Australian Journal of

Crop Science

AJCS 14(08):1319-1327 (2020) doi: 10.21475/ajcs.20.14.08.p2591

Fuzzy logic simulation of oat yield after using hydrogel and nitrogen biopolymer management

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Abstract

The fuzzy logic is an efficient tool for simulation and validation of new technologies in agriculture. The objective of the study is to adapt the fuzzy logic model for simulation of biomass and oat grain yield by nitrogen involving the nonlinearity of the maximum air temperature in the conditions of use of the biopolymer hydrogel, considering high succession systems and low release of residual N. The study was conducted in 2014 and 2015, in a randomized block design with four replicates in a 5 x 5 factorial. Five hydrogel doses (0, 30, 60, 90 and 120 kg ha⁻¹) were added in the groove next to the seed; and 5 doses of N-fertilizer (0, 30, 60, 90 and 120 kg ha⁻¹) applied at the fourth expanded leaf stage, respectively. The cultivar was URS Corona. The pertinence functions and the linguistic values established in the input and output variables to simulate the biomass yield and oat grains in the succession systems are adequate observed productivity. The fuzzy model makes it possible to estimate the biomass and oat grains productivity efficiently under the conditions of use of the hydrogel as a function of the nitrogen doses and maximum air temperature, adding to the existing models of simulation.

Keywords: Avena sativa, maximum air temperature, innovation, diffuse logic, sustainability. **Abbreviations:** BY_biological yield; GY_grain yield; N_nitrogen; T_{MÁX}_maximum air temperature.

Introduction

In agriculture, mathematical modeling techniques are based on processes involving multiple factors. Due to this condition, it is one of the growing areas in research that seeks to improve the understanding of environmental and management conditions in agricultural crops (Leal et al., 2015; Brezolin et al., 2017). In this perspective, the phenomena of nature together with biological processes, because they represent data that behave in an imprecise way, need efficient models that facilitate the understanding and the possibility of simulations (Mota et al., 2007; Schiassi et al., 2015). The fuzzy models are techniques that allow the description of complex systems of nonlinear behaviors, produced from rules, that must be elaborated by specialists, providing their experience to the elaboration of an "If <condition>Then<result> " system (De et al. 2009; Silva et al., 2014).

In recent years, oat harvesting in southern Brazil has become an important alternative in winter cropping systems, due to its high acceptance in the food industry (Crestani et al., 2014; Arenhardt et al., 2017). However, because it is a grass, it is highly nitrogen-dependent to reach higher yields with grain quality required by the industry (Silva et al., 2016; Marolli et al., 2017). It is worth noting that nitrogen management shows great complexity on the environment, and can be leached in rainy years and volatilized in high temperature conditions, generating nutrient losses, consequently increasing production costs and environmental contamination ambiental (Mantai et al., 2015; Silva et al., 2016). The maximum efficiency of nutrient utilization by the plant is strongly dependent on adequate soil moisture (Acosta et al., 2014; Marolli et al., 2018). Therefore, under actual growing conditions, the nitrogen fertilization moment does not always coincide with adequate soil moisture and air temperature conditions (Arenhardt et al., 2015; Ward et al., 2018). In this context, the use of water hydro-retentive added to the soil can favor the maintenance of moisture and improve the efficiency of nitrogen use with reduced nutrient losses (Oliveira, et al., 2004; Reza et al., 2011). Hydrogels are biodegradable threedimensional polymer networks, which retain water in their structure, swell, forming a gel, capable of hydrating and releasing water for a long period of time (Sartore et al., 2013; Guilherme et al., 2015).

The use of fuzzy logic may represent a potential tool for the simulation of biological processes involving non-linear

relationships of environmental conditions with cultivated agroecosystems. In addition, in the validation and optimization of new management technologies aimed at greater sustainability of yield in agriculture, such as the innovative use of technology of hydro-retentors in grainproducing crops. In this context, the objective of the study is to adapt the fuzzy logic model to the simulation of biomass and oat grain yield by nitrogen involving the non-linearity of the maximum air temperature in the conditions of use of the biopolymer hydrogel, considering high and reduced residual N release.

Results and discussion

Meteorological conditions

In Figure 1, in the oat crop cycle temperatures were higher in 2014 than in 2015. In addition, higher precipitation values were also observed in 2014 compared to 2015. In 2014, accumulated precipitation was of 952 mm (Figure 1A) and in 2015 of 817 mm (Figure 1B). These volumes are close to the historical average of the last 20 years (900 mm), but with different precipitation distribution between the years of cultivation. In 2014, lower rainfall periods occurred at the beginning of the crop cycle and higher peak temperatures over the cycle. These conditions favor the losses of nitrogen by volatilization and reduce the stimuli to the production of new tillers, a component directly linked to grain yield. From mid-cycle to near-maturation (2014), rainfall volumes were more expressive, which favored longer periods of less sunshine, consequently reducing the efficiency of photosynthesis. In the year 2015, the highest volume of rainfall was from the emergence until close to 35 days of oat development, and with maximum temperatures lower than those recorded in 2014. These conditions favor maintenance of soil moisture promoting greater efficiency of nitrogen use by the plant. From the middle of the cycle to maturation, rainfall volumes were better distributed and of lower intensity, development conditions that justify the greater yield of oat in the year 2015.

