Engenharia Agrícola

ISSN: 1809-4430 (on-line)

www.engenhariaagricola.org.br

Scientific Paper

Doi: http://dx.doi.org/10.1590/1809-4430-Eng.Agric.v42n1e20200150/2022

FUZZY MODELING OF SALINITY EFFECTS ON PUMPKIN (*Cucurbita pepo*) DEVELOPMENT

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KEYWORDS

artificial intelligence, agronomy, irrigation, ROC curve.

ABSTRACT

The low quality of the water currently used for irrigation purposes harms the quality of the products and can lead to a reduction in production. Thus, the objective of this work was to verify the effect of saline water in irrigation water, on biometric variables of pumpkin crop using a system based on fuzzy rules. The agronomic experimental part of this work was carried out in a greenhouse. The experimental design was in randomized blocks, with 5 doses of salinity (0, 1.25, 2.5, 3.75, and 5 dS m^{-1}) and with 5 repetitions. The salinity doses and evaluations carried out throughout the cycle (days after transplanting) were defined as input variables in the mathematical model. For the output variables, the collected biometric responses were defined: number of leaves, number of flowers, leaf fresh mass, leaf dry mass, stem fresh mass, stem length, root fresh mass, and root length. After evaluation, the mathematical model was developed and its validation was carried out using statistical methods and Receiver Operating Characteristic Curves (ROC). It was observed that salinity affects the bush pumpkin crop with a reduction in the evaluated parameters. The mathematical model proved to be efficient for this evaluation.

INTRODUCTION

Pumpkin (*Cucurbita pepo*) belongs to the Cucurbitaceae family, including chayote, watermelon, strawberry, and cucumber. Its commercial part is an immature succulent fruit with poorly developed seeds (Cardoso & Pavan, 2013). Its consumption has increased recently by more than 80%, ranking among the 12 vegetables with the highest economic value in Brazil (Schabarum & Triches, 2019).

Pumpkin has a low salinity tolerance. As a result, effects are more severe on plant growth biometric parameters when irrigated with saline water (Xu et al., 2017; Niu et al., 2017).

This study sought to carry out an agronomic experiment with controlled factors: salinity (five levels) and measurement times during the cycle (three days after transplanting). To do so, we used fuzzy mathematical modelling to evaluate minimum and maximum salinity for all evaluation days.

Fuzzy modelling has been applied in agricultural sciences to increase interpretation power and field result precision. In this context, applications for salinity (Viais Neto et al., 2019a; 2019b) and orchid (Putti et al., 2014, 2017a) management have been reported.

This type of modelling is also a theory that can help farmers (Gabriel Filho et al., 2011) and ranchers (Mota et al., 2018) in decision-making. In husbandry, fuzzy rules have been used to decide the time of slaughter and to detect oestrus in dairy cows. In the latter, the model used ROC (Receiver-Operating Characteristic) curves that returned a sensitivity of 84.2%; therefore, it could detect oestrus with almost ideal precision.

Fuzzy modelling can be used with knowledge gained from experts in the field under study. For instance, Sicat et al. (2005) gathered knowledge from farmers in India to develop a fuzzy model for classifying agricultural land with higher suitability. On the other hand, other studies did not use experts, such as the case by Valente et al. (2012), who

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Area Editor: Jefferson Vieira José
Received in: 9-15-2020
Accepted in: 11-30-2021

applied fuzzy logic to determine areas suitable for coffee production using soil electrical conductivity.

Given the above, our study aimed to develop fuzzy mathematical models to analyse the water salinity effect on pumpkin biometric variables.

MATERIAL AND METHODS

Experiment description

The experiment

Was carried out at the Experimental Farm Lageado. It is located in the Department of Rural Engineering of the College of Agricultural Sciences, São Paulo State University (UNESP), in the municipality of Botucatu, São Paulo State, Brazil (22º 51' South Latitude, 48º 26' West Longitude, and 786-m average altitude). According to Köppen's classification, the local climate is a Cfa type, which stands for warm temperate (mesothermal) and humid climate, with average temperatures above 22°C in the warmest month. The average annual rainfall is 945.15 mm (Cunha & Martins, 2009).

The experiment was conducted in a tunnel-type greenhouse (27 m long, 7 m wide, lateral heights of 1.7 m, and central height of 3 m). The environment was covered with a 150-µm-thick additived transparent polyethylene film. The sides were protected with 30% shading screens to intercept insects and animals. The greenhouse is oriented in a north-south direction along its length.

