engenharia agrícola

Journal of the Brazilian Association of Agricultural Engineering
ISSN: 1809-4430 (on-line)

FUZZY MODELING ON WHEAT PRODUCTIVITY UNDER DIFFERENT DOSES OF SLUDGE AND SEWAGE EFFLUENT

Doi:http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v37n6p1103-1115/2017

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ABSTRACT: This study aimed to evaluate the effects of fertilization with composted sewage sludge and irrigation with drinking water (DW) and fertigation with wastewater (WW) in wheat crop using fuzzy rule-based system. The experiment was conducted in the Department of Soil and Environmental Resources, of FCA, UNESP - Botucatu, with factorial 6 × 2, which were applied 6 doses of sewage sludge (0, 50, 100, 150, 200 and 250% of nitrogen recommendation) and two types of effluents (treated water and sewage). In the developing of the system based in fuzzy rules, it was used the Mamdani inference method, where the input variables were sewage sludge doses and water types and the output variables used were the number of tillers, length and number spike per plant; number of spikelet per plant, grain mass per spike and dry mass of the aerial parts. It can be seen that the sewage sludge and the effluent contributed to the higher increase of production, and at 150% sludge dose occurred higher production.

KEY WORDS: sustainability, nitrogen, Mamdani, fuzzy system.

INTRODUCTION

The increasing population in Brazil makes the sanitation network present in all cities, so the treatment of effluents of the population should be increasingly efficient in order to reduce the number of transmittable diseases and water contamination (Vilani & Machado, 2015). The vestige from the treatment is called sewage sludge which is allocated in sanitary landfills, and the total cost for the sludge disposal can reach 50% of the operating cost of a wastewater treatment plant (WWTP) (Lobo et al., 2014).

The use of sewage sludge is highly promising for agricultural purposes because it is an organic fertilizer, so its use can reduce the application of mineral fertilizer and provide organic matter (Lobo et al., 2015).

The residual water originating from treatments is rich in essential nutrients for the plant, and also features a sustainable potential due to the possibility of rationalizing its use, reduction of pollution, environmental degradation, economic fertilizer, preservation and conservation of soil, and increasing agricultural production (Silva et al., 2014). It should be noted that Brazil currently has no relevant legislation for the reuse of wastewater for agricultural purposes.

To check the effects of sewage sludge and sewage effluent, the use of statistical models would be appropriate however due to its printing becomes more interesting modeling based on fuzzy rules in which Putti (2015) found that fuzzy models were more accurate than the regression models. The modeling based on fuzzy rules aims to contribute to the presentation of generalization of results as well as the modeling of specific intervals analyzed (Blanco-Fernández et al., 2014; Ross, 2010; Coppi et al., 2006).

The mathematical algorithms help decision making and optimization, as in the case of the application of artificial neural networks as an alternative to volumetric water balance in drip

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Received in: 8-19-2016
Accepted in: 7-7-2017

irrigation management in watermelon crop (Rocha Neto et al., 2015). It is also worth noting the work in which the application of algorithms helps to determine the vitality of orchids in relation to global warming (Putti et al., 2017).

This study aimed to evaluate the effects of fertilization with composted sewage sludge and irrigation with drinking water (DW) and fertirrigation with wastewater (WW) in wheat crop using fuzzy rule-based system.

MATERIAL AND METHODS

Experiment Description

The experiment was developed by Kummer (2013) which was conducted in pots arranged in a greenhouse at the Department of Soil and Environmental Resources belonging to the College of Agricultural Sciences at the Universidade Estadual Paulista "Julio de Mesquita Filho", FCA / UNESP, Botucatu / SP. Kummer (2013) classified the soil used in the experiment is originally as Dystrofic Oxsoil (Santos, 2013). Before the establishment of the experiment, in the same pots were cultivated two consecutive cycles of wheat and soybeans planted in May and November 2011, respectively, with application of composted sewage sludge (CSS) and irrigation with potable water (PW) and wastewater (WW), following the same experimental setup and the same research structure. Therefore this study started from the third application of composted sludge (Kummer, 2013).

The seeding took place in May 2012, which were sowed 30 seeds per pot of CD150 cultivar. At the time of seeding a template was used to provide the correct distribution in the pot. After emergence was performed plant thinning, leaving 24 plants per pot (KUMER, 2013).