In the cropping systems, the condition of the agricultural year is the factor that contributes most to the yield variation (Neto et al., 2012; Hideo et al., 2016). In wheat and oat, the condition of agricultural year is predominantly defined by air temperature and distribution and volume of rainfall (Arenhardt et al., 2015). The temperature and precipitation interfere with the decomposition rate of the residues in contact with the soil and affect the efficiency of nitrogen use by the plant (Acosta et al., 2014). Arenhardt et al. (2015) point out that long periods of rain during the cycle reduce the efficiency of light and nutrient utilization to photosynthesis, interfering with the development, yield and quality of grains during harvest (Castro et al., 2012). The air temperature is also decisive on the yield elaboration, acting as catalyst of the biological processes, reason why the plants require a minimum and maximum temperature for normality of the physiological activities (Guarienti et al. 2004). In oat, the favorable climate is described as one of milder temperatures and of radiation quality in favor of tillering and grain filling, without occurrence of rains in great quantity and intensity, however, that favors the adequate supply of moisture stored in the soil (Castro et al., 2012; Marolli et al., 2017).

Biological behavior of oat productivity

Figures 2 and 3 show the parameters of linear $(y = \pm b_1 x \pm b_0)$ and quadratic $(y = \pm b_2 x^2 \pm b_1 x \pm b_0)$ functions for the interpretation of the biological behavior of oat yield by nitrogen in the conditions of use of the biopolymer hydrogel. In linear functions the starting point of agronomic performance is given by the linear coefficient (b_0) and slope of the line by the angular coefficient (b_1) in the comparison between the real data and those estimated by the fuzzy logic. The parameter b_1 of the linear function provides the agronomic efficiency, indicating the relationship between the yield obtained per unit of nitrogen supplied. In quadratic functions, the vertex $\left(\frac{-b_1}{2b_2}\right)$ represents the maximum use of nitrogen on the expression of yield, ie, maximum technical efficiency.

In the soybean/oat system, for grain yield (Figure 2), regardless of the condition of hydrogel use, all functions presented quadratic behavior, with the possibility of calculating the maximum nutrient utilization. In this sense, using as an example the functions of graph C of Figure 2, the points observed in the field and simulated by fuzzy logic were approximate, and with maximum grain yield by the technical efficiency of 76 kg ha⁻¹ of nitrogen. In the corn/oat system (Figure 2), the doses 0 and 30 kg ha⁻¹ of hydrogel presented quadratic behavior and those of 60, 90 and 120 kg ha⁻¹ of hydrogel indicated a linear trend. The linear behavior functions showed very approximate estimates of agronomic efficiency, with emphasis on the equations of the graphs I and J of Figure 2, with an angular coefficient (b_1) around 13, that is, for every 1 kg of nitrogen supplied per hectare, there is increase of 13 kg ha⁻¹ of grain yield, either in the real condition or simulated by fuzzy logic.

In Figure 3, for biomass yield, independent of the succession system and hydrogel use condition, all functions exhibited linear behavior. The agronomic efficiency of the equations expressing the real condition and simulated by fuzzy logic were also approximate. In this perspective, the example of the functions of Graph J, such as 53 and 54 kg of biomass yield per hectare for each 1 kg ha⁻¹ of nitrogen supplied, in the real condition and simulated by fuzzy logic, respectively, is highlighted. Therefore, Graphs A and C show a greater distance between the angular coefficients, but within an acceptable perspective of the variability of biomass yield for each 1 kg of nitrogen supplied. Therefore, by providing the dimension that the linear functions of expression of biomass yield simulated in the fuzification process accompany the results obtained in the actual bio-experimental conditions. In addition, allowing inference that associate the meteorological condition with management technologies in the actual representation of cultivated biosystems.

Simulation of oat productivity by Fuzzy Logic

Tables 3 and 4 present the mean and lower and upper limits of the confidence interval of the real and simulated values by fuzzy logic to the biomass and oat grains yield in the use of hydrogel and nitrogen. In this perspective, regardless of the succession system and hydrogel dose, the N-fertilizer doses provided a change in the biomass and grains yield. In the soybean/oat system (Table 3), in general, the increase of N-fertilizer provided an increase in grain yield to the point of 90 kg ha⁻¹. Fact indicating reaching stability of nutrient utilization, regardless of hydrogel dose. On the other hand, in general, the increase of N-fertilizer promoted greater

Table 1. Fuzzy logic rules for simulation of oat grain yield in succession systems.

