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Fuzzy control systems for decision-making in cultivars recommendation

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ABSTRACT. The objective of the present study was to propose fuzzy control systems to support the recommendation of cultivars of different agronomic crops. Grain yield data from 23 lines and 2 cultivars of red bean were used to evaluate the applicability of these controllers. Genotypes were evaluated in nine environments in the Zona da Mata region, Minas Gerais State, Brazil. Using the parameters of Eberhart and Russell analysis, fuzzy controllers were developed with the Mamdani and Sugeno inference systems. Analyses of adaptability and stability were carried out by the method of Eberhart and Russell. The parameters obtained for each genotype were submitted to the respective controllers. There were significant genotypes x environments interaction, which justified the necessity of performing an adaptability and stability analysis. For both controllers (Mamdani and Sugeno), seven lines presented general adaptability, while only one presented adaptability to unfavorable environments. It was also found that both inference systems were useful for developing controllers that had the aim of recommending cultivars. Thus, it was noted that fuzzy control systems have the potential to identify the behavior of bean genotypes.

Keywords: common bean; adaptability and stability; computational intelligence.

Sistemas de controle fuzzy para tomada de decisão na recomendação de cultivares

RESUMO. O presente estudo tem como objetivo propor sistemas de controle fuzzy para auxiliar na recomendação de cultivares de diversas culturas agronômicas. Para avaliar a aplicabilidade desses controladores foram utilizados dados de produtividade de grãos de 23 linhagens e duas cultivares de feijão do grupo comercial vermelho, avaliados em nove ambientes da Zona da Mata do Estado de Minas Gerais, Brasil. A partir dos parâmetros da análise de Eberhart e Russell foram desenvolvidos controladores fuzzy com sistemas de inferência Mamdani e Sugeno. Foram realizadas análises de variância conjunta e de adaptabilidade e estabilidade pelo método de Eberhart e Russell e os parâmetros obtidos para cada linhagem foram submetidos aos respectivos controladores. Verificou-se a ocorrência de interação genótipos por ambientes significativa, existindo a necessidade da realização de análises de adaptabilidade e estabilidade. Em ambos os controladores (Mamdani e Sugeno), sete linhagens (2, 9, 14, 16, 17, 20 e 23) apresentaram adaptabilidade geral, enquanto que somente a linhagem 15 apresentou adaptabilidade a ambientes desfavoráveis. Verificou-se também que ambos os sistemas de inferência adotados, são úteis para desenvolver controladores que visam recomendação de cultivares. Assim, constatou-se potencialidade dos sistemas de controle fuzzy na identificação do comportamento das linhagens de feijoeiro.

Palavras-chave: feijão comum; adaptabilidade e estabilidade; inteligência computacional.

Introduction

The phenotypic value of an individual, when evaluated in an environment, is the result of the action of the genotypic effect on the influence of the environment to which it is subjected. However, when evaluating the same genotype in several environments, an additional component resulting from the interaction between genotypic and environmental effects is found (Cruz, Regazzi, & Carneiro, 2012). Ramalho, Abreu, Santos, and Rodrigues (2012) reported that this interaction is due to the variation of the individual performance of each genotype in several environments since gene expression is influenced and/or regulated by the environment (Kang, 1997).

Identification of genotype x environment interaction (G x E) is of great importance in plant breeding since genotypes may present different behaviors in relation to environmental variations. Thus, G x E interaction, as well as the effects attributed to dominance deviation, with epistasis and gametic disequilibrium are considered to be complicating agents by many plant breeding programs (Borém & Miranda, 2013; Cruz et al., 2012).

Since, in general, the phenotypic response of each genotype to environmental variations is different and reduces the correlation between phenotypic and genotypic values, it is necessary to carry out a large number of evaluations of genotypes in different cultivation environments to have greater accuracy for the selection or recommendation of cultivars. However, studies on quantification of the magnitude and nature of G x E interaction do not provide detailed information on the behavior of each genotype in relation to environmental variations (Cruz et al., 2012). Thus, an adaptability and stability analysis may assist in the recommendation of cultivars since they enable the identification of genotypes of predictable performance that are responsive to environmental variations (Silva & Duarte, 2006).