The soil used has the main characteristics: pH ($CaCl_2$) = 5,1; M.O. = 11 g dm^{-3}; P (resina) = 6 mg dm^{-3}; K = 0,60 $mmol_c$ dm^{-3}; Ca = 22 $mmol_c$ dm^{-3}; Mg = 7 $mmol_c$ dm^{-3}; H+Al = 26 $mmol_c$ dm^{-3}; SB = 29 $mmol_c$ dm^{-3}; B = 0,22 $mmol_c$ dm^{-3}; Cu = 6 $mmol_c$ dm^{-3}; Fe = 20 $mmol_c$ dm^{-3}; Mn = 10,1 $mmol_c$ dm^{-3}; Zn = 0,80 $mmol_c$ dm^{-3}; CTC = 55 $mmol_c$ m^{-3} e V = 53%.

The seedlings were prepared in 128-cell expanded polystyrene trays filled with commercial substrate Bioplant®.

Data were collected at 15, 30, and 45 days after transplantation (DAT), measuring the following characteristics: Number of Leaves [-], Number of Flowers [-], Leaf Fresh Mass [g], Leaf Dry Mass [g], Stem Fresh Mass [g], Stem Length [mm], Root Fresh Mass [g], and Root Length [cm]. Weight measurements were taken on a scale with an accuracy of 0.0001 g, while fruit length and diameter were measured with the aid of a calliper.

The experimental design was a fully randomized block with 5 salinity levels (0, 1.25, 2.5, 3.75, and 5 dS m^{-1}) and 5 repetitions. Each plot consisted of a 12-L pot with one pumpkin plant. Salinity levels used were adopted based on the literature (Ayers & Westcot, 1991). Irrigation was performed daily to keep soil tension constant at -10 kPa.

Fuzzy Model Development

The fuzzy modelling proposed in the present work sought to explain the crop development characteristics of pumpkins as a function of salinity and plant development. To do so, we considered different salinity levels (0, 1.25, 2.5, 3.75, and 5 dS m^{-1}) as treatments, which were evaluated throughout the crop cycle (15, 30, 45, days after transplantation). The crop yield traits were analysed comprised the following biometric variables: Number of Leaves (NL), Number of Flowers (NF), Leaf Fresh Mass (LFM), Leaf Dry Mass (LDM), Stem Fresh Mass (SFM), Stem Length (SL), Root Fresh Mass (RFM), and Root Length (RL).

Thus, we define the mathematical model $f: \mathbb{R}^2 \rightarrow \mathbb{R}^8$, with $y = f(x)$, where $\mathbb{R}$ is the set of real numbers, $x = (x_1, x_2)$ is defined by $x_1 =$ evaluations along the cycle, and $x_2 =$ salinity doses (dS m^{-1}), and $y = (y_1, \dots, y_8)$ is defined by the averages of the values of biometric characteristics: $y_1 = \overline{NL}$, $y_2 = \overline{NF}$, $y_3 = \overline{LFM}$, $y_4 = \overline{LDM}$, $y_5 = \overline{SFM}$, $y_6 = \overline{SL}$, $y_7 = \overline{RFM}$ e $y_8 = \overline{RL}$.

To create the system based on fuzzy rules, it was necessary to define an input processor, a set of linguistic rules, a fuzzy inference method (Mamdani), and an output processor, generating a real number as output (Figure 1).

