation conditions showed an increase in grain yield, usually between 90 and 120 kg ha\(^{-1}\) of nitrogen. On the other hand, in biomass productivity the increase of nitrogen doses showed an increase until the point of maximum use of nutrient. This same behavior was also recognized by the fuzzification process. In the simulation of grain yield and biomass (Tables 3 and 4) by fuzzy logic, it was observed that the results obtained were close to the observed mean, regardless of the conditions of nitrogen and hydrogel use, confirming the appropriate established rule base and the possibility of using nebulous logic in predicting wheat yield.

Fuzzy logic has been used in many areas of knowledge to assign linear and nonlinear effects of processes to the observer’s acquired experience (Marques et al., 2016). He & Dong (2018) using fuzzy and neural networks obtained good predictive performance in the interaction between robot and environment. Schiassi et al. (2015) simulated the productivity of chicken meat with greater efficiency in feed consumption from the nebulous logic. Silva et al. (2014), developed a neuro-fuzzy hybrid model that made it possible to estimate wheat yield values as a function of nitrogen doses. In studies with hydrogel in oat cultivation, Scremin et al. (2017) showed increased efficiency of nitrogen utilization, especially under conditions of 30 and 60 kg ha\(^{-1}\) of the biopolymer, but the beneficial effect was dependent on the succession system

### Table 3. Fuzzy logic in simulation of wheat productivity by nitrogen and maximum air temperature in hydrogel use, in soybean/wheat system

| N (kg ha\(^{-1}\)) | L\(_0\) | X | L\(_1\) | PG (kg ha\(^{-1}\)) | L\(_0\) | X | L\(_1\) | PB (kg ha\(^{-1}\)) | Simulation/Fuzzy (kg ha\(^{-1}\)) | Absolute Error (kg ha\(^{-1}\)) |
|-----------------|-------|---|-------|-------------------|-------|---|-------|-------------------|-----------------------------|-----------------------------|
| Hydrogel 0 (kg ha\(^{-1}\)) | | | | | | | | | | |
| 0 | 1238 | 1382 | 1463 | 6096 | 6532 | 6944 | 1460 | 6430 | 78 | 12 |
| 30 | 1815 | 2168 | 2470 | 7473 | 7811 | 8101 | 2200 | 7590 | 32 | 22 |
| 60 | 2116 | 2507 | 2843 | 8344 | 8659 | 8929 | 2230 | 8630 | 277 | 29 |
| 90 | 2627 | 2756 | 2886 | 9138 | 9725 | 9799 | 2610 | 9140 | 146 | 585 |
| 120 | 2360 | 2728 | 3045 | 10328 | 10697 | 10928 | 2610 | 10400 | 118 | 297 |
| Mean | 2041 | 2308 | 2541 | 8276 | 8689 | 8940 | 2222 | 8438 | 86 | 251 |
| Hydrogel 30 (kg ha\(^{-1}\)) | | | | | | | | | | |
| 0 | 1364 | 1518 | 1649 | 5882 | 7034 | 8022 | 1530 | 6390 | 12 | 644 |
| 30 | 1966 | 2334 | 2651 | 8241 | 8613 | 8932 | 2330 | 8520 | 4 | 93 |
| 60 | 2305 | 2522 | 2707 | 8777 | 9128 | 9428 | 2680 | 9170 | 158 | 42 |
| 90 | 2400 | 2709 | 2975 | 5580 | 9580 | 11153 | 2770 | 9090 | 61 | 510 |
| 120 | 2522 | 2908 | 3239 | 10460 | 10961 | 11391 | 2980 | 10800 | 28 | 161 |
| Mean | 2111 | 2398 | 2644 | 7784 | 8863 | 9785 | 2438 | 8794 | 40 | 69 |
| Hydrogel 60 (kg ha\(^{-1}\)) | | | | | | | | | | |
| 0 | 1351 | 1680 | 1963 | 6831 | 7481 | 8038 | 1910 | 7500 | 230 | 19 |
| 30 | 1770 | 2173 | 2518 | 8037 | 8290 | 8507 | 2380 | 8300 | 207 | 250 |
| 60 | 2167 | 2540 | 2859 | 8802 | 9183 | 9509 | 2410 | 9110 | 130 | 73 |
| 90 | 2284 | 2690 | 3038 | 9681 | 10109 | 10476 | 2730 | 10300 | 40 | 191 |
| 120 | 2445 | 2876 | 3246 | 10413 | 11073 | 11639 | 2840 | 11000 | 36 | 73 |
| Mean | 2003 | 2392 | 2725 | 8753 | 9227 | 9634 | 2454 | 9190 | 52 | 37 |
| Hydrogel 90 (kg ha\(^{-1}\)) | | | | | | | | | | |
| 0 | 1336 | 1614 | 1863 | 6565 | 7211 | 7764 | 1840 | 7560 | 226 | 349 |
| 30 | 1720 | 2220 | 2648 | 7330 | 8224 | 8990 | 2240 | 8730 | 20 | 506 |
| 60 | 2103 | 2515 | 2968 | 8170 | 9071 | 9843 | 2270 | 9320 | 245 | 249 |
| 90 | 2151 | 2576 | 2940 | 8938 | 9806 | 10651 | 2270 | 10600 | 306 | 794 |
| 120 | 2273 | 2691 | 3049 | 9795 | 10912 | 11870 | 2650 | 11000 | 41 | 88 |
| Mean | 1917 | 2323 | 2672 | 8160 | 9045 | 9824 | 2254 | 9442 | 69 | 397 |