Several methodologies for performing an adaptability and stability analysis have been proposed to evaluate the behavior of genotypes in several environments. There are methods based on analysis of variance (Plaisted & Peterson, 1959; Wricke, 1965), regression (Cruz, Torres, & Vencovsky, 1989; Eberhart & Russell, 1966; Finlay & Wilkinson, 1963; Tai, 1971; Barroso et al., 2015), nonparametric methods (Lin & Binns, 1988; Rocha, Muro-Abad, Araújo, & Cruz, 2005; Nascimento et al., 2015), linear mixed models Reml/Blup (Resende, 2004), bayesian methods (Couto et al., 2015), and artificial neural networks (Barroso et al., 2013; Nascimento et al., 2013).

The great number of methods for determining adaptability and stability reflects the importance and complexity of studies in relation to G x E interaction. When choosing the method or methods to be employed, some aspects should be considered, such as the number of available environments, required accuracy, desired type of information, and ease of analysis and interpretation of results (Cruz et al., 2012). Some methods should also be considered to be alternatives, while others are complementary and can be jointly employed (Cargnelutti Filho et al., 2009). In bean crops, the method of Eberhart and Russell (1966) has been the most used method (Backes, Elias, Hemp, & Nicknich, 2005; Melo et al., 2007; Ribeiro, Antunes, Souza, & Poersch, 2008; Ribeiro, Souza, Antunes, & Poersch, 2009).

Since the strategies that are used to generate information for the recommendation of lines are varied or even complex and are usually associated with some difficulty in interpretation, there is the need to use and/or aggregate new approaches to assist breeders in making decisions. Accordingly, computational intelligence is an interesting approach that can be used in plant breeding since it has great potential and is widely consolidated in the computer field.

Fuzzy logic is a computational intelligence technique inspired that is inspired by human reasoning based on approximations and uncertainties. When this system is applied, it goes beyond Boolean logic, which offers true or false values for a particular element, while fuzzy logic assigns degrees of membership to elements (Klir & Yuan, 1995). This technique provides a method for translating qualitative and verbal expressions that are common to human communication into numerical values (Simões & Shaw, 2007). Thus, fuzzy logic allows the human experience to be converted into a form that is understandable by computers. Thus, the technology provided by the fuzzy approach has significant practical value, which allows it to include the experience of human operators in fuzzy control system, enabling decision-making strategies for complex problems.

The objective of the present study was to propose fuzzy control systems to support the recommendation of cultivars of different agronomic crops.

Material and method

To apply fuzzy logic to the recommendation of cultivars and determination of the behavior of genotypes, evaluation data on the yield (kg ha^{-1}) of 23 lines and two cultivars of red common bean, “Ouro Vermelho” and “Vermelhinho”, in nine experiments were carried out in the Zona da Mata region, Minas Gerais State, Brazil. Experiments were carried out in the 2009 dry season in the municipality of Florestal (lat. 19°53'22” S, long. 44°25'57” W, at 776 m asl); in the 2009 and 2010 dry seasons and 2013 rainy season in the municipality of Viçosa (lat. 20°45'14”S, long. 42°52'55” W, at 648 m asl); and in the 2009 winter season, 2010 dry season, 2012 winter season and dry season, and 2013 dry season in the municipality of Coimbra (lat. 20°45' S, long. 42°51' W, at 690 m asl), totaling three municipalities in the state of Minas Gerais, Brazil.

The experiments were carried out in a randomized block design with three replications. Plots consisted of two 4-m rows, spaced 0.5 m apart. Planting, fertilization and crop handling were carried out according to the recommendations for bean crops in the region (Carneiro, Paula Júnior, & Borém, 2014).

Data from the experiments were subjected to joint analysis of variance to identify the G x E interaction. Furthermore, an adaptability and stability analysis was carried out according to the method of Eberhart and Russell (1966). These analyses were carried out using the GENES software (Cruz, 2013).