A completely randomized design was adopted with two types of water (drinking water and wastewater) and 6 levels of nitrogen fertilization, totaling 12 treatments with 10 repetitions. Nitrogen fertilization was based on the N dose recommended (80 kg N ha^{-1}) for the full development of the culture (Raij et al., 1997). In treatments with composted sewage sludge, fertilization levels were defined on the basis of partial, total or higher replacement of the recommended N rate by the equivalent of this element present in the composted sewage sludge.

Distribution of treatments in the experimental plots follows the principle of randomization and were defined as follows: N1 = without nitrogen fertilization; N2 = 50% mineral nitrogen fertilizer + 50% nitrogen fertilizer from composted sewage sludge – CSS (totaling 80 kg N ha^{-1}); N3 = 100% of nitrogen fertilizer from the CSS (80 kg N ha^{-1} from sludge); N4 = 150% of nitrogen fertilizer from the CSS (120 kg N ha^{-1}, via sludge); N5 = 200% of nitrogen fertilizer from the CSS (160 kg N ha^{-1} via sludge); N6 = 250% of nitrogen fertilizer from the CSS (200 kg N ha^{-1}, via sludge).

The quantities of composted sewage sludge were calculated based on the nitrogen content in the organic material and mineralized fraction of N that was 30%, since the rates established by Resolution CONAMA nº 375/2006 are based on North American values, specific to soils of temperate climate different from tropical conditions (Andrade et al., 2010). It was considered for 100 kg of sludge in dry basis we have 1.1 kg of N and 30% of this N will be mineralized in the first year.

All treatments received complementary chemical fertilizers with P_2O_5 and K_2O (Raij et al., 1997) in order to standardize the soil in 150 mg dm^{-3} of P and 80 mg dm^{-3} of K.

The composted sewage sludge originated from the sewage treatment plant - STP from the city of Jundiaí-SP, and the wastewater was from the sewage treatment plant - STP of Botucatu-SP. Information on the characteristics of sewage sludge and wastewater is in Kummer (2013).

The water supply to the plants was carried out through drip irrigation, daily in order to restore the amount of water used by the plant due to the culture evapotranspiration, daily estimated from the evaporation of the water from a Class A tank, located in the center of the agricultural greenhouse.

The following parameters were evaluated from productivity components: dry mass of the aerial part, represented by the stem mass sum + mass of leaves excluding the spikes and roots (g pot^{-1}); number of spikes per plant; spike length (cm); number of spikelet per spike; number of grains per spike; mass of grains per spike, corrected to 13% of moisture (g).

Drafting method of fuzzy system

The fuzzy mathematical model proposed in this study sought to explain the wheat crop productivity characteristics when subjected to different doses of sewage sludge and fertirrigation with wastewater and potable water in the intermediate intervals to the factors levels of the agronomical experiment carried out, namely $[0\%, 50(k+1)\%], 1 \leq k \leq 4$. In the levels of $50k\%, 1 \leq k \leq 4$, and for the two types of water, being potable water (PW) and wastewater (WW), and the output variables were the number of tillers, number of spike per plant, spike length, number of spikelet per spike, grain mass by spike, dry mass per aerial part per pot, number of grains per spike and mass of 100 grains.

Considering an agronomic model characteristics, thus we have $f: \mathbf{X_1} \times \mathbf{X_2} \subset \mathbb{R}^2 \rightarrow \mathbb{R}^7$ on which $\mathbf{X_1}$ is "Water Type" and $\mathbf{X_2}$ is "N doses" with $y = f(x^-)$, wherein $\mathbb{R}$ is the set of real numbers; wherein $x = (x_1 1, x_1 2)$ **is defined by** $x_1 1$ = "Type of water" $x_1 \in \mathbf{X_1} = \{0.1\}$; and x_2= "Doses of N", with $x_2 \in \mathbf{X_2} = \{0.250\}$; and $y = (y_1, \ldots, y_5)$, is defined by the mean values of biometric characteristics, namely $y_1 = \overline{NT}$, $y_2 = \overline{NSP}$, $y_3 = \overline{SL}$, $y_4 = \overline{NSLS}$, $y_5 = \overline{GWS}$, $y_6 = \overline{SDW}$ and $y_7 = \overline{W100}$

This system based on fuzzy rules represents the function $F: [0.1] \times [0.250] \rightarrow \mathbb{R}^7, F(x,y) = (f_1(x,y), f_2(x,y), f_3(x,y), f_4(x,y), f_5(x,y), f_6(x,y) f_7(x,y))$, where the Cartesian product that represents the area of water type ratings (potable water or wastewater) and N levels (0 to 250%) in which the $\mathbb{R}^7$ codomain represents the seven response variables evaluated in the experiment. Figure 1 shows the model in which is observed the inputs and outputs.