N - nitrogen; L\(_0\), X, and L\(_1\) - Lower and upper limit of confidence interval at 0.05 probability of error; X - Mean; PG - Grain Productivity; PB - Biomass Productivity
Table 4. Fuzzy logic in the simulation of wheat yield by nitrogen and maximum air temperature involving hydrogel use in the corn/wheat system

| N (kg ha⁻¹) | PG (kg ha⁻¹) | PB (kg ha⁻¹) | Simulation/Fuzzy (kg ha⁻¹) | Absolute error (kg ha⁻¹) |
|-------------|--------------|--------------|---------------------------|-------------------------|
|             | Lₖ | X | Lₘ |             | PG | PB |             | PG | PB |
| Hydrogel 0 (kg ha⁻¹) |   |   |   |   |   |   |   |   |   |
| 0            | 554 | 880 | 1160 | 4557 | 5027 | 5429 | 1100 | 5090 | 115 | 63 |
| 30           | 1184 | 1468 | 1712 | 5582 | 6600 | 7473 | 1550 | 5980 | 82 | 620 |
| 60           | 1385 | 1751 | 2065 | 5770 | 7247 | 8514 | 1580 | 7040 | 171 | 207 |
| 90           | 1485 | 1888 | 2233 | 6634 | 8894 | 10831 | 1680 | 7770 | 308 | 1124 |
| 120          | 1589 | 2040 | 2440 | 7499 | 9276 | 10800 | 1920 | 7770 | 428 | 1506 |
| Mean         | 1239 | 1607 | 1922 | 6008 | 7409 | 9609 | 1419 | 6730 | 158 | 679 |
| Hydrogel 30 (kg ha⁻¹) |   |   |   |   |   |   |   |   |   |
| 0            | 669 | 996 | 1276 | 5060 | 5733 | 6309 | 885 | 5490 | 111 | 243 |
| 30           | 1195 | 1468 | 1712 | 5533 | 6469 | 7272 | 1240 | 6440 | 196 | 29 |
| 60           | 1345 | 1692 | 1990 | 5514 | 7173 | 8595 | 1690 | 7550 | 2 | 377 |
| 90           | 1690 | 2008 | 2280 | 7280 | 8889 | 10269 | 2060 | 8320 | 52 | 569 |
| 120          | 1972 | 2324 | 2626 | 8441 | 10302 | 11897 | 2150 | 9620 | 174 | 682 |
| Mean         | 1374 | 1691 | 1963 | 6366 | 7713 | 8868 | 1605 | 7484 | 86 | 229 |
| Hydrogel 60 (kg ha⁻¹) |   |   |   |   |   |   |   |   |   |
| 0            | 657 | 1043 | 1374 | 4907 | 6586 | 7999 | 1210 | 6270 | 167 | 296 |
| 30           | 1213 | 1584 | 1903 | 5088 | 7434 | 9446 | 1640 | 8850 | 56 | 1416 |
| 60           | 1236 | 1714 | 2125 | 5723 | 7859 | 9376 | 1640 | 8850 | 74 | 1161 |
| 90           | 1601 | 1965 | 2278 | 7417 | 9252 | 10825 | 1980 | 9310 | 15 | 58 |
| 120          | 1840 | 2151 | 2417 | 8827 | 10437 | 11818 | 2060 | 9710 | 91 | 727 |
| Mean         | 1309 | 1691 | 2019 | 6392 | 8276 | 9891 | 1706 | 8598 | 15 | 322 |
| Hydrogel 90 (kg ha⁻¹) |   |   |   |   |   |   |   |   |   |
| 0            | 689 | 1036 | 1333 | 4735 | 6275 | 7596 | 1210 | 6140 | 174 | 135 |
| 30           | 1104 | 1404 | 1661 | 5406 | 6750 | 7904 | 1570 | 6140 | 166 | 610 |
| 60           | 1225 | 1694 | 2096 | 5672 | 7838 | 9696 | 1570 | 8520 | 124 | 682 |
| 90           | 1503 | 1866 | 2178 | 7148 | 8845 | 10301 | 1600 | 8030 | 266 | 815 |
| 120          | 1727 | 2057 | 2340 | 8307 | 9950 | 11358 | 1920 | 9330 | 137 | 620 |
| Mean         | 1250 | 1611 | 1922 | 6253 | 7932 | 9371 | 1574 | 7632 | 37 | 300 |
| Hydrogel 120 (kg ha⁻¹) |   |   |   |   |   |   |   |   |   |
| 0            | 702 | 1044 | 1337 | 4548 | 6274 | 7755 | 1000 | 5920 | 156 | 354 |
| 30           | 1022 | 1306 | 1505 | 5512 | 6490 | 7311 | 1200 | 5920 | 106 | 560 |
| 60           | 1187 | 1685 | 2112 | 5678 | 8080 | 10140 | 1540 | 7940 | 145 | 140 |
| 90           | 1401 | 1781 | 2108 | 6959 | 8831 | 10066 | 1570 | 7760 | 211 | 871 |
| 120          | 1593 | 1944 | 2245 | 7965 | 9619 | 11037 | 1860 | 9020 | 84 | 599 |
| Mean         | 1181 | 1552 | 1861 | 6132 | 7817 | 9262 | 1434 | 7312 | 118 | 505 |

N - nitrogen; Lₖ and Lₘ - Lower and upper confidence interval limit at 0.05 probability of error; X - Mean; PG - Grain Productivity; PB - Biomass Productivity

and weather conditions. Studies involving hydrogel and nitrogen with possibility of simulation considering biological and environmental indicators were not found in the world literature. This highlights the innovative character of this research.

**Conclusions**

1. The pertinence functions together with the quantitative and linguistic values for the input and output variables are suitable for the use of fuzzy logic in wheat yield simulation.

2. The fuzzy model makes it possible to estimate the yield values of biomass and wheat grain by nitrogen and non-linearity of maximum air temperature under conditions of use of hydrogel biopolymer in high and low N-residual release systems.

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