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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(de 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

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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 hydropolymer 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 $cmol_c$ dm^{-3}, Ca = 6.3 $cmol_c$ dm^{-3} e 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}). 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 m^2. 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 P_2O_5 and K_2O 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 V_3 (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 °C 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 $T_{Máx}$ (°C), the domain was considered in the range [21, 25], representing the ranges: < 22.5 °C (Low Temperature) and > 22.5 °C (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

N (kg ha^{-1})		Year	$T_{Máx}$(°C)		Output Linguistic variables				
V_L	V_Q		V_L	V_Q	PG_{H0}	PG_{H30}	PG_{H60}	PG_{H90}	PG_{H120}
Soybean/wheat system									
MB	[0, 15[	2015	B	<22.5	MB	MB	B	B	B
		2014	A	>22.5	MB	MB	MB	MB	MB
B	[15, 45[	2015	B	<22.5	M	M	M	M	M
		2014	A	>22.5	B	B	B	B	B
M	[45, 75[	2015	B	<22.5	A	M	A	A	A
		2014	A	>22.5	B	M	B	B	B
A	[75, 105[	2015	B	<22.5	A	A	M	A	A
		2014	A	>22.5	M	M	M	B	B
MA	[105, 120]	2015	B	<22.5	A	A	A	A	A
		2014	A	>22.5	M	A	M	M	B
Real value (2014+2015)		Minimum			1214	1257	1265	1266	1151
		Maximum			3189	3395	3487	3222	3165
Corn/wheat system									
MB	[0, 15[	2015	B	<22.5	MB	MB	B	B	B
		2014	A	>22.5	MB	MB	MB	MB	MB
B	[15, 45[	2015	B	<22.5	M	B	M	M	B
		2014	A	>22.5	MB	MB	B	MB	MB
M	[45, 75[	2015	B	<22.5	M	M	M	M	M
		2014	A	>22.5	B	B	B	MB	MB
A	[75, 105[	2015	B	<22.5	M	M	M	M	M
		2014	A	>22.5	B	M	M	B	B
MA	[105, 120]	2015	B	<22.5	A	A	A	M	M
		2014	A	>22.5	B	M	M	M	M
Real value (2014+2015)		Minimum			487	609	616	653	682
		Maximum			2678	2779	2657	2556	2450

N -Nitrogen; $T_{Máx}$ -Maximum average temperature; V_L -Linguistic variables; V_Q- Quantitative variables; PG -Grain yield; MB -Very Low; B -Low; M -Medium; A-High; H - Hydrogel (kg ha^{-1})

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

N (kg ha^{-1})		Year	$T_{Máx}$(°C)		Output Linguistic variables				
V_L	V_Q		V_L	V_Q	PB_{H0}	PB_{H30}	PB_{H60}	PB_{H90}	PB_{H120}
Soybean/wheat system									
MB	[0, 15[	2015	B	<22.5	B	B	B	B	B
		2014	A	>22.5	MB	MB	B	B	MB
B	[15, 45[	2015	B	<22.5	M	A	M	A	A
		2014	A	>22.5	B	M	B	M	B
M	[45, 75[	2015	B	<22.5	A	A	A	A	MA
		2014	A	>22.5	M	A	M	B	B
A	[75, 105[	2015	B	<22.5	A	MA	MA	A	MA
		2014	A	>22.5	A	MB	A	M	M
MA	[105, 120]	2015	B	<22.5	MA	MA	MA	MA	MA
		2014	A	>22.5	MA	MA	MA	A	A
Real value (2014+2015)		Minimum			6038	5255	6424	6396	5755
		Maximum			11212	11782	11796	12238	13021
Corn/wheat system									
MB	[0, 15[	2015	B	<22.5	MB	MB	B	B	B
		2014	A	>22.5	MB	MB	MB	MB	MB
B	[15, 45[	2015	B	<22.5	B	B	A	M	B
		2014	A	>22.5	MB	MB	MB	MB	MB
M	[45, 75[	2015	B	<22.5	M	M	A	A	MA
		2014	A	>22.5	MB	MB	MB	MB	MB
A	[75, 105[	2015	B	<22.5	MA	MA	MA	MA	MA
		2014	A	>22.5	B	B	B	B	B
MA	[105, 120]	2015	B	<22.5	MA	MA	MA	MA	MA
		2014	A	>22.5	B	M	M	M	M
Real value (2014+2015)		Minimum			4400	4763	4453	4466	4287
		Maximum			11671	12451	12786	12168	11789

N -Nitrogen; $T_{Máx}$ -Maximum average temperature; V_L -Linguistic variables; V_Q -Quantitative variables; PB -Biomass productivity; MB -Very low; B -Low; M -Medium; A-High; MA -Very High; H -Hydrogel (kg ha^{-1})

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

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

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_i 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:

$$\mu_R(a,b) = \max_{1 \le i \le n}\left\{\mu_{A_i}(a) \wedge \mu_{B_i}(b)\right\} \tag{3}$$

where ^ represents the MIN operator.