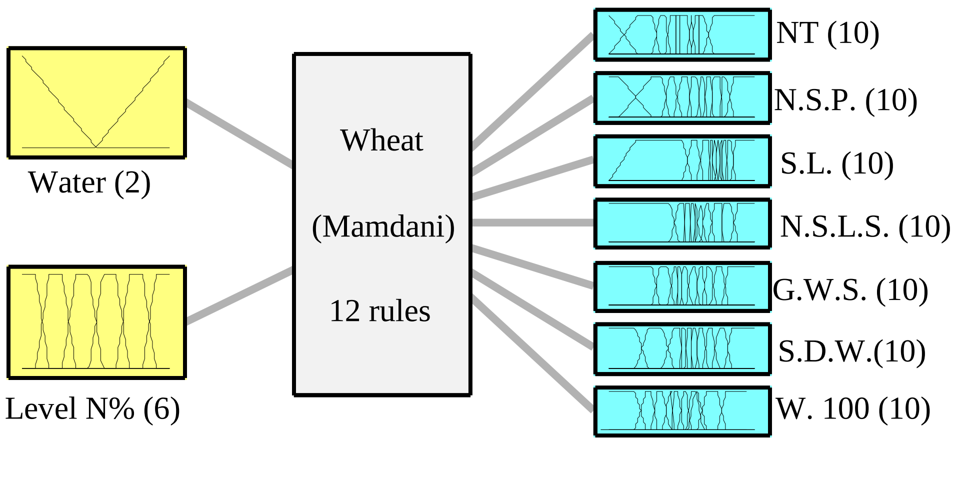


FIGURE 1. System based on fuzzy logic to evaluate the wheat crop in which "Water" represents the two types of water (potable water and wastewater) and "N Level" represents nitrogen levels provided by sewage sludge.

Legend: NT: number of tillers; NSP: Number of spike per plant; SL: spike length; NSLS: number of spikelet per spike; GWS: grain weight per spike; SDW: shoot dry weight; W100: weight of a hundred grains.

Fuzzy sets developed

Input variables

To define the input variable "Levels of N%" were adopted fuzzy sets of trapezoidal type according to Yet (2009) since it is a set presenting one continuous variable, the trapezoidal set model fits best the model response, as for the variable "Water", it was adopted the triangular sets because the variables are crisp. Thus, the adoption of two sets with "Potable Water" and "Wastewater" was possible to carry out the drafting of Table 1.

TABLE 1. Definitions of fuzzy sets with their respective degree of membership of the input variable "Water".

Fuzzy set	Type	Delimiters
Wastewater	Triangular	[-0.5 10.5]
Potable Water	Triangular	[0.5 11.5]

For the input variable "Level of N (%)", six fuzzy sets were considered by L_i, i = 1, 2, 3, 4, 5, 6. This definition is due to the fact that the agronomic experiment conducted there were six dimensioned nitrogen levels according to the need of the wheat crop, namely $(50i)\%, \quad i = 0, \quad 1, 2, 3, 4, 5$. Pertinence function was adopted (trapezoid) for L_i sets.The calculation of the delimiters was based on Putti (2015) where the functions were defined, so that each tested level of nitrogen has a pertinence degree equal to 1 for its corresponding fuzzy set $\left(u_{L_i}(50i\%) = 1\right)$ and, in addition, $u_{L_i}(x) = 1, x_{i-1} \leq x \leq x_{i+1},$ with $x_{i+1} - x_{i-1} = k$, to a certain k , in which 11$k = 250\%$, since it was adopted in this study Degree of membership. Thus, for the determination of the eleven sets delimiters and aiming a symmetrical variation between the delimiters it was used the following equation:

$$k = \frac{x_{max} - x_{min}}{2n - 1} \Rightarrow k = \frac{250\% - 0\%}{11} \Rightarrow k = 22.73\% \quad (1)$$

where,

x_{max} is the highest valued point;

x_{min} is the minimum valued point, and

n is the number of fuzzy sets.

To the variance of “Level of N (%) " were adopted 6 sets from the levels established in the conducted experiment “L1”, “L2”, “L3”, “L4”, “L5” and “L6”, referring to levels of 0%, 50%, 100%, 150%, 200% and 250% of Nitrogen dose. From the developed method it was possible to design Figure 2.