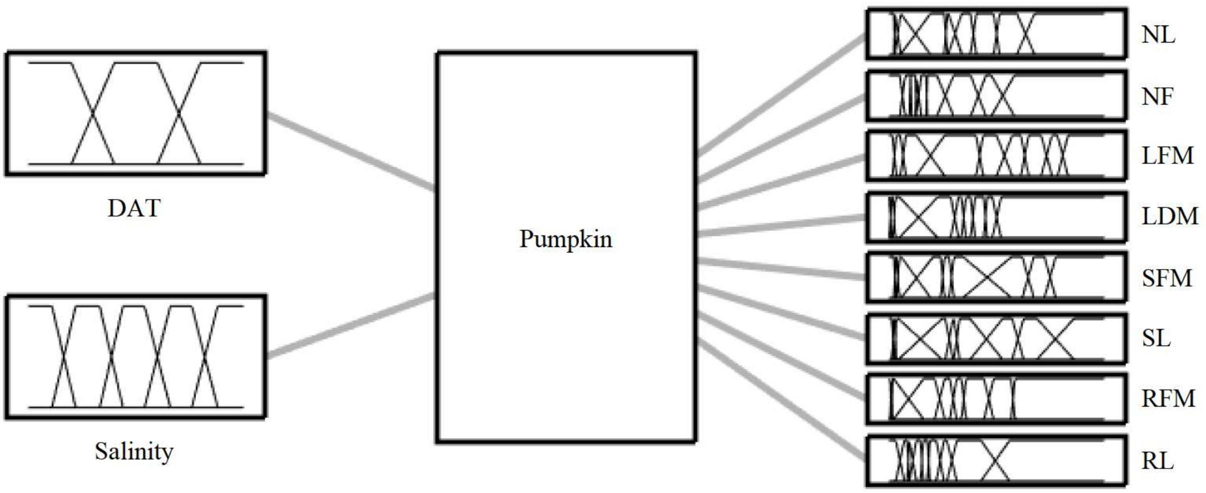

FIGURE 1. Fuzzy Rule-Based Systems (FRBS) for the evaluation of biometric variables in pumpkin crop.

The present FRBS represents the function $f: [15, 45] \times [0, 5] \to \mathbb{R}^8$, $f(x, y) = (f_1(x, y),\ f_2(x, y),\ f_3(x, y),\ f_4(x, y),\ f_5(x, y),\ f_6(x, y),\ f_7(x, y),\ f_8(x, y))$, where the domain represents the "Days after transplantation" ([15 45], with each point representing a time along the cycle) and the Salinity doses ([0 5], with each point representing a salinity level). The counter domain $\mathbb{R}^8$ represents the eight output variables: NL, NF, LFM, LDM, SFM, SL, RFM and RL.

Thus, the input variables of the system were: "Days after transplanting (DAT)" and "Salinity". For DAT, 3 fuzzy sets named P1, P2, and P3 were defined, and for the Salinity variable, 5 fuzzy sets named Very Low (VL), Low (L), Medium (M), High (H), and Very High (VH) (Table 1 and Figure 2).

TABLE 1. Definitions of the trapezoidal membership functions of the DAT and Salinity input variables.

Variables	**Fuzzy sets**	**Delimiters**
Days after transplanting (DAT)	P1	[14 15 21 27]
	P2	[21 27 33 39]
	P3	[33 39 45 46]
Salinity	Very Low (VL)	[-1 0 0.55 1.1]
	Low (L)	[0.55 1.1 1.66 2.2]
	Medium (M)	[1.66 2.2 2.7 3.3]
	High (H)	[2.7 3.3 3.8 4.4]
	Very High (VH)	[3.8 4.4 5 6]

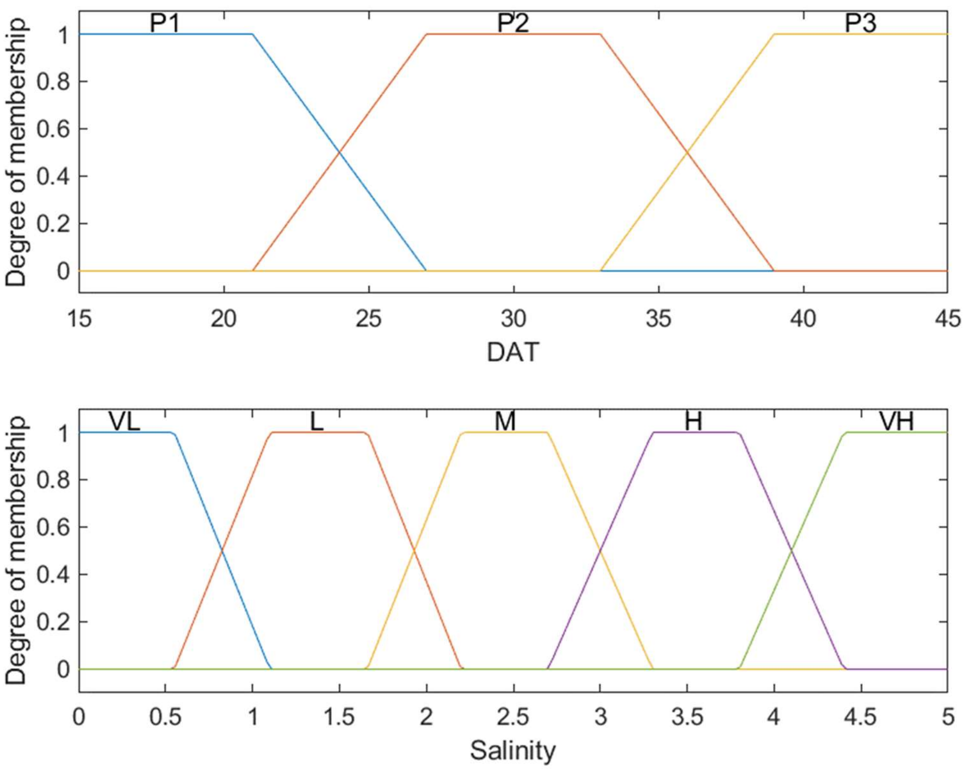

FIGURE 2. Membership functions defined for fuzzy sets of DAT and Salinity input variables.