Stability and adaptability analysis

Method of Eberhart and Russell (1966)

Data were subjected to a stability and adaptability analysis by the method proposed by Eberhart and Russell (1966), which is based on a simple linear regression analysis and measures the response of each genotype in relation to environmental variations. This method considers that the regression coefficient of the phenotypic values for each genotype (β_1), in relation to the environmental index, provides an estimate of the adaptability parameter, while deviations of this regression (σ^2_{di}) and the coefficient of determination (R^2) provide estimates of the stability parameters.

For Eberhart and Russell (Eberhart and Russell, 1966), adaptability refers to the ability of genotypes to take advantage of environmental stimuli, classifying them into genotypes with wide and general adaptability ($\beta_1 = 1$), specific adaptability to unfavorable environments ($\beta_1 < 1$), or specific adaptability to favorable environment ($\beta_1 > 1$). This classification is based on the result of the *t* test for the parameter in question, in which the hypothesis of $\beta_1 = 1$ is evaluated. On the other hand, stability refers to the ability of genotypes to show predictable behavior to environmental stimuli. Genotypes can be classified according to the variance component that is attributed to regression deviation (σ^2_{di}) with high predictability ($\sigma^2_{di} = 0$) or with low predictability ($\sigma^2_{di} > 0$). In this case, the hypothesis of $\sigma^2_{di} > 0$ is evaluated by the test based on the F distribution. The coefficient of determination (R^2) is also considered as a parameter that reflects the predictability of the behavior of genotypes, in which a larger value of R^2 signifies greater predictability.

Eberhart and Russell (1966) consider the genotype that has a high mean production (β_o), coefficient of regression (β_1) equal to 1, high coefficient of determination (R^2), and regression deviation (σ^2_{di}) as low as possible (or not significant at a certain level of probability) to be ideal. Oliveira et al. (2002) considered that genotypes with a coefficient of determination (R^2) above 80% have high stability.

Fuzzy Control System

To establish a support system for the recommendation of cultivars, fuzzy controllers were developed for use in the method of Eberhart and Russell (1966). All controllers were developed with the aid of the Matlab software (2016) and were implemented in the BIOFUZZY software, available in www.fenomica.com.br.

Fuzzy Controller - Eberhart and Russell (1966)

For the method of Eberhart and Russell (1966), two fuzzy controllers were developed. One was based on the fuzzy inference system proposed by Mamdani (Mamdani and Assilian, 1975), while the other was based on the inference system proposed by Sugeno (Sugeno & Kang, 1988a; Sugeno & Kang, 1988b; Sugeno & Tanaka, 1991; Sugeno & Yasukawa, 1993; Takagi & Sugeno, 1985). In both controllers, the following parameters were used as input fuzzy linguistic variables: the overall mean (β_o), coefficient of regression (β_1), and coefficient of determination (R^2). For each variable, fuzzy sets were generated by means of membership functions, which allowed the classification of each genotype regarding the variable in question by the fuzzyfication process.

The overall mean was placed on the “Low” and “High” fuzzy sets by means of the membership functions of the Z form (‘*zmf*’) and S form (‘*smf*’), respectively (Figure 1A). The overall means of genotypes were standardized to a scale from 0 to 100 since the objective was to develop an overall algorithm for different agronomic crops and for those characteristics in which there is an interest in obtaining higher mean values. Standardization was based on the normal distribution of the data, on the overall mean value (μ), and on the standard deviation (σ) of these data. The values associated with μ - 3σ were assigned a value of 0, and the values associated with $\mu + 3\sigma$, were assigned a value of 100.