Ν		Voar	T _{MÁX} (°C)		Output Li	Output Linguistic Variables				
Lv	Q _v	fear	Lv	Qv	GY _{Hy0}	GY _{Hy30}	GY _{Hy60}	GY _{Hy90}	GY _{Hy120}	
soybea	an/oat system									
M	[0.15]	2015	L	<22.5	L	L	Μ	L	L	
VL	[0,13]	2014	Н	>22.5	L	L	L	L	L	
		2015	L	<22.5	Н	Н	Н	Н	Μ	
L	[15,45[2014	Н	>22.5	Μ	М	Μ	Μ	L	
N.4		2015	L	<22.5	VH	VH	VH	VH	Н	
IVI	[45,75]	2014	Н	>22.5	Н	Н	Н	Н	Μ	
		2015	L	<22.5	VH	VH	VH	VH	VH	
н	[75,105]	2014	Н	>22.5	Н	н	Н	н	М	
	[105,120]	2015	L	<22.5	Н	VH	Н	н	Н	
VH		2014	Н	>22.5	Μ	н	М	М	М	
Real value		М	inimum		1850	2021	1965	1905	1836	
(2014+2015)		М	aximum		4025	4286	4124	4036	4005	
corn/c	oat system									
M	[0.15]	2015	L	<22.5	L	L	L	L	L	
VL	[0,13]	2014	Н	>22.5	L	L	L	L	L	
	[15,45[2015	L	<22.5	Н	Н	Μ	Н	Н	
L		2014	Н	>22.5	Μ	М	L	Μ	Μ	
N 4		2015	L	<22.5	VH	Н	VH	VH	VH	
IVI	[45,75]	2014	Н	>22.5	Н	Н	Н	Μ	Μ	
ы	[75,105[2015	L	<22.5	VH	VH	VH	VH	VH	
п		2014	Н	>22.5	Н	VH	Н	Н	Н	
	[105,120]	2015	L	<22.5	VH	VH	VH	VH	VH	
vп		2014	Н	>22.5	Н	VH	VH	VH	VH	
Real va	alue	M	inimum		1164	1159	1510	1304	1211	
(2014-	+2015)	M	aximum		3620	3821	3724	3725	3745	
N = nitrog	gen (kg ha 1); T _{MÁX} = maxii	mum average t	emperature;	L _v = linguistic v	ariables; Q _v = quantita	tive variables; GY = gra	ain yield; VL = very low;	L = low; M = medium; H	I = high; VH = very high; Hy =	

hydrogel (kg ha⁻¹)





Fig 1. Rainfall and maximum sowing temperature at oat harvest. (A) Agricultural year 2014; (B) Agricultural year 2015

Table 2. Basis of fuzzy logic for the simulation of oat biomass yield in succession systems.

Ν			T _{MÁX} (°	T _{MÁX} (°C)		Output				
L_V	Qv	rear	Lv		Qv	BY _{Hy0}	BY _{Hy30}	BY _{Hy60}	BY _{Hy90}	BY _{Hy120}
Soybe	ean/oat system									
M	[0.45]	2015	L		<22.5	М	М	М	М	L
VL	[0,15[2014	н		>22.5	VL	VL	VL	VL	VL
		2015	L		<22.5	Н	Н	М	М	М
L	[15,45[2014		н	>22.5	L	L	Μ	М	Μ
N.4		2015	L		<22.5	н	VH	VH	н	Н
IVI	[45,75]	2014	Н		>22.5	М	М	Μ	Н	Н
ы		2015	L		<22.5	VH	VH	VH	VH	VH
п	[/5,105[2014	н		>22.5	н	Н	Н	Н	Н
VL	[105 120]	2015	L		<22.5	VH	VH	VH	VH	VH
VП	[105,120]	2014	Н		>22.5	Н	VH	Н	VH	VH
Real value		Mir	iimum			4517	5601	6017	6782	7348
(2014+2015)		Ma	ximum			15289	14984	13361	14167	14835
Corn/	oat system									
M		2015	L		<22.5	L	L	М	М	L
VL	[0,15[2014	Н		>22.5	VL	VL	L	VL	VL
		2015	L		<22.5	Н	Н	Н	М	Μ
L	[15,45[2014	Н		>22.5	М	L	VL	L	L
N.4		2015	L		<22.5	Н	Н	Н	Н	Н
IVI	[45,75]	2014	Н		>22.5	н	М	Μ	М	Μ
ы		2015	L		<22.5	VH	Н	VH	Н	Н
п	[75,105]	2014	Н		>22.5	Н	Н	Н	Н	Н
V/II	[105 120]	2015	L		<22.5	VH	VH	VH	VH	VH
vн	[105,120]	2014	Н		>22.5	VH	Н	VH	VH	VH
Real	value	Mir	iimum			4231	4122	5601	4659	4066
(2014	+2015)	Ma	ximum			12534	12132	12982	13167	13572
N = nitro	ogen (kg ha⁻¹); T _{Máx} = m	aximum averag	e temperatur	e; L _v = ling	uistic variables;	Q _v = quantitative va	riables; BY = biomas	s yield; VL = very low; L	= low; M = medium; H	t = high; VH = very high; H