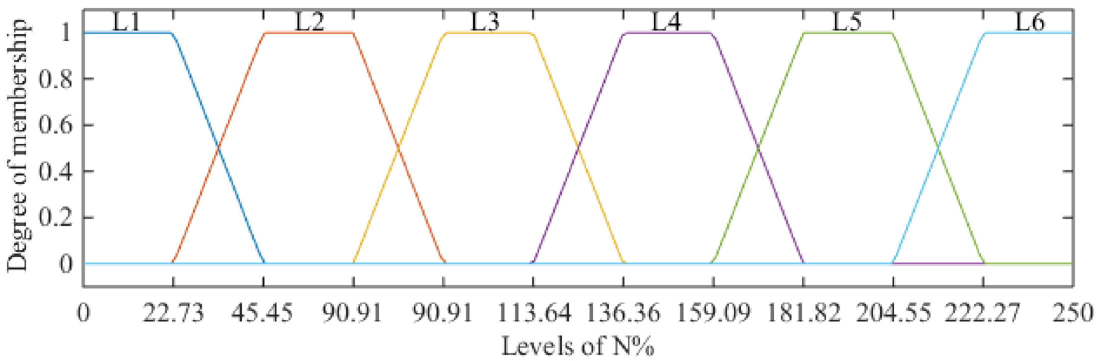


FIGURE 2. Degree of membership definitions on the input variables "fertirrigation depth."

Output variables

The output variables were chosen by electing the variables of the observed production components analysis that showed significant differences (p<0.001).

So for the determination of fuzzy sets, it was based on Cremasco et al., (2010), Gabriel Filho et al. (2011, 2016) and Putti et al., (2014, 2015), who defined ten fuzzy set, C_n, $m = 1, 2, ..., 10,$ with trapezoidal Degree of membership. Calculating the various delimiters that enabled to define the trapezoidal shape of the ten pertinence sets, it was needed 19 delimiters that were adopted as percentiles from the measured data sets of each output variable. Such percentiles in $x\%$, denoted by $P(x\%)$, depend on a constant k , since19 necessary delimiters are from the form $P(mk)$, $0 \leq m \leq 18$. The constant k is calculated as:

$$k = \frac{x_{max} - x_{min}}{2m - 1} \Rightarrow k = \frac{100\% - 0\%}{19} \Rightarrow k = 5.26\%$$

where,

x_{max} is the peak observed point for the output variables;

x_{min} is the minimum observed point for the output variable, and

n is the number of fuzzy set.

It was adopted the same procedure from the input variables in order to adjust the model, at the 1st point of the "C1" set it was adopted the value $P_1 - k$, and at the 4th point of the "C10" set, the value $P_{19} + k$, as shown in Figure 3.

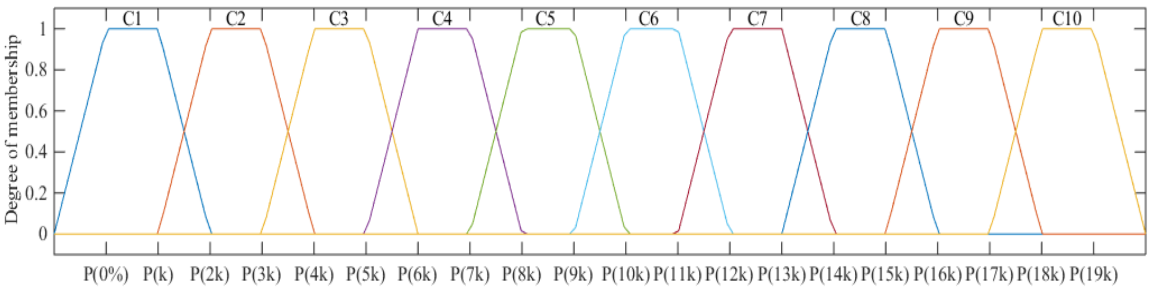


FIGURE 3. Degree of membership defined for the fuzzy set of output variables.

Rules Base

From the base rule developed by the fuzzy system, which demonstrates how the system model the results. Based on the premise of the fuzzy rule where:

- If "premise (antecedent)" then "conclusion (consequent)", it was possible to calculate the model outputs from the combination of the established factors as *inputs*.

Such expression is referred as the form of rule based on cause and effect. The rules base created for the proposed fuzzy model were based and developed by Cremasco et al. (2010) and Gabriel Filho et al. (2011; 2016), in which, after the preparation of the output fuzzy sets were calculated the highest pertinence degree of each median of the treatments, thereby associating the input variables with the output. From the input variables it was possible to create 12 pairs of rules ($Type\ of\ Water \times Levels\ of\ N\%$) and associated with 7 output variables.