The values of the coefficient of regression (β_1) were allocated in sets of “Lower than 1”, “Equal to 1” and “Higher than 1”, by means of the membership functions Z form (‘zmf’), “π“ form (“pimf”), and S form (‘smf’), respectively (Figure 1B). In this classification, it was taken into consideration that the genotypes that presented a membership greater than 50% for the ‘Equal to 1’ set would present β_1 values that were statistically equal to 1 according to Student’s *t* test. The original β_1 values of each genotype, when subjected to the controller, were standardized to a scale of -5 to 7 since the first value was equidistant from the ends of this scale. This standardization was based on the *t* test confidence interval, which was based on the *t* distribution. The lower limit of the confidence interval was assigned a value of -2, and the upper limit was assigned a value of 4 (Figure 1B).

The values of the coefficients of determination (R^2) were allocated in the 'Low' and 'High' fuzzy sets by means of the membership functions Z form ('*zmf*') and S form ('*smf*'), respectively (Figure 1C). R^2 was not standardized since this parameter has a common scale to any agronomic trait.

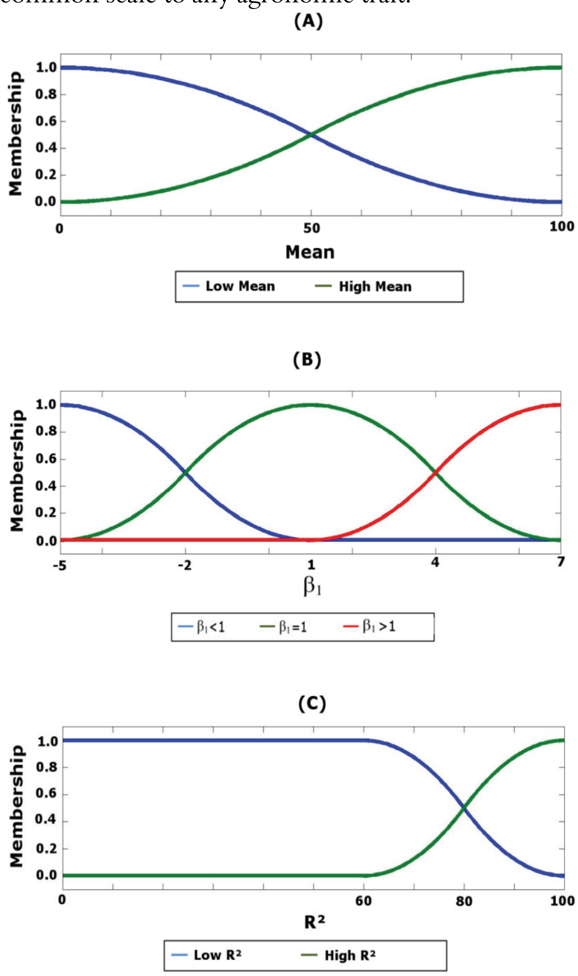

Figure 1. Input fuzzy variables (Mean, β_1, and R^2) used in the developed controllers.

For the fuzzy controller based on the inference system proposed by Mamdani (Mamdani & Assilian, 1975), an output fuzzy linguistic variable named "Mamdani Behavior" was generated with a scale ranging from -100 to 100. The values of 'Mamdani Behavior' were allocated into five fuzzy sets based on the performance of the adaptability and stability of the evaluated genotypes: "unfavorable general" (GD) "unfavorable" (UNF), "poorly adapted" (PA), "favorable" (FAV) and "favorable general" (GF) (Figure 2A). For "general behavior", it was considered both 'unfavorable general' and 'favorable general'.

For the fuzzy controller based on the inference system proposed by Sugeno (Sugeno & Kang, 1988; Sugeno & Tanaka, 1991; Sugeno & Yasukawa, 1993; Takagi & Sugeno, 1985), the same input variables of the controller were used, which used the Mamdani inference system. However, for the fuzzy controller based on the inference system proposed by Sugeno, a linguistic fuzzy variable named "Sugeno Behavior" was generated, with a scale ranging from 0 to 100. This variable was allocated into 4 "singletons", which were specific sets of this inference system, based on constant functions: 'poorly adapted' (f (x) = 25), 'unfavorable' (f (x) = 50), 'favorable' (f (x) = 75), and 'general' (f (x) = 100) (Figure 2B).