N = nitrogen (kg ha⁻¹); T_{MÁX} = maximum average temperature; L_v= linguistic variables; Q_v = quantitative variables; BY = biomass yield; VL = very low; L = low; M = medium; H = high; VH = very high; Hy = hydrogel (kg ha⁻¹)



Fig 2. Behavior of grain yield observed and estimated by fuzzy logic. GYo = Observed grain yield (kg ha⁻¹); GYe = Estimated grain yield (kg ha⁻¹); A, B, C, D, E = Graph of grain yield in the soybean/oat system under conditions of use of hydrogel 0, 30, 60, 90 and 120 kg ha⁻¹, respectively; F, G, H, I, J = Graph of grain yield in the corn/oat system under conditions of use of hydrogel 0, 30, 60, 90 and 120 kg ha⁻¹, respectively; F, G, H, I, J = Graph of grain yield in the corn/oat system under conditions of use of hydrogel 0, 30, 60, 90 and 120 kg ha⁻¹, respectively; •= Observed grain yield; \bullet = Grain yield estimated by fuzzy logic; $-GY_{OA} = -0.186N^2 + 30.18N + 2241$, R²=99; $-GY_{EA} = -0.235N^2 + 35.18N + 2119$, R²=99; $-GY_{OB} = -0.192N^2 + 31.04N + 2416$, R²=93; $-GY_{EB} = -0.171N^2 + 30.97N + 2337$, R²=98; $-GY_{OC} = -0.196N^2 + 29.45N + 2438$, R²=99; $-GY_{EC} = -0.236N^2 + 35.34N + 2226$, R²=99; $-GY_{OD} = -0.180N^2 + 29.72N + 2247$, R²=99; $-GY_{ED} = -0.232N^2 + 34.67N + 2167$, R²=99; $-GY_{OE} = -0.179N^2 + 30.47N + 2110$, R²=98; $-GY_{EE} = -0.231N^2 + 34.81N + 2102$, R²=99; $-GY_{OF} = -0.169N^2 + 32.83N + 1577$, R²=99; $-GY_{EF} = -0.184N^2 + 33.35N + 1511$, R²=98; $-GY_{OG} = -0.168N^2 + 35.29N + 1528$, R²=99; $-GY_{EG} = -0.148N^2 + 34.31N + 1518$, R²=99; $-GY_{OH} = 12.99N + 1928$, R²=98; $-GY_{EH} = 14.1N + 1862$, R²=90; $-GY_{OI} = 13.53N + 1859$, R²=95; $-GY_{EI} = 13.76N + 1796$, R²=92; $-GY_{OI} = 13.6N + 1809$, R²=95; $-GY_{EI} = 13.7N + 1750$, R²=91; R² = coefficient of determination; N= Nitrogen.