TABLE 2. Combinations of input variables with points of *pertinence* degree 1 associated with the fuzzy sets for the construction of the rules base.

Input variables		
Days after Transplanting		Type of water
Fuzzy set	Point with pertinence degree associated to 1	
D1	0	PW
D2	50	PW
D3	100	PW
D4	150	PW
D5	200	PW
D6	250	WW
D1	0	WW
D2	50	WW
D3	100	WW
D4	150	WW
D5	200	WW
D6	250	WW

Legend: PW: potable water; WW: wastewater; L: N doses

Inference method and Defuzzification

The inference method adopted in the model, was proposed by Mamdani & Assilian (1975), as in this study the propositions of the antecedent and consequent are fuzzy propositions, and that according to Ross (2010) is the most common method practiced in the literature.

To calculate the defuzzyfication of the system was considered the aerial center method or centroid, which is the most commonly used technique and presents the results closer to those observed (Ross, 2010; Lababidi & Baker), this method can be calculated as follows:

$$y = \frac{\sum_x \mu_a(x)x}{\sum_x \mu_a(x)}$$

Statistical analysis

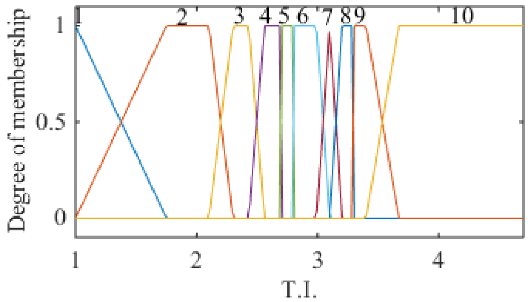
In order to verify the relationship of the variables, Pearson's correlation was applied to the variables under study, we adopted a to verify the significance α = 5%

RESULTS AND DISCUSSION

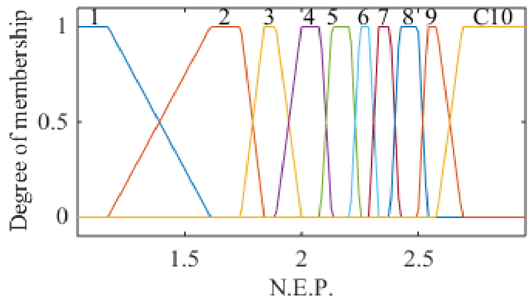
From the developed models, first were obtained the results for the development of the SBFR, which will be presented in the theoretical results topic and followed models of simulations were performed that will be presented on the practical results topic.

Theoretical results

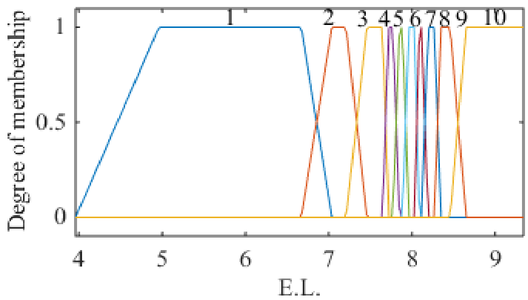
After the development of SBFR was obtained fuzzy set for the output variables, which represented the wheat yield components (Figure 4).



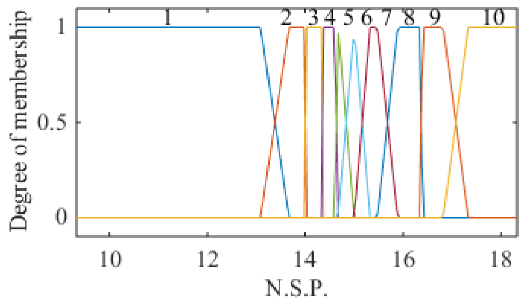
(a) Number of tillers per plant [-]



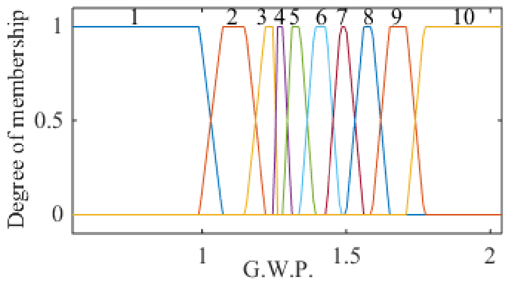
b) Number of spikes per plant [-]