Membership functions were constructed to assign the DAT (15, 30, and 45) a membership degree 1 (P1, P2, and P3, respectively) and the salinity levels (0, 1.25, 2.5, 3.75, and 5 dS m^{-1}) also a membership degree 1 (VL, L, M, H, and VH, respectively). Their supporting associated trapezoidal membership functions were calculated to have a centre with points of membership degree 1, while the other parts had decreasing membership degrees. In this context, such support was divided into three equal parts, and the centre, therefore representing one-third of the support.

Nine fuzzy sets were used to generalize output data, namely C_n, $1 \leq n \leq 9$. To this purpose, several delimiters had to be calculated to enable defining a trapezoidal shape for each membership function of each fuzzy set C_n (Figure 3 and Table 2).

The trapezoidal membership functions required the calculation of 17 delimiters, which were defined in this work as percentiles of the data sets measured for each output variable. Such percentiles in $x\%$, denoted by $P(x\%)$, depend on a constant k, since the 17 required delimiters are of the form $P(mk)$, $1 \leq m \leq 17$. The constant k was calculated as:

$$17k = 100\% \Rightarrow k = \frac{100\%}{17} \Rightarrow k = 5.88\%.$$

In Figure 3, there is a methodological proposal for the creation of membership functions for the output variables. The trapezoidal membership functions C_1 and C_9 stand out, in which, for each of them, the two disjoint intervals of the support, whose point does not have membership degree 1, were defined with the same amplitude, namely: $P(2k) - P(k)$ and $P(16k) - P(15k)$.

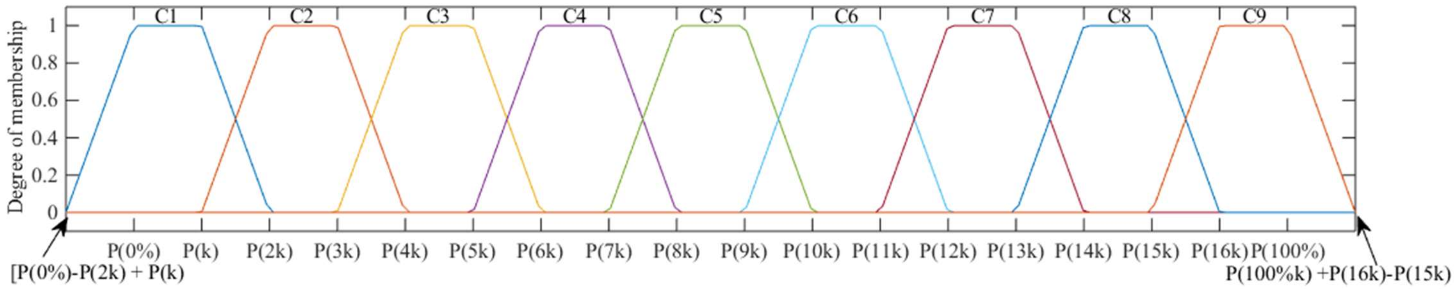

FIGURE 3. Membership functions (with generic delimiters) of fuzzy sets C_n, $1 \leq n \leq 9$.

TABLE 2. Definitions of the trapezoidal membership functions of the output variable of the proposed model.