Table 3. Fuzzy lo	gic in the si	imulation of oat	yield by nitroge	en and temper	ature in the use o	of the hydrogel, in	the soybear	/oat system.			
Ν	GY (kg ha ⁻¹)			BY (kg ha⁻¹)			Fuzzy (kg ha	a ⁻¹)	rror (kg ha ⁻¹)		
(kg ha⁻¹)	Լ	Ń	UI	L	Ń	UI	GY	BY	GY	BY	
Joint Analysis (2014+2015)											
Hydrogel (0 kg h	a ⁻¹)										
0	1987	2220 c	2420	5067	7481 d	9553	2130	8430	90	949	
30	2750	3035 b	3278	8847	10414 c	11758	2940	9910	95	504	
60	2872	3342 a	3745	10854	11531 b	12113	3390	11300	48	231	
90	2934	3449 a	3891	11457	12466 a	13332	3390	12900	59	434	
120	2643	3192 b	3663	11920	13004 a	14671	2940	12900	252	104	
Average	2637	3047	3399	9626	11059	12285	2958	11088	89	29	
Hydrogel (30 kg	ha ⁻¹)										
0	2150	2327 d	2478	6120	8616 e	10757	2310	9000	17	384	
30	2892	3106 c	3290	8976	10613 d	12017	3150	10300	44	313	
60	2964	3483 a	3929	10101	11789 c	13237	3630	11500	147	289	
90	3170	3634 a	4031	12164	12974 b	13669	3630	12900	4	74	
120	3061	3466 a	3814	13589	14159 a	14648	3630	14000	164	159	
Average	2847	3203	3508	10190	11630	12648	3270	11540	67	90	
Hydrogel (60 kg	ha⁻¹)										
0	2035	2442 c	2790	6344	7908 d	9249	2240	8680	202	772	
30	2783	3138 b	3442	9261	9676 c	10031	3040	9690	98	14	
60	2954	3502 a	3973	10514	11784 b	12873	3500	10700	2	1084	
90	2985	3505 a	3952	11400	12194 a	12875	3500	11800	5	394	
120	2618	3146 b	3599	11680	12604 a	13053	3040	11800	6	804	
Average	2675	3146	3551	9839	10883	11616	3064	10534	82	349	
Hydrogel (90 kg	ha ⁻¹)										
0	2041	2225 c	2381	7156	8271 e	9500	2180	9460	45	1189	
30	2631	3036 b	3384	9588	10112 d	10561	2970	10500	66	388	
60	2864	3335 a	3740	11272	11852 c	12350	3420	12300	85	448	
90	2963	3462 a	3891	12100	12669 b	13157	3420	12600	42	69	
120	2792	3222 b	3591	12872	13485 a	14012	2970	13500	252	15	
Average	2658	3056	3397	10597	11277	11916	2992	11672	64	395	
Hydrogel (120 kg	g ha ⁻¹)										
0	1957	2070 c	2168	7721	8367 e	8990	2110	8980	40	613	
30	2488	2969 b	3381	9791	10204 d	11300	2920	11100	49	896	
60	2787	3215 a	3583	11660	11902 c	13100	3370	13000	155	1098	
90	2897	3398 a	3828	12359	12830 b	13234	3370	13200	28	370	
120	2808	3199 b	3534	12757	13759 a	14617	2950	14100	249	341	
Average	2587	2970	3298	10857	11412	12248	2944	12076	26	664	

 Average
 2507
 2570
 3250
 1007
 11412
 1210
 2547
 1000
 1

 N = nitrogen; L₁ = lower limit; U₁ = upper limit (L₁ and U₁ of the confidence interval at 5% probability of error); X = average; GY = grain yield; BY = biomass yield; Means followed by the same letter within each hydrogel use condition constitute a statistically homogeneous group by the Skott-Knott model with a 5% probability of error.
 End of the same letter within each hydrogel use condition constitute a statistically homogeneous group by the Skott-Knott model with a 5% probability of error.

Table 4. Fuzz	y logic in the	simulation of d	at yield by hitr	ogen and temp	erature in the us	e of nyarogei in t	ne corn/oat sy	stem.		
N GY (kg ha ⁻¹)				BY (kg ha	1)		Fuzzy (kg	ha⁻¹)	rror (kg ha⁻¹)	
(kg ha⁻¹)	L	Ý	UI	ել	Ń	UI	GY	BY	GY	BY
Joint Analysis	(2014+2015)								
Hydrogel (0 k	g ha ⁻¹)									
0	1240	1551 c	1818	4469	5993 e	7299	1480	6040	71	47
30	2163	2476 b	2745	8393	9003 d	9527	2390	9420	86	417
60	2451	2902 a	3289	10080	10455 c	10770	2900	10500	2	45
90	2789	3144 a	3449	10408	10927 b	11372	2900	10700	244	227
120	2778	3094 a	3364	10982	11645 a	12215	2900	11700	194	55
Average	2284	2633	2933	8866	9604	10222	2514	9672	119	67
Hydrogel (30	kg ha⁻¹)									
0	1231	1502 d	1735	4275	6416 e	8253	1500	5870	2	546
30	2254	2511 c	2731	7726	9106 d	10289	2490	8130	21	976
60	2655	2979 b	3258	8954	9777 c	10482	2930	9130	49	647
90	3014	3351 a	3640	9609	10488 b	11241	3480	10100	129	388
120	3009	3348 a	3639	10378	11189 a	11885	3480	11300	132	111
Average	2432	2738	3000	8188	9395	10430	2776	8906	38	489
Hydrogel (60	kg ha ⁻¹)									
0	1584	1891 e	2154	6065	7991 e	9643	1790	8280	101	289
30	1982	2281 d	2537	6598	8218 d	9606	2150	9500	131	1288
60	2524	2837 c	3105	9320	9826 c	10261	3080	10200	243	374
90	2852	3097 b	3307	10349	11010 b	11577	3080	11300	17	290
120	3224	3432 a	3610	11599	12300 a	12902	3440	12200	8	100
Average	2433	2707	2942	8786	9869	10797	2708	10296	1	427
Hydrogel (90	kg ha ⁻¹)									
0	1374	1689 e	1958	4912	6736 e	8300	1610	6510	79	226
30	2104	2392 d	2639	6975	8259 d	9360	2510	7850	118	679
60	2491	2811 c	3086	9124	9644 c	10091	2550	9980	261	336
90	2812	3097 b	3342	10352	10937 d	11440	3020	11100	209	163
120	3109	3367 a	3589	11798	12308 a	12745	3420	12400	53	92
Average	2378	2671	2922	8632	9576	10387	2622	9568	48	8
Hvdrogel (12	0 kg ha ⁻¹)									
0	1296	1634 e	1924	4471	6188 e	7661	1530	6140	104	48
30	2006	2363 d	2669	6199	7691 d	8971	2480	7630	117	61
60	2425	2757 c	3041	8949	9521 c	10011	2520	10000	237	479
90	2736	3033 b	3289	10477	11014 b	11475	3010	11200	23	186
120	3061	3340 a	3580	12074	12591 a	13035	3320	12600	20	9
Average	2204	2625	2000	0121	0401	10220	2572	0514	E 2	112