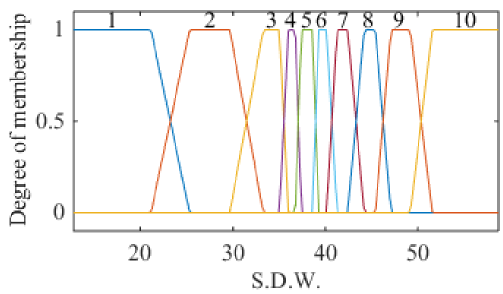
c) Spikes length [mm]



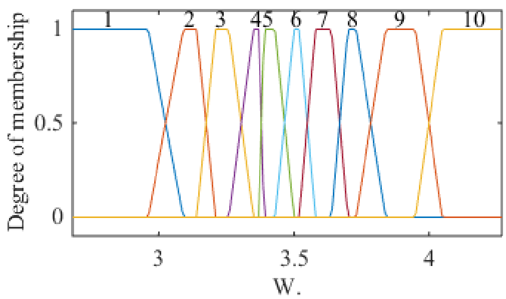
d) Number of spikelet per spike [-]



e) Grain weight per Spike [g]



f) Shoot dry weight (g)



g) Weigh to f100 grain (kg)

FIGURE 4. Degree of membership of fuzzy set for the output variables of wheat crop fertirrigation with wastewater and potable water with different levels of nitrogen.

The rule base of the fuzzy system proposed was developed from the methodology in which determined the highest pertinence degree of the analyzed variable in the condition verified experimentally, for example, for the treatment in which was adopted the wastewater and the dose 0 of N, it was obtained the values for the production components (Table 3).

TABLE 3. Rules bases of the fuzzy system for the evaluation of wheat production components subjected to different N doses and water types.

Types of water	Doses of N	NT	NSP	SL	NSLS	GWS	SDW	W100
WW	0	C3	C3	C3	C4	C4	C2	C5
WW	50	C6	C8	C7	C7	C5	C8	C4
WW	100	C7	C7	C5	C6	C4	C6	C6
WW	150	C6	C6	C6	C7	C5	C6	C4
WW	200	C8	C8	C6	C6	C5	C8	C4
WW	250	C8	C8	C8	C7	C7	C7	C9
DW	0	C2	C2	C2	C2	C3	C2	C6
DW	50	C4	C5	C4	C6	C6	C5	C7
DW	100	C3	C3	C7	C7	C9	C4	C7
DW	150	C7	C6	C10	C10	C9	C8	C4
DW	200	C8	C7	C8	C9	C8	C9	C7
DW	250	C8	C9	C6	C6	C9	C8	C9

Legend: NT: number of tillers; NSP: Number of spike per plant; SL: spike length; NSLS: number of spikelet per spike; GWS: grain weight per spike; SDW: shoot dry weight; W100: weight of a hundred grains.

Model Simulation

For wheat production components was carried out at first, the correlation analysis between variables in order to verify the degree of intensity among them, thereby assisting in the discussions of the results obtained from the model (Table 4).

TABLE 4. Correlation between the variables with significant difference.

	NSP	SL	NSLS	GWS	SDW	M100
Tillers	0.804*	0.648*	0.469*	0.432*	0.808*	0.113^{NS}
NSP	-	0.552*	0.347*	0.246*	0.765*	0.127 ^{NS}
SL	-	-	0.741*	0.725*	0.748*	-0.006 ^{NS}
NSLS	-	-	-	0.553*	0.565*	0.033 ^{NS}
GWS	-	-	-	-	0.572*	0.126 ^{NS}
SDW	-	-	-	-	-	0.049 ^{NS}

Legend NT: number of tillers, NSP: Number of spike per plant; SL: spike length; NSLS: number of spikelet per spike; GWS: grain weight per spike; SDW: shoot dry weight; M100: weight of a hundred grains. NS: Not significant; * Significant p <0.001.

It can be inferred that only the weight of a hundred grain showed no significant correlation (p < 0.001) with the other variables. From this analysis was noted that the spikelet length × the weight of grain per spike showed significant relationships, wherein the longest length of spike may have helped in the development of the grain due to a greater area or have contributed to the higher number of grains. It was found that the tiller number showed significant positive relationship with other components. Thus influence significantly to the higher dry weight per pot, except the weight of hundred grains.

From the fuzzy model developed was verified the effects of wastewaters and different doses of sewage sludge in wheat crop and the effects were determined for the production of components. In the analysis of the number of spikes and tillers per plant, it can be seen that the doses of N provided by sewage sludge up to 150% N showed higher amount when irrigated with wastewater (Figure 5).