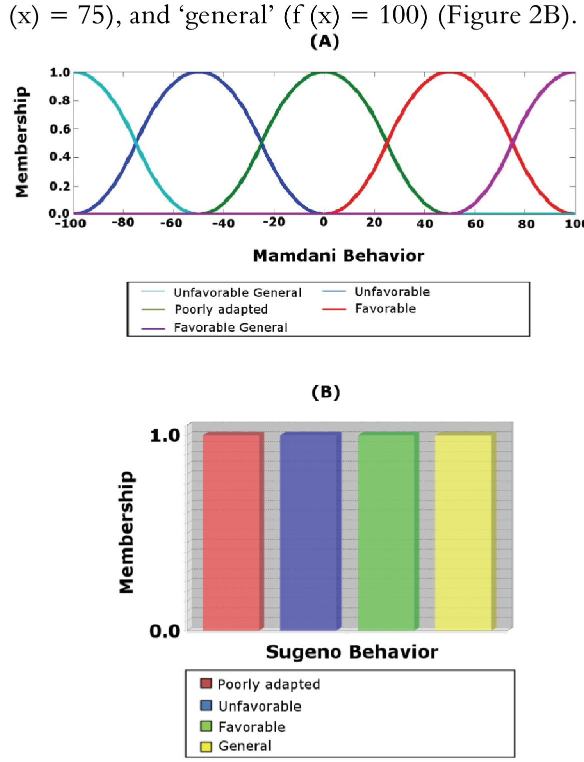

Figure 2. Output fuzzy variables ("Mamdani Behavior" and "Sugeno Behavior") used in the developed controllers.

The combination of fuzzy sets for each variable into linguistic fuzzy rules based on each inference system allowed the development of controllers that were able to determine the behavior of each evaluated genotype. The rules used in the developed fuzzy controllers (Table 1) were based on the interpretation of the parameters of the method proposed by Eberhart and Russell (1966) to apply a consensus that is provided in the literature regarding decision-making for this method (Cruz et al., 2012).

Table 1. Language fuzzy rules implemented in the fuzzy controllers (Mamdani and Sugeno) based on the method of Eberhart and Russell (1966).

Inputs			Outputs	
Mean	β_1	R^2	Mamdani Behavior	Sugeno Behavior
Low	Lowerthan 1	Low	*Poorly adapted*	*Poorly adapted*
Low	Lowerthan 1	High	*Poorly adapted*	*Poorly adapted*
Low	Equalto 1	Low	*Poorly adapted*	*Poorly adapted*
Low	Equalto 1	High	*Poorly adapted*	*Poorly adapted*
Low	Higher than 1	Low	*Poorly adapted*	*Poorly adapted*
Low	Higher than 1	High	*Poorly adapted*	*Poorly adapted*
High	Lowerthan 1	Low	*Poorly adapted*	*Poorly adapted*
High	Lowerthan 1	High	*Unfavorable*	*Unfavorable*
High	Equalto 1	Low	*Poorlyadapted*	*Poorly adapted*
High	Equalto 1	High	*Unfavorable general*	*General*
High	Equalto 1	High	*Favorable general*	*General*
High	Higher than 1	Low	*Poorly adapted*	*Poorly adapted*
High	Higher than 1	High	*Favorable*	*Favorable*
High	Lowerthan 1	Low	*Poorly adapted*	*Poorly adapted*

Once the ideal fuzzy controllers were developed, the estimated parameters (β_0, β_1, and R^2) of the 23 lines and 2 cultivars of red bean cultivars were subjected to the controllers to determine the behavior of these lines by means of the membership values obtained in the controllers.

Result

Table 2 shows a summary of analysis of variance regarding the grain yield of the 23 lines and 2 cultivars of red bean cultivars that were evaluated in nine experiments. There was a significant effect ($p < 0.01$) for G x E interaction (Table 2), indicating differential behaviors of the genotypes in relation to environmental variations. There was no significant effect for the effects of the genotypes. The coefficient of variation was 13.1 for this characteristic, indicating high experimental precision.