er within each hydrogel use condition constitute a statistically homogeneous group by the Skott-Knott model with a 5% probability of error.



Fig 3. Behavior of biomass yield observed and estimated by fuzzy logic. BYo = Observed biomass yield (kg ha⁻¹); BYe = Estimated biomass yield (kg ha⁻¹); A, B, C, D, E = Graph of the biomass yield in the soybean/oat system under conditions of use of hydrogel 0, 30, 60, 90 and 120 kg ha⁻¹, respectively; F, G, H, I, J = Graph of biomass yield in the corn/oat system under conditions of use of hydrogel 0, 30, 60, 90 and 120 kg ha⁻¹, respectively; F, G, H, I, J = Graph of biomass yield in the corn/oat system under conditions of use of hydrogel 0, 30, 60, 90 and 120 kg ha⁻¹, respectively; •= Observed biomass yield; •= Estimated biomass yield by fuzzy logic. $-BY_{OA} = 43,66N + 8359, R^2=99; -BY_{EA} = 3.76N + 8702, R^2=94; -BY_{OB} = 44.81N + 8940, R^2=98; -BY_{EB} = 42N + 9020, R^2=99; -BY_{OC} = 29.45N + 2438, R^2=99; -BY_{EC} = 35.34N + 2226, R^2=99; ; -BY_{OD} = 29.72N + 2247, R^2=99; -BY_{ED} = 34.67N + 2167, R^2=99; ; -BY_{OE} = 30.47N + 2110, R^2=98; -BY_{EE} = 34.81N + 2102, R^2=99; -BY_{OF} = 32.83N + 1577, R^2=99; -BY_{EF} = 33.35N + 1511, R^2=98; -BY_{OG} = 35.29N + 1528, R^2=99; -BY_{EG} = 34.31N + 1518, R^2=99; ; -BY_{OH} = 12.99N + 1928, R^2=98; -BY_{EH} = 14.1N + 1862, R^2=90; ; -BY_{OI} = 13.53N + 1859, R^2=95; -BY_{EI} = 13.76N + 1796, R^2=92; ; -BY_{OJ} = 13.6N + 1809, R^2=95; -BY_{EJ} = 13.7N + 1750, R^2=91; R^2 = coefficient of determination; N= Nitrogen.$

expression of biomass yield at the highest nutrient dose, indicating a trend towards linearity. The analysis in paired form in the comparison of the real and simulated values by fuzzy logic in each condition of use of the hydrogel showed similar values in the expression of grain biomass yield. These facts report the effectiveness of the rules base developed for the developmental quality of fuzzy modeling.

In the corn/oat system (Table 4), regardless of the use of the biopolymer hydrogel, in general, the increase of N-fertilizer promoted increased yield of biomass and grains to the highest nutrient dose, indicating a trend of linearity in the more restrictive N-residual condition. In the simulation of grain yield by diffuse logic, the results were close to those obtained by bio-experimentation. Although differences are

obtained between the different points of analysis, all presented results within the established confidence interval, independent of the conditions of nitrogen and hydrogel use. In the overall average in each hydrogel use condition, results between the observed and simulated values were very close to the expression of biomass and grain yield. The condition of reduced release of N-residual shows behavior of yield growth with the provision of higher doses of fertilizer. Therefore, a trend of linearity between the real and simulated points by the fuzification process, also ensuring quality of the rules base established for this system. The results obtained from the simulations, although closer to or far from the actual points of the bio-experiment, all the results at their respective levels were within the confidence interval of the mean. A condition that justifies the established basis of rules and the possibility of using nebulous logic in the predictability of biomass and oat grain yields involving nonlinearity of air temperature with important management technologies.