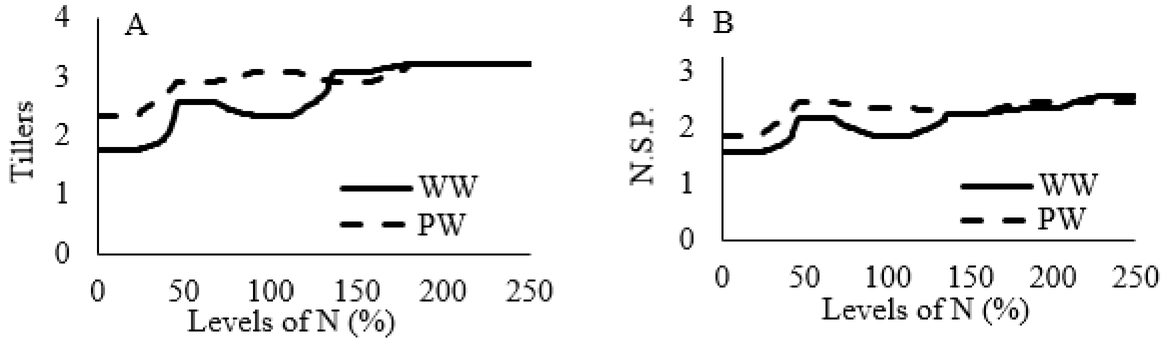


FIGURE 5. Number of tillers per plant (A); number of spikes per plant (B), for wheat crop under different N levels and type of water.

Irrigation using potable water to dose 150% of N resulted in more tillers, and consequently of spikes per plant, from this dose it was not observed any difference, reaching the highest value observed for both variables. Nitrogen is the most required element for plant growth, wherein the excess can cause layering of wheat grown due to the growth and then reduce productivity (Zhang et al., 2014; Cormier et al., 2013).

Another factor that may have led to further development of production components is slow nitrogen mineralization into organic form (Taiz & Zeiger, 2009), which is contained in sewage sludge and wastewater and it is known as having a high nitrogen content.

Díaz-Rojas et al. (2014) found that wheat crop when irrigated with wastewater provided greater number of tillers and also favored for higher spikelet number per plant. They were also observed by Hossain et al. (2015), thus corroborating with the observation in this study.

The length of the wheat spike and the number of spikelet per plant were determined, and was found a significant correlation ($R^2=0.55$; $p<0.001$) between the variables and both exhibit the same behavior as a function of nitrogen doses (Figure 6).

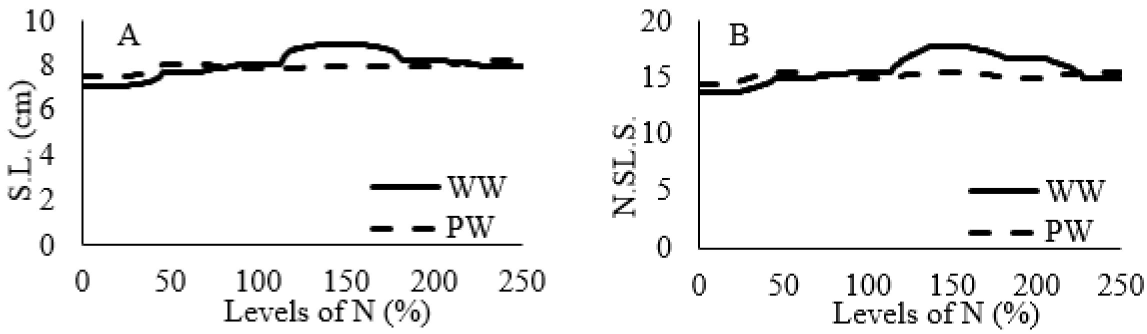


FIGURE 6. Spike length (A) and number of spikelet per spike (B) for the wheat crop under different N levels and types of water.

The length of spike and the number of spikelet showed similar behavior in doses up to 100% N irrigated with potable water providing higher production from that dose of wastewater, which contributed to the further development of these components. These results are due to the high N content in the sludge and wastewater (Duarte et al., 2008).

The rice crop irrigated with wastewater and fertilized with sewage sludge provided greater spike length (Latare et al., 2014). Martínez et al., (2013) found that when wheat cultivars were fertirrigation with different levels of wastewater and sludge doses provided similar behavior to that obtained in this study with better development when irrigated with wastewater.