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

$$\mu_B(b) = \max_{1 \le i \le n}\left\{\max_a\{\mu_A(a) \wedge \mu_{Ai}(a)\right\} \wedge \mu_{Bi}(b)\} \tag{4}$$

If the input is a classic unitary set, then μ_A (a) = 1 and μ_A (a) ≤ 1. Therefore, the above expression results in:

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

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:

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

and discrete variables by the expression:

$$m(B) = \frac{\sum_b b_{\mu B}(b)\,db}{\sum_b b_{\mu B}(b)\,b} \tag{7}$$

The fuzzy controller is described as a function f: $R^n \rightarrow R^m$, 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

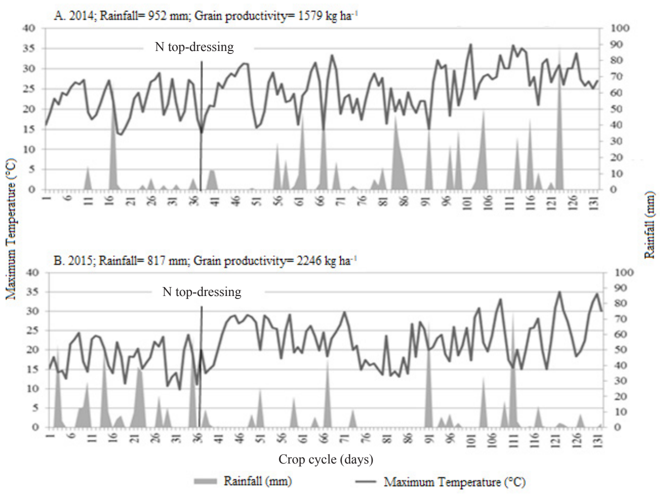
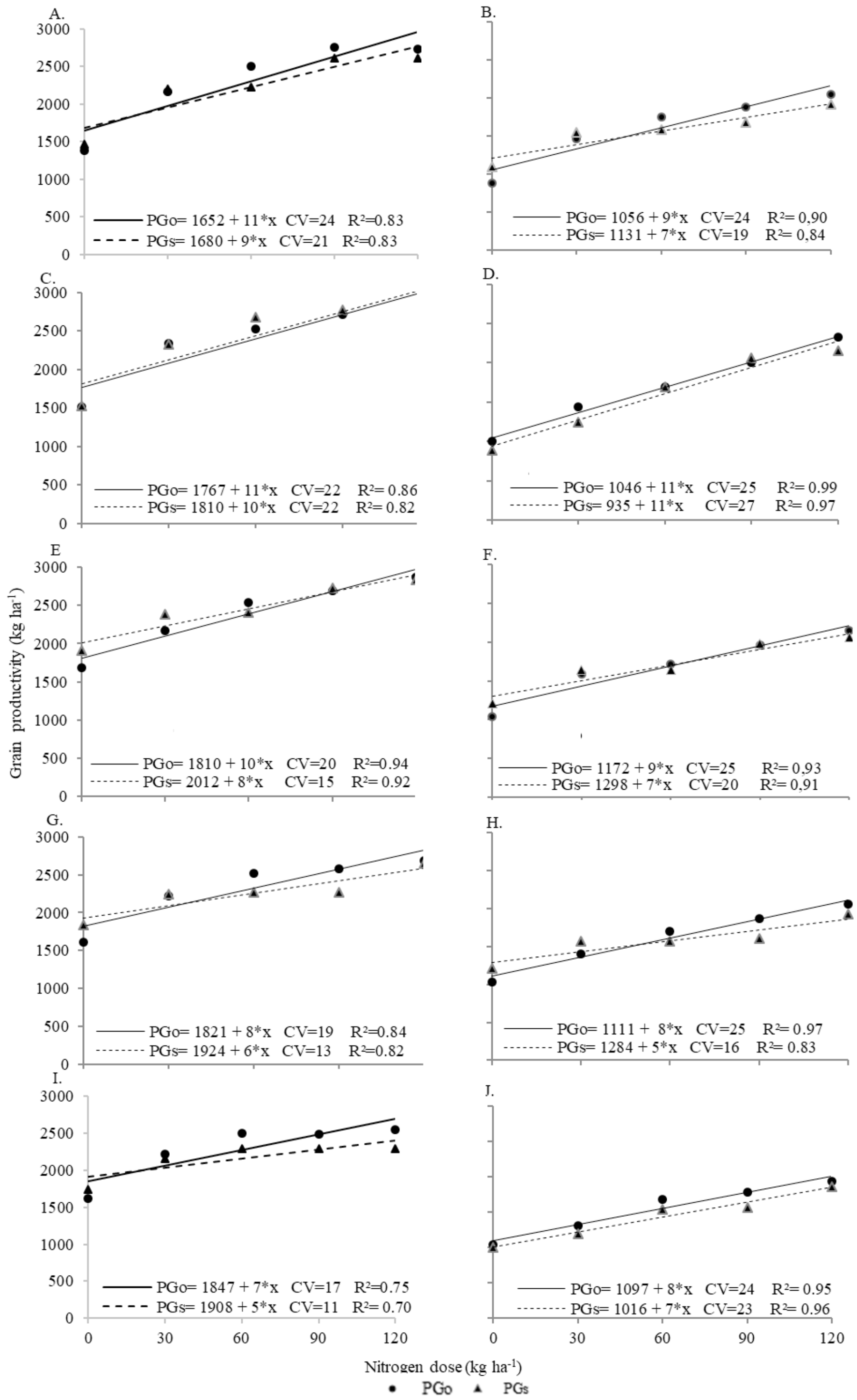