The fuzzy models are techniques that allow the description of complex systems, produced from rules, that must be elaborated by specialists, providing their experience to the elaboration of an inference system (Freitas et al., 2013). In this perspective, fuzzy logic has been increasingly used in different areas of knowledge, allowing to assign linear and non-linear effects of the processes with the experience gained from the observer (Malaman & Amorim, 2017). In agriculture Silva et al. (2014) made use of the fuzzy neuro in the estimation of grain yield of wheat as a function of nitrogen fertilization. Francisco et al. (2007), developed a fuzzy model to estimate soybean area from vegetation indexes of images, being highly correlated with estimates recorded by official bodies. Giusti & Marsili-Libelli, (2015), studied the use of fuzzy logic as irrigation controller by the cumulative days, total water applied to the crop and evapotranspiration in corn, kiwi and potato crops, being highly comparative to existing irrigation agricultural models.

Materials and methods

Crop area description

The works were developed in the field, in the agricultural years of 2014 and 2015, in the municipality of Augusto Pestana, RS, Brazil (28 ° 26 '30' 'S and 54 ° 00' 58 " W longitude). The soil of the experimental area was classified as Typical Dystrophic Red Latosol (Oxisol) and the climate of the region, by classification of Köppen, Cfa type (subtropical humid). In the study, ten days before sowing, soil analysis was performed and the following chemical characteristics were identified (Tedesco et al., 1995): i) maize/oat system (pH= 6,5; P= 34,4 mg dm⁻³; K= 262 mg dm⁻³; OM= 2,9 %; Al= 0 cmol_c dm⁻³; Ca= 6,6 cmol_c dm⁻³ and Mg= 3,4 cmol_c dm⁻³) and; ii) soybean/oat system (pH= 6,2; P= 33,9 mg dm⁻³; K= 200 mg dm⁻³; OM= 3,0 %; Al= 0 cmol_c dm⁻³; Ca = 6,5 cmol_c dm^{-3} and Mg = 2,5 cmol_c dm^{-3}). Independent of the agricultural year, sowing was carried out in the third week of June, according to the cultivation recommendation, considering two succession systems of high and low release of residual N, corn/oat and soybean/oat systems, respectively.

Experimental design

At sowing, the seeder was used in the composition of the plot with 5 lines of 5 m in length and spacing between rows of 0.20 m, forming the experimental unit of 5 m². The population density was 400 viable seeds m⁻², using the URS-Corona white oat cultivar. During the execution of the study, tebuconazole fungicide of commercial name FOLICUR[®] CE was applied at a dosage of 0.75 L ha⁻¹. Weed control was carried out with commercially available metysulfuronmethyl herbicide (ALY) at the dose of 4 g ha⁻¹ of the commercial product and additional weeding when necessary. In the experiments, at sowing, 45 and 30 kg ha⁻¹ of P₂O₅ and K₂O were applied, based on the levels of P and K in the soil for expectation of grain yield of 3 t ha⁻¹, respectively, and 10 kg ha⁻¹ of nitrogen (except in the standard experimental unit), with the remainder to contemplate the doses proposed for top dressing at the

fourth expanded leaf stage. It should be noted that the different doses of the biopolymer hydrogel were added to the oat seed, being in the soil at the same depth and line of cultivation, approximately 3 cm deep. It is noteworthy that the hydrogel is a fine granulated biopolymer, which when in contact with moisture forms a gelatinous structure, capable of storing water and making it available to plants for a long period of time.

In each succession system of high and low residual N release (corn/oat and soy/oat systems) two experiments were conducted, one to quantify biomass yield (BY, kg ha⁻¹), the other to estimate grain yield (GY, kg ha⁻¹). Therefore, in the four experiments, the experimental design was a randomized block with four replicates, with the hydrogel and nitrogen treatments, following a 5 x 5 factorial scheme in the sources of variation of 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.

Data measurement

The grain yield was obtained by cutting three central lines of each plot at the maturity stage, with grain moisture around 22%. The plants were harvested with a stationary harvester and directed to the laboratory for correction of grain moisture to 13% and weighing to estimate grain yield (GY, kg ha⁻¹). In the experiments aimed at quantifying the biomass yield, the plant material was harvested close to the soil, starting from the collection of a 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 constant weight was reached to estimate the total biological yield (BY, kg ha⁻¹).