It was found the greater weight of grain per spike and 100 grains to the wheat crop when subjected to irrigation with wastewater and that the sewage sludge doses also contribute to the increased weight of these components (Figure 7).

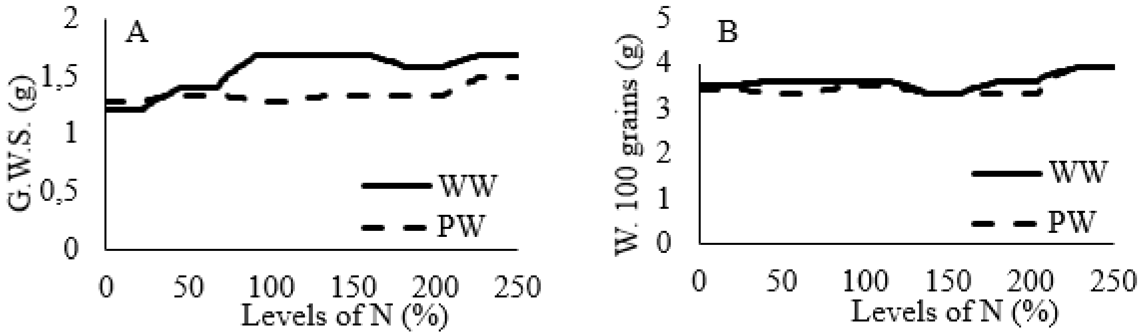


FIGURE 7. Grain weight per spike, (A) and weight of 100 grains (B) for wheat crop under different N level and types of water.

The grain mass per spike was higher in the range of 100% to 200% N, and in this interval occurred greater spike length, which these variables showed significant correlation ($R^2 = 0.725$ $P < 0.001$) and can state that the spike length showed higher amount of grain and not larger grain size. This fact explains why the weight of 100 grains did not show significant correlation with other production components, and did no show greater weight variance in this component.

Xie et al. (2015) and Li et al., (2015) observed that for the corn crop there was greater grain weight per Spike, with greater length and width of it due to higher availability of N in the wastewater. When applied “manipueira” effluent, it showed higher development for corn crop because it was noted that there was a greater availability of N for the plant from the effluent (Barreto et al., 2014).

Thus, the application of sewage sludge in order to meet the need for nitrogen causes greater development of the plant, then contributing to higher grain yield and not grain size, therefore providing higher production.

The shoot dry weight per pot of wheat showed greater accumulation after the dose of 100% N and fertirrigation with wastewater (Figure 8).

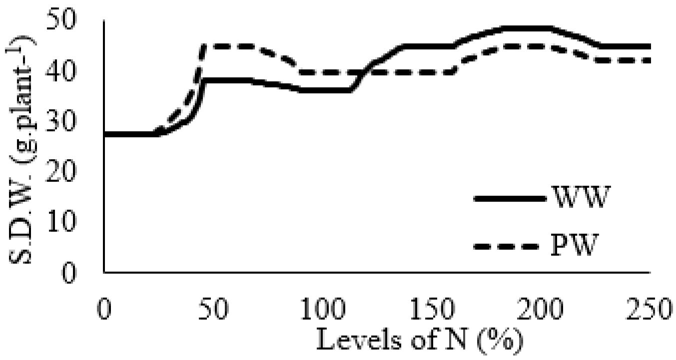


FIGURE 8. Shoot dry weight per pot of wheat.

The application of potable water only influenced until the dose of 100% of N; after this levels the wastewater contributed to the higher dry matter accumulation. This fact is due to high concentrations of N in the soil provided by sewage sludge and wastewater, as due to non-volatilization and leaching of nitrogen, unlike that occurs when applied urea, may have caused higher dry matter accumulation. Nitrogen provided by different effluents has the same behavior in provide dry matter accumulation as noted by Júnior et al., (2015).

CONCLUSIONS

It can be concluded that the fuzzy model developed is possible to observe the wheat crop behavior when submitted to different nitrogen levels and types of water.

The availability of nitrogen from sewage sludge application contributes to greater development of production components. It should be noted that there was no greater weight of 100 grains, but the highest number of grains per spike, as occurred greater length of the spike. This fact was caused by the release of nitrogen along the cycle and did not occurring volatilization and / or leaching.

ACKNOWLEDGEMENTS

To the Minas Gerais State Agency for Research and Development for (APQ-00498-16), to the UNESP by postdoctoral granted to the first author (Process 408/2015), and to National Council for Scientific and Technological Development (CNPq) by Productivity in Research scholarship granted to the fourth author (Process 306964/2014-7).

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