Figure 1. Rainfall and maximum temperature in the wheat cycle. (A) agricultural year 2014 and (B) agricultural year 2015

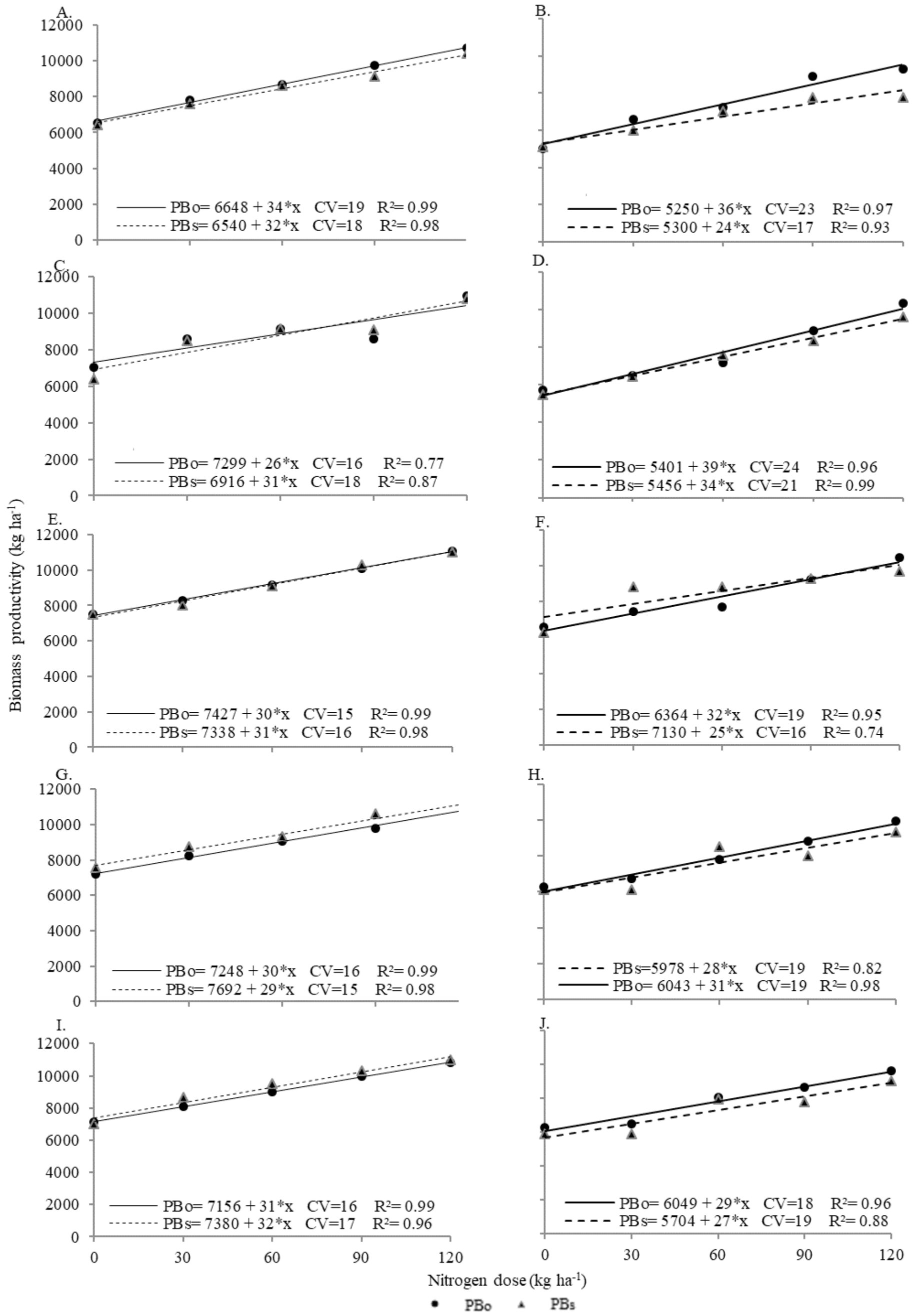
adequate distribution of milder temperatures (Arenhardt et al., 2015). Water deficit corroborates N-fertilizer volatilization, increasing nutrient losses to the environment and increasing production costs, not to mention lower productivity by reducing photosynthesis efficiency (Minuzzi & Lopes, 2015). 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