Fuzzy Sets	Delimiters
C1	[P(0%)-P(2k) + P(k); P(0%); P(k); P(2k)] = [(P(0)-P(11%)+P(5%); P(0); P(5%); P(11%)]
C2	[P(k); P(2k); P(3k); P(4k)] = [P(5%) P(11%) P(17%) P(23%)]
C3	[P(3k); P(4k); P(5k); P(6k)] = [P(17%) P(23%) P(29%) P(35%)]
C4	[P(5k); P(6k); P(7k); P(8k)] = [P(29%) P(35%) P(41%) P(45%)]
C5	[P(7k); P(8k); P(9k); P(10k)] = [P(41%) P(47%) P(52%) P(58%)]
C6	[P(9k); P(10k); P(11k); P(12k)] = [P(52%) P(58%) P(64%) P(70%)]
C7	[P(11k); P(12k); P(13k); P(14k)] = [P(64%) P(70%) P(76%) P(82%)]
C8	[P(13k); P(14k); P(15k); P(16k)] = [P(76%) P(82%) P(88%) P(94%)]
C9	[P(15k); P(16k); P(100%); P(100%k)+P(16k)-P(15k)] = [P(88%) P(94%) P(100%) P(100%)+P(94%)-P(88%)]

To obtain the basis of rules for the fuzzy system, the 15 (5 × 3) combinations between the fuzzy sets of the input variables were considered, thus creating 15 pairs of the form (DAT × Salinity). This methodology was used similarly by Cremasco et al. (2010), Gabriel Filho et al. (2011, 2015, 2016, 2022), Pereira et al. (2008), Putti et al. (2014, 2017a, 2017b, 2021, 2022), Viais Neto et al. (2019a, 2019b), Martínez et al. (2020), Matulovic et al. (2021), Góes et al. (2021), Boso et al. (2021a, 2021b), and Maziero et al. (2022). Table 3 presents the 15 described combinations associated to the respective fuzzy sets.

TABLE 3. Combinations of input variables with membership degree 1 points associated with fuzzy sets for the generation of the Rule Base.

Days after transplanting [DAT]		Salinity [dS m^{-1}]	
Fuzzy set	Point with associated degree of membership	Fuzzy set	Point with associated degree of membership
P1	15	VL	0
P1	15	L	1.25
P1	15	M	2.50
P1	15	H	3.75
P1	15	VH	5
P2	30	VL	0
P2	30	L	1.25
P2	30	M	2.50
P2	30	H	3.75
P2	30	VH	5
P3	45	VL	0
P3	45	L	1.25
P3	45	M	2.50
P3	45	H	3.75
P3	45	VH	5

A value of the output variable was associated with each day after transplantation (DAT) and salinity level (S). That value, in turn, was related to the fuzzy set at the highest degree of membership.

Mamdani's inference method was used to compute numerical values for output variables. With the help of the Fuzzy Logic Toolbox of the MATLAB R2020a software (MATLAB, 2020), we could build a system based on computational fuzzy rules and develop three-dimensional plots and contour maps of the representation function of the associated system.

The fuzzy system was evaluated using the nonparametric Wilcoxon Signed-Ranks test, considering a $p < 0.05$ as statistically significant. Such validation was carried out by comparing the system results with real data collected in the field.

In the case of normal distribution, data were subjected to a paired t-test at a significance level of 5% ($\alpha = 0.05$), while for non-normal distribution, the non-parametric Wilcoxon test was used.

Subsequently, Receiver Operating Characteristic Curve (ROC curve) was built. The elaboration occurred applying the Sensitivity ordinate and the 1-Specificity in the abscissa. The analysis of the ROC curve also allowed for the calculation of the accuracy of the parameters. This analysis was performed using SPSS 20.1 software.

RESULTS AND DISCUSSION

Using the proposed methodology for creating the 9 fuzzy sets, it was possible to build the membership functions for each variable (Figure 4). The construction of the rule base according to the proposed methodology was established in Table 4.

TABLE 4. Rule base of fuzzy system.

Input variables		Output variables							
DAT	Salinity	NL	NF	LFM	LDM	SFM	SL	RFM	RL
P1	VL	C2	C4	C2	C2	C7	C7	C6	C2
P1	L	C2	C3	C2	C2	C8	C8	C2	C2
P1	M	C2	C3	C1	C1	C8	C8	C2	C1
P1	H	C2	C4	C3	C3	C9	C9	C3	C3
P1	VH	C2	C5	C3	C3	C8	C8	C2	C3
P2	VL	C5	C8	C6	C6	C2	C2	C8	C6
P2	L	C6	C9	C6	C5	C1	C1	C6	C5
P2	M	C5	C8	C8	C7	C3	C3	C5	C4
P2	H	C5	C8	C8	C7	C2	C2	C5	C5
P2	VH	C5	C7	C8	C8	C2	C2	C4	C5
P3	VL	C9	C6	C5	C6	C4	C4	C6	C7
P3	L	C7	C4	C5	C6	C6	C6	C7	C7
P3	M	C8	C2	C6	C7	C4	C4	C8	C9
P3	H	C8	C4	C8	C8	C6	C6	C8	C8
P3	VH	C8	C5	C4	C5	C5	C5	C6	C8