Table 2. Summary of analysis of variance on the grain yield of 23 lines and two bean controls in nine experiments.

FV	GL	QM	F	Probability
Blocks/Environments	18	629749,03	-	-
Genotypes (G)	24	441112,68	1,25	20,29^{ns}
Environments (E)	8	27685321,36	43,96	0,00**
G x E	192	352444,94	2,873	0,00**
Residue	432	122683,46		
Mean	2674,53			
CV (%)	13,10			

** significant by the F test, at 5% probability. ns: not significant.

The standardized averages of lines and cultivars ranged between 8.2% (Vermelhinho) and 90.5% (L19) (Table 3). It was verified that 11 lines presented standardized averages higher than 50%, that is, they were allocated in the set "High Mean". However, only the L19 presented average greater than 80%. Regarding the fuzzy variable β_1, that reflects the adaptability of the genotypes, the cultivars Ouro Vermelho and Vermelhinho and 85% of the lines (1, 3, 4, 5, 7, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 20, and 23) were allocated in "$\beta_1 = 1$" set. Lines 15, 19, and 22 constituted the "$\beta_1 < 1$" set, while only L8 belonged to the "$\beta_1 > 1$" set. For the fuzzy variable R^2, lines 1, 2, 3, 6, 7, 8, 9, 10, 14, 15, 16, 17, 20, 21, and 23 were allocated in the "High R^2" set, that is, its have high predictability of behavior. Both cultivars were also allocated in this set with R^2 values higher than 91% (Table 3).

Table 3. Standard inputs and classification of the behavior ("General" (GE), "Poorly adapted" (PA), "Favorable" (FAV) and "Unfavorable" (UNF)) of the 23 lines and two cultivars submitted to the fuzzy controllers (Mamdani and Sugeno) based on the Eberhart and Russell (1966) method.

Lines	Inputs			Membership of Behavior (%)			
	Mean	β_1	R^2	GE	PA	FAV	UNF
L1	45.6	1.77^A	86.7	42	58	3	0
L2	63.7	3.93	85.9	52	26	48	0
L3	35.3	0.60	83.0	25	64	0	1
L4	41.9	0.41	71.4	16	65	0	2
L5	41.8	-1.68	69.9	12	60	0	12
L6	59.4	1.34	77.2	37	63	1	0
L7	48.5	2.99	91.0	47	53	22	0
L8	37.9	4.83	83.7	26	67	29	0
L9	61.5	1.98	92.9	70	30	5	0
L10	42.8	3.16	87.8	37	63	26	0
L11	33.6	3.31	74.5	23	70	23	0
L12	75.3	1.45	58.9	0	88	0	0
L13	58.9	0.69	73.5	23	66	0	1
L14	59.2	-1.49	89.2	65	33	0	35
L15	66.5	-3.84	83.6	8	34	0	66
L16	52.7	0.17	86.2	55	45	0	4
L17	60.0	0.93	89.6	68	32	0	0
L18	48.8	-0.89	57.0	0	52	0	0
L19	90.5	-6.00	21.1	0	98	0	0
L20	57.9	0.56	82.9	63	37	0	1
L21	38.2	5.30	96.1	16	71	29	0
L22	27.5	-4.19	62.6	1	85	0	1
L23	55.2	3.94	89.6	52	40	48	0
OV	39.2	2.29	92.9	31	69	9	0
VE	8.2	3.44	91.0	1	67	1	0

[A]Values between - 2 and 4 were statistically equal to 1 and 5% probabilities by Student's *t* test; OV – Ouro Vermelho; VE – Vermelhinho.