Modeling for Fuzzy Logic

Based on the initial analysis of the data, the rules were developed, in linguistic terms, with the help of a plant specialist. The input variables of the model (independent variables) were nitrogen (N) and maximum air temperature (T_{MAX}) . It is noteworthy that the maximum air temperature value was obtained by the Automatic Weather Station, installed at 200 meters distance from the experiment. The output variables (dependent variables) were grain yield (GY) and biological productivity (BY). For the T_{MAX} independent variable (ºC), the domain in the range 21 to 25 was considered, representing the bands: <22.5ºC (low temperature) and >22.5°C (high temperature). For the independent variable N (kg ha⁻¹), the range zero to 120 was considered, representing the intervals: <15 [very low dose (VL)]; 15-45 [low dose (L)]; 45-75 [mean dose (M)]; 75-105 [high dose (H)] and> 105 [very high dose (VH)]. For the output variable (dependent variable), the image intervals were the maximum and minimum values of the experimentally collected biomass and oat grain yield data, considering the cumulative effect of the growing years, in each hydrogel use condition. Thus, in the development of the modeling process 10 simulators were constructed. The variable GY was divided into four equidistant intervals (Table 1), being: low (L), medium (M), high (H) and very high (VH) and BY variable in five intervals (Table 2): very low (VL), low (L), medium (M), high (H) and very high (VH). For the simulations the nitrogen doses and the average maximum air temperature in the years of cultivation were used as inputs.

In Tables 1 and 2, the classifications are presented for the simulation of grain and biomass yield, respectively, as a function of nitrogen (kg ha^{-1}) and maximum air temperature (°C), respectivel in each hydrogel condition.

In the development of fuzzy logic programming, the *Fuzzy Logic Toolbox* of MATLAB® software was used. In the prediction applications the Mamdani fuzzy model was used, which includes interface modules in the transformation of input variables into fuzzy sets and, later, outputs in proportional numerical quantities (Cecconello et al., 2010). The fuzzification process was carried out by four successive modules. In module 1 (fuzzification), the information of the input variables was mathematically modeled by means of fuzzy sets. From the expert, for each entry variable, linguistic terms representing the states of this variable were assigned and, for each linguistic term, a fuzzy set associated with a pertinence function. In module 2 (rule base), the variables were adjusted in their linguistic classifications, where each rule base satisfied the following structure:

If A is in A_i then B is in B_i

where A_i and B_i are the fuzzy sets. The expression A is in A_i means that $\mu_{A_i}(a)\epsilon[0,1]$. Both the A_i and B_i sets are the Cartesian product of fuzzy sets, that is, $A_i = A_{i1} \times A_{i2} \times$ $... \times A_{\mathfrak{I}} \in B_i = B_{i1} \times B_{i2} \times ... \times B$. In this case, each set fuzzy 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:

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

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

 $\mu_{R_i}(a,b) = \min\{\mu_{A_i}(a), \mu_{B_i}(b)$ (2) The relationship between each rule is characterized by the operator (MAX), of the fuzzy relation *R* 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) is obtained:

$$\mu_R(a,b) = \max_{1 \le i \le n} \{\mu_{A_i}(a)_{B_i}^{\mu}(b)\}$$
(3)

where ^ represents the MIN operator.

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

$$\mu_B(b) = \max_{\substack{1 \le i \le n}} \{\max_a \mu_A(a)_{Ai}^{\mu}(a)\}_{Bi}^{\mu}(b)\}$$
(4)

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

$$\mu_B(b) = \max_{1 \le i \le n} \{\mu_{Ai}(a)_{Bi}^{\mu}(b)\}$$
(5)
Therefore the fuzzy set B represents the act

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 numerical value. One of the main methods of defuzzification is the center of mass for continuous variables, given by the expression:

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

and of discrete variables by the expression:

$$m(B) = \frac{\sum_{b} b_{\mu B}(b) db}{\sum_{b} b_{\mu B}(b) b}$$
(7)

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

For validation of the rules base and the simulated values of biomass and oat grain yields by fuzzy logic, the polynomial regression behavior and parameters obtained from bioexperimentation under real growing conditions were considered. And of the lower and upper limits of the confidence interval of the average values of two agricultural crops, at a level of 5% of error probability. In the determination of the regression models and confidence interval, the Genes computational program was used.

Conclusions

The pertinence functions and the linguistic values established in the input and output variables to simulate the biomass and oat grain yield in the succession systems are adequate.

The *fuzzy* model makes it possible to estimate efficiently the biomass and oat grain yield under the conditions of use of the hydrogel as a function of the nitrogen doses and maximum air temperature, adding to the existing models of simulation.

Acknowledgment

To the CAPES, CNPq, FAPERGS, the UNIJUÍ and to IFRS for the financial support to the research and for the Scientific and Technological Initiation Scholarship, Postgraduate Scholarship and Research Productivity Grant. To the Graduate Program in Mathematical Modeling at UNIJUÍ for the resources available in the development of this research, which was part of the master's thesis of the first author of this work.

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