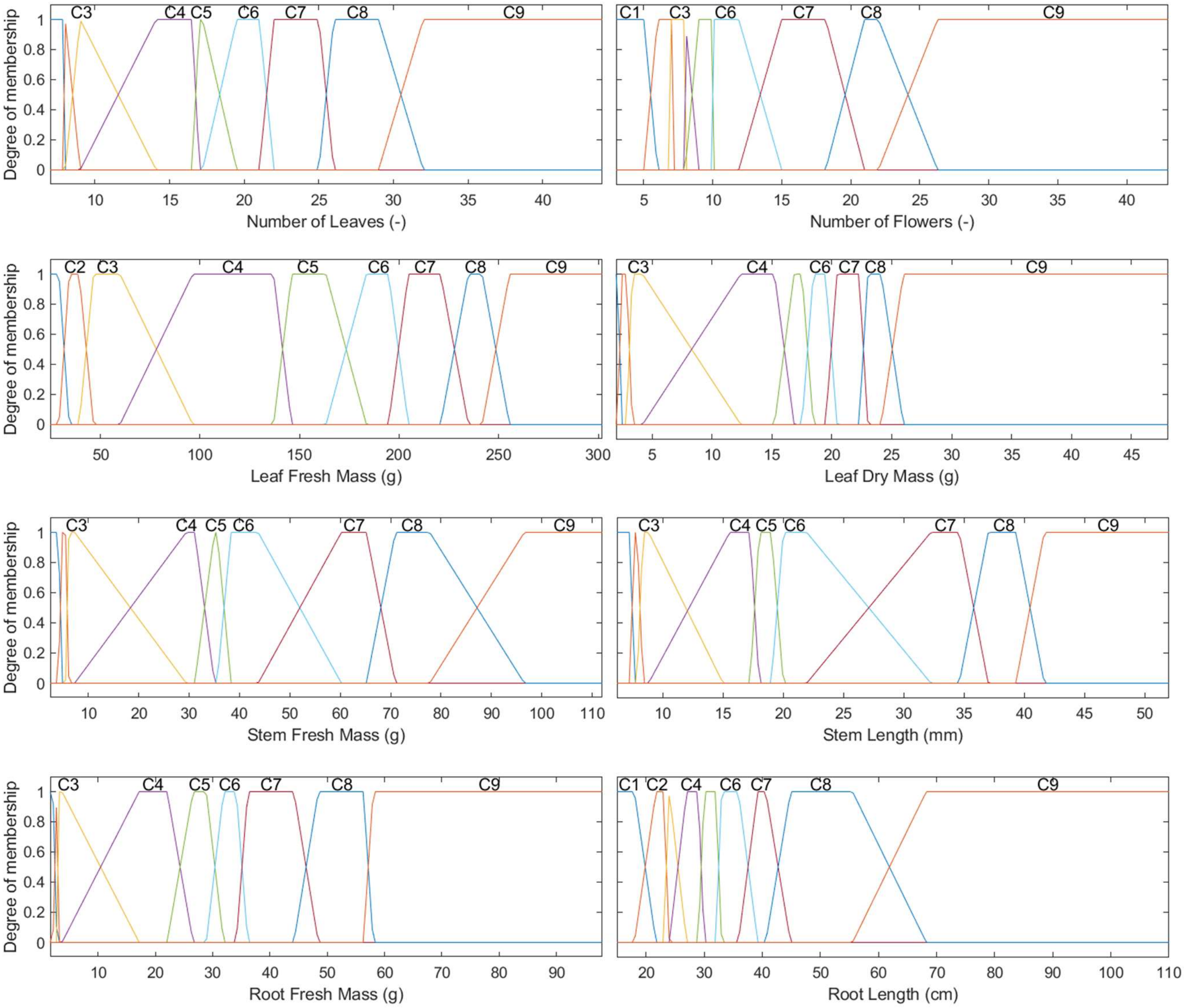

FIGURE 4. Membership functions of fuzzy sets of output variables Number of Leaves (NL), Number of Flowers (NF), Leaf Fresh Mass (LFM), Leaf Dry Mass (LDM), Stem Fresh Mass (SFM), Stem Length (SL), Root Fresh Mass (RFM), and Root Length (RL).