Controllers based on the method of Eberhart and Russell (1966), regardless of the adopted inference system, showed the same membership and classification results regarding the behavior of the lines (Table 3). Thus, in both controllers (Mamdani and Sugeno), seven lines were identified (2, 9, 14, 16, 17, 20, and 23) that presented general adaptability, while only line 15 presented adaptability to unfavorable environments (Table 3), since these lines showed the highest membership values in these respective sets. Among the 7 lines of general adaptability identified by these controllers, line 9 showed the greatest potential to be recommended for any type of environment since its membership of 70% was the highest value observed in this set. Line 15 presented the greatest potential to be recommended for small producers since it had membership of 66% in the set of genotypes with adaptability to unfavorable environments. Although lines with adaptability to favorable environment were not identified, lines 2 and 23, which were classified as having general adaptability, also presented high membership (48%) in the set of lines with adaptability to favorable environments.

Discussion

Genotypes presented differential behavior in relation to environmental variations since significant G x E interaction was found. Thus, the recommendation of a line based solely on means is not appropriate since lines may differ regarding this parameter, and a genotype may have better performance in a certain environment than in another. G x E interaction, when presenting a high magnitude, may hinder the selection or recommendation of cultivars, which is the establishment of statistically similar overall means, as observed in the non-significance of the genotype effect in the joint analysis of the experiments, highlighting the fact that this interaction is a complicating agent in plant breeding (Cruz et al., 2012; Ramalho et al., 2012).

Both the controller based on the method of Eberhart and Russell (1966), Mamdani (Mamdani & Assilian, 1975) and that based on Sugeno (Sugeno & Kang, 1988a; Sugeno & Tanaka, 1991; Sugeno & Yasukawa, 1993; Takagi & Sugeno, 1985) presented the ability to properly classify all of the lines in relation to the behavior in response to environmental variations since this classification was consistent with the literature on this method of adaptability and stability (Eberhart and Russell, 1966) as well as in relation to the implemented fuzzy rules. Thus, the for a line to be cultivar candidate, it must have a high mean yield (β_0 > overall mean) and coefficient of determination (R^2) higher than 80%, which according to Oliveira et al. (2002), indicate superior genotypes.

The method proposed by Eberhart and Russell (1966) is widely used to identify the performance of genotypes evaluated in various environments. However, the interpretation of these parameters (overall mean, β_1, and R^2) - always performed by the breeder - besides difficult, is not enough to identify potential cultivars to be recommended. Incorrect interpretation of these parameters leads to mistaken decision making, which makes breeding programs less efficient. The fuzzy control systems of this work aggregate all the experience present in the literature through fuzzy variables and rules in a single system, which already informs how much each genotype belongs to each class of phenotypic adaptability and stability. Therefore, the interpretation of the parameters is performed by these automated systems that become the decision making, in the cultivars recommendation, more accurate and standardized.

Methodologies based on regression, although difficult to interpret, are widely used in breeding programs. Some of them present more parameters than the methodology proposed by Eberhart and Russell (1966). While this one presents three parameters, the proposals by Cruz et al. (1989) and Verma, Chahal and Murty (1978) present more than five parameters to be interpreted, which increases the risk of error in the cultivars recommendation. Therefore, the use of fuzzy control systems associated to these methodologies are even more justified to help decision making in this stage.

In general, both the inference system proposed by Mamdani and that proposed by Sugeno can be used to develop controllers that are designed to assist in the recommendation of cultivar, since the results of the controllers using the same method of adaptability and stability were similar. However, Sugeno-type controllers are simpler, easier to implement and have higher computational efficiency (Jang, Sun, & Mizutani, 2012).

Fuzzy logic proved to be a useful tool for breeding programs, especially for the recommendation of cultivars, since it allows linking information from different parameters to understand the behavior of the lines in relation to environmental variations. Furthermore, this technique allows, by means of membership, identification of superior genotype among those that are processed by the experimental network. Given this potential for the analysis of adaptability and stability, fuzzy controllers were developed in Matlab software (2016) and implemented in BIOFUZZY software to be applied for the recommendation of cultivars of any crop.

Conclusion

A controller based on the method of Eberhart and Russell (1966) has the potential to be used in the recommendation of cultivars in breeding programs. Both the Mamdani and Sugeno inference systems are suitable for the development of fuzzy controllers aimed at recommending cultivars.

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