PGo - Observed grain yield (kg ha^{-1}); PGs - Simulated grain yield (kg ha^{-1}); * Significant at p≤0,05 error by the F test; R^2 = coefficient of determination; CV - Coefficient of variation (%)

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



PBo - Observed biomass productivity (kg ha^{-1}); PBs - Simulated biomass productivity (kg ha^{-1}); * Significant at p≤0,05 error by the F test; R^2 = coefficient of determination; CV - Coefficient of variation (%)

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

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})	PG (kg ha^{-1})			PB (kg ha^{-1})			Simulation/Fuzzy (kg ha^{-1})		Absolute Error (kg ha^{-1})	
	L_i	$\bar{X}$	L_s	L_i	$\bar{X}$	L_s	PG	PB	PG	PB
Joint analysis (2014 + 2015)										
Hydrogel 0 (kg ha^{-1})										
0	1286	1382	1463	6096	6552	6944	1460	6430	78	122
30	1815	2168	2470	7473	7811	8101	2200	7590	32	221
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	2880	10800	28	161
Mean	2111	2398	2644	7788	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	8040	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	62	37
Hydrogel 90 (kg ha^{-1})										
0	1336	1614	1853	6565	7211	7764	1840	7560	226	349
30	1720	2220	2648	7330	8224	8990	2240	8730	20	506
60	2103	2515	2868	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
Hydrogel 120 (kg ha^{-1})										
0	1274	1616	1909	6071	7137	8050	1740	7020	124	117
30	1616	2213	2725	6607	8094	9369	2160	8660	53	566
60	2011	2503	2924	7597	9001	10206	2290	9520	313	519
90	2013	2485	2891	8370	9962	11327	2290	10300	295	338
120	2103	2544	2923	9126	10820	12273	2290	11000	354	180
Mean	1803	2272	2674	7554	9003	10245	2154	9300	118	297

N-nitrogen; L_i and L_s - 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})	
	L_i	$\bar{X}$	L_s	L_i	$\bar{X}$	L_s	PG	PB	PG	PB
Joint analysis (2014 + 2015)										
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	2048	2440	7499	9276	10800	1920	7770	428	1506
Mean	1239	1607	1922	6008	7409	8609	1419	6730	188	679
Hydrogel 30 (kg ha^{-1})										
0	669	996	1276	5060	5733	6309	885	5490	111	243
30	1195	1436	1643	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	6566	7989	1210	6270	167	296
30	1213	1584	1903	5088	7434	9446	1640	8850	56	1416
60	1236	1714	2125	5723	7689	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	6480	7311	1200	5920	106	560
60	1187	1685	2112	5678	8080	10140	1540	7940	145	140
90	1401	1781	2108	6959	8631	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; L_i and L_s-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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Literature Cited

Arenhardt, E. G.; Silva, J. A. G.; Gewehr, E.; Oliveira, A. C.; Binelo, M. O.; Valdiero, A. C.; Silva, J. A. G. The nitrogen supply in wheat cultivation dependent on weather conditions and succession system in southern Brazil. African Journal of Agricultural Research, v.10, p.4322-4330, 2015. https://doi.org/10.5897/AJAR2015.10038

Barioni, L. G.; Albertini, T. Z.; Medeiros, S. R. Modelagem matemática do balanço de gases do efeito estufa na pecuária de corte. Revista Brasileira de Zootecnia, v.40, p.201-212, 2011.