Table 4 represents the rules base of fuzzy system. Its first 3 lines are explained below (while the others are interpreted analogously):

- If (DAT is 15) and (Salinity is Very Low) then (NL is C2, NF is C4, LFM is C2, LDM is C2, SFM is C6, SL is C7, RFM is C7 and RL is C2);
- If (DAT is 15) and (Salinity is Low) then (NL is C2, NF is C3, LFM is C2, LDM is C2, SFM is C2, SL is C8, RFM is C8 and RL is C2);
- If (DAT is 15) and (Salinity is Medium) then (NL is C2, NF is C3, LFM is C1, LDM is C1, SFM is C2, SL is C8, RFM is C1 and RL is C2).

Using the Mamdani inference method, three-dimensional graphics (Figure 5) and respective contour maps (Figure 6) are obtained.

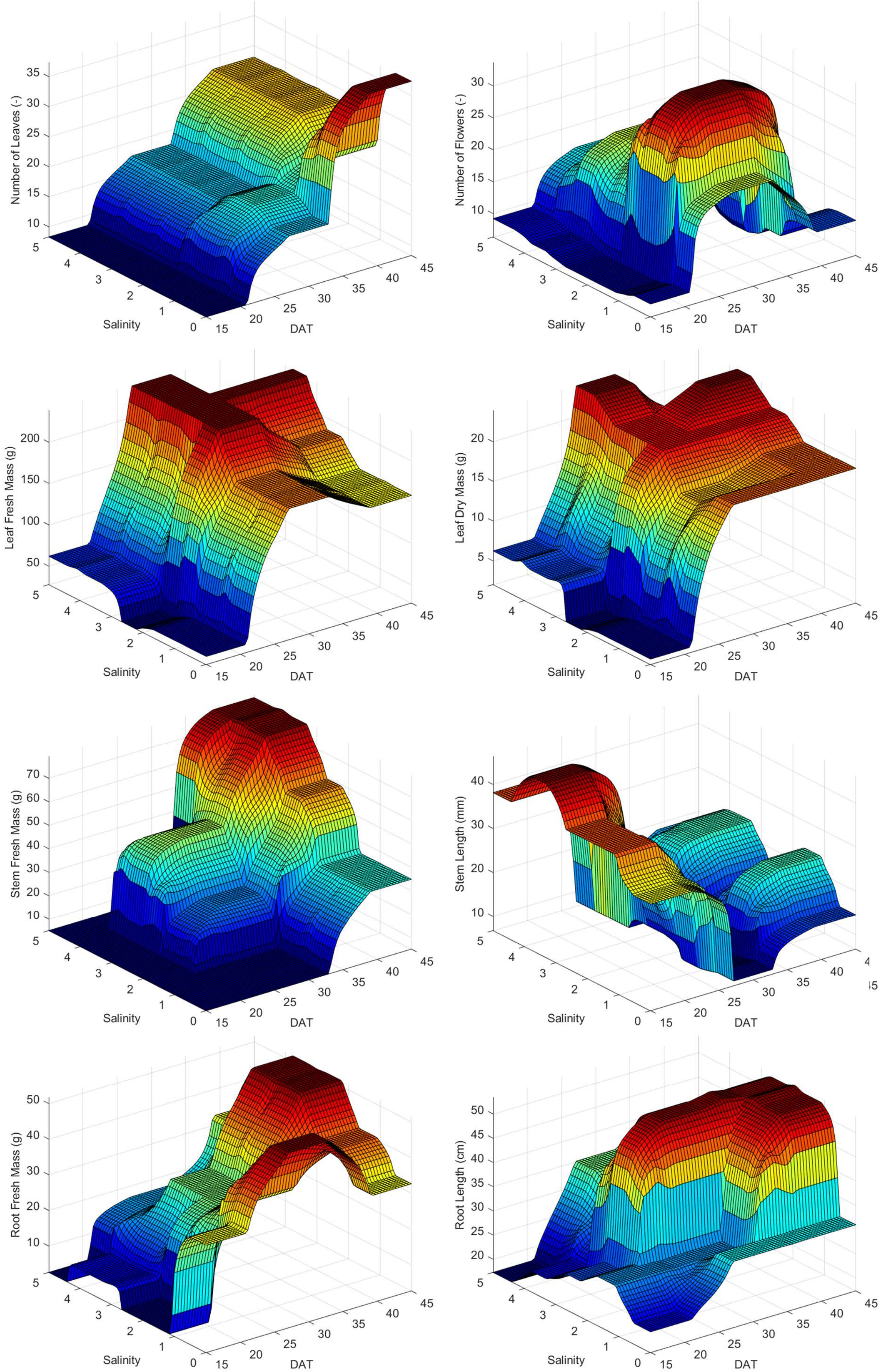

FIGURE 5. Three-dimensional surfaces of the fuzzy system of the pumpkin crop.