Bischoff, T. Z.; Simonetti, A. P. M. M.; Nuernberg, P. H. Influencia de las diferentes temperaturas eneldesarrollo de semillas de trigo. Revista de Ciencia y Tecnología, v.17, p.12-15, 2015.

Camponogara, A. da S.; Oliveira, G. A.; Georgin, J.; Rosa, A. L. D. da. Avaliação dos componentes de rendimento do trigo quando submetido a diferentes fontes de nitrogênio. Revista Eletrônica em Gestão, Educação e Tecnologia Ambiental, v.2, p.524-532, 2016.

Campos, A. T.; Castro, J. D. O.; Schiassi, L.; Yanagi Junior, T.; Pires, M. D. F. Á.; Mattioli, C. C. Prediction of free-stall occupancy rate in dairycattle barns through fuzzy sets. Engenharia Agrícola, v.33, p.1079-1089, 2013. https://doi.org/10.1590/S0100-69162013000600001

Castro, J. D. O.; Yanagi, J.; Schiassi, L.; Fassani, E. J.; Ferraz, P. F. P. Fuzzy model to predict feed intake of Japanese quails. Journal of Animal Behaviour and Biometeorology, v.7, p.18-24, 2019.

Cecconello, M. S.; Silva, J. de D. M. de; Bassanezi R. C. Sistemas dinâmicos fuzzy: Modelagens alternativas para sistemas biológicos. 50.ed. São Carlos: Sociedade Brasileira de Matemática Aplicada, 2010. 120p.

Costa, J. S. P.; Mantai, R. D.; Silva, J. A. G. da; Scremin, O. B.; Arenhardt, E. G.; Lima, A. R. C. de. Single and split nitrogen dose in wheat yield indicators. Revista Brasileira de Engenharia Agrícola e Ambiental, v.22, p.16-21, 2018. https://doi.org/10.1590/1807-1929/agriambi.v22n1p16-21

Fernandes, D. A.; Araujo, M. M. V.; Camili, E. C. Crescimento de plântulas de maracujazeiro-amarelo sob diferentes lâminas de irrigação e uso de hidrogel. Revista de Agricultura, v.90, p.229-236, 2015.

He, W.; Dong, Y. Adaptive fuzzy neural network control for a constrained robot using impedance learning. IEEE Transactions on Neural Networks and Learning Systems, v.29, p.1174-1186, 2018. https://doi.org/10.1109/TNNLS.2017.2665581

Kaewpirom, S.; Boonsang, S. Electrical response characterisation of poly (ethylene glycol) macromer (PEGM)/chitosan hydrogels in NaCl solution. European Polymer Journal, v.42, p.1609-1616, 2006. https://doi.org/10.1016/j.eurpolymj.2006.01.010

Li, Y.; Tong, S.; Li, T. Observer-based adaptive fuzzy tracking control of MIMO stochastic nonlinear systems with unknown control directions and unknown dead zones. IEEE Transactions on Fuzzy Systems, v.23, p.1228-1241, 2015. https://doi.org/10.1109/TFUZZ.2014.2348017

Marques, J. I.; Lopes Neto, J. P.; Lopes, F. F. M.; Furtado, D. A.; Araújo, T. G. P. Fuzzy modeling in the prediction of climate indices and productive performance of quails kept in climate chamber. Engenharia Agrícola, v.36, p.604-612, 2016. https://doi.org/10.1590/1809-4430-Eng.Agric.v36n4p604-612/2016

Marolli, A.; Silva, J. A. G.; Sawicki, S.; Binelo, M. O.; Scremin, A. H.; Reginatto, D. C.; Dornelles, E. F.; Lambrecht, D. M. A simulação da biomassa de aveia por elementos climáticos, nitrogênio e regulador de crescimento. Arquivo Brasileiro de Medicina Veterinária e Zootecnia, v.70, p.535-544, 2018. https://doi.org/10.1590/1678-4162-9504

Mendel, J. M. Uncertainrule-basedfuzzy systems. 2.ed. Los Angeles: Springer,2017. 675p.

Minuzzi, R. B.; Lopes, F. Z. Desempenho agronômico do milho em diferentes cenários climáticos no Centro-Oeste do Brasil. Revista Brasileira de Engenharia Agrícola e Ambiental, v.19, p.734-740, 2015. https://doi.org/10.1590/1807-1929/agriambi.v19n8p734-740

Ramos, F. S.; Souza, C. C.; Reis Neto, J. F.; Frainer, D. M. Practical tool in classification of animals for slaughter by fuzzy logic. African Journal of Agricultural Resarch, v.10, p.604-612, 2015. https://doi.org/10.5897/AJAR2014.9429

Santi, A.; Vicari, M. B.; Pandolfo, C.; Dalmago, G. A.; Massignam, A. M.; Pasinato, A. Impacto de cenários futuros de clima no zoneamento agroclimático do trigo na região Sul do Brasil. Revista da Sociedade Brasileira de Agrometeorologia, v.25, p.303-311, 2018. https://doi.org/10.31062/agrom.v25i2.26167

Schiassi, L.; Yanagi Júnior, T.; Reis, G. M.; Abreu, L. H.; Campos, A. T.; Castro, J. D. O. Modelagem Fuzzy aplicada na avaliação do desempenho de frangos de corte. Revista Brasileira de Engenharia Agrícola e Ambiental, v.19, p.140-146, 2015. https://doi.org/10.1590/1807-1929/agriambi.v19n2p140-146

Scremin, O. B.; Silva, J. A. G.; Mamann, A. T. W.; Mantai, R. D.; Brezolin, A. P.; Marolli, A. Nitrogen efficiency in oat yield through the biopolymer hydrogel. Revista Brasileira de Engenharia Agrícola e Ambiental, v.21, p.379-385, 2017. https://doi.org/10.1590/1807-1929/agriambi.v21n6p379-385

Silva, A. A.; Silva, I. A. F.; Teixeira Filho, M. C. M.; Buzetti, S.; Teixeira, M. C. M. Estimativa da produtividade de trigo em função da adubação nitrogenada utilizando modelagem neuro fuzzy. Revista Brasileira de Engenharia Agrícola e Ambiental, v.18, p.180-187, 2014. https://doi.org/10.1590/S1415-43662014000200008

Souza, J. L. M.; Gerstemberger, E.; Araujo, M. A. Calibração de modelos agrometeorológicos para estimar a produtividade da cultura do trigo, considerando sistemas de manejo do solo, em Ponta Grossa-PR. Revista Brasileira de Meteorologia, v.28, p.409-418, 2013. https://doi.org/10.1590/S0102-77862013000400007

Tedesco, M. J.; Gianello, C.; Bissani, C. A.; Bohnen, H.; Volkweiss, S. J. Análise de solo, plantas e outros materiais. 2.ed. Porto Alegre: UFRGS, 1995. 174p.

Trautmann, A. P. B.; Silva, J. A. G.; Binelo, M. O.; Scremin, O. B.; Mamann, A. T. W.; Bandeira, L. M. Simulation of wheat biomass yield by thermal time, rainfall and nitrogen. Revista Brasileira de Engenharia Agrícola e Ambiental, v.21, p.763-768, 2017. https://doi.org/10.1590/1807-1929/agriambi.v21n11p763-768

Tonin, R. F. B.; Lucca Filho, O. A.; Labbe, L. M. B.; Rossetto, M. Potencial fisiológico de sementes de milho híbrido tratadas com inseticidas e armazenadas em duas condições de ambiente. Scientia Agropecuaria, v.5, p.7-16, 2014. https://doi.org/10.17268/sci.agropecu.2014.01.01

Venturoli, F.; Venturoli, S. Recuperação florestal em uma área degradada pela exploração de areia no Distrito Federal. Ateliê Geográfico, v.5, p.183-195, 2011. https://doi.org/10.5216/ag.v5i1.13831

Wei, Y.; Qiu, J.; Karimi, H.R. Reliable output feedback control of discrete-time fuzzy affine systems with actuator faults. IEEE Transactions on Circuits and Systems I: Regular Papers, v.64, p.170-181, 2017. https://doi.org/10.1109/TCSI.2016.2605685