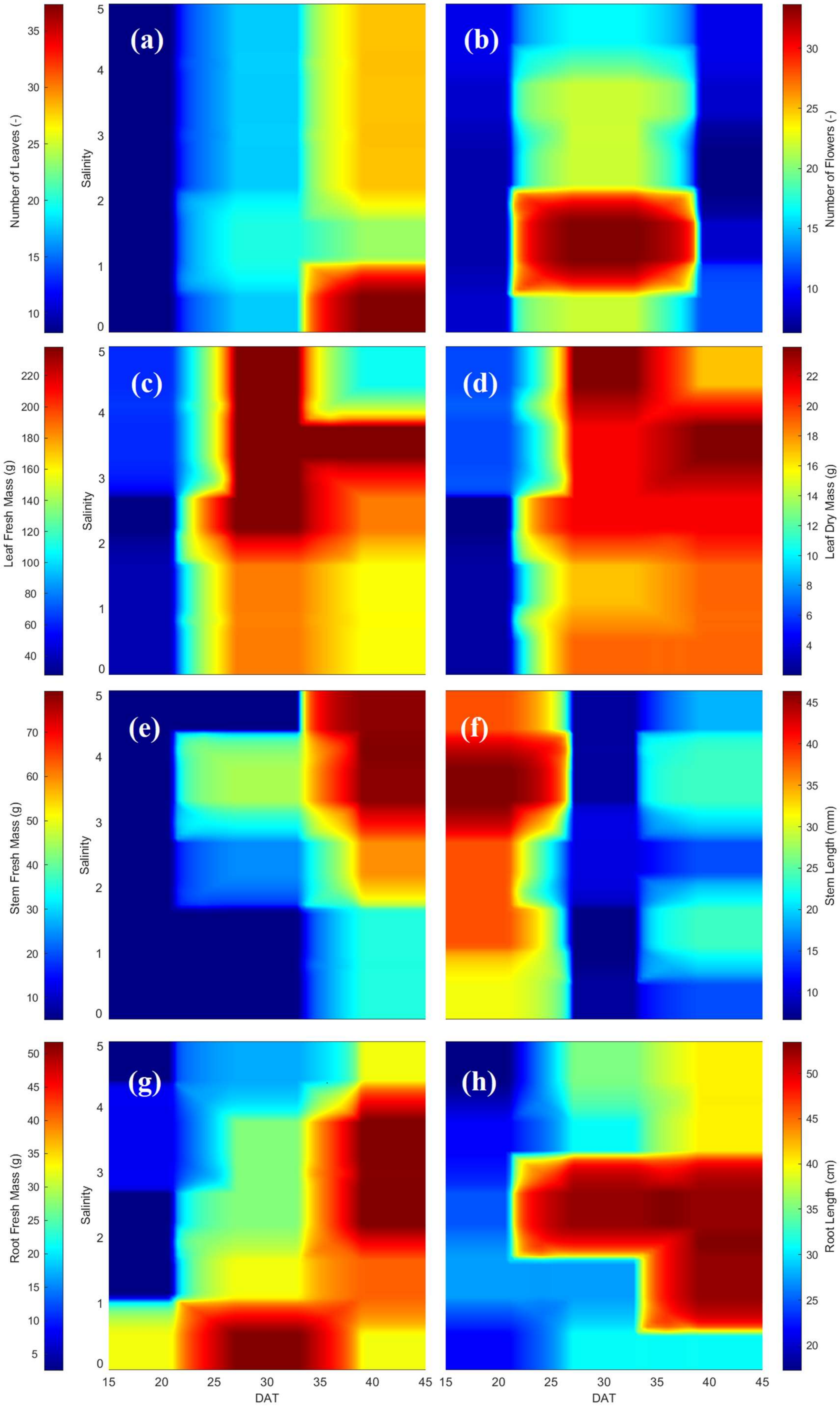

FIGURE 6. Contour Maps of the surfaces generated by fuzzy system of variables (a) NL, (b) NF, (c) LFM, (d) LDM, (e) SFM, (f) SL, (g) RFM, and (h) RL.

Salinity levels did not affect NL from 15 to 21 DAT (Figure 6a). However, between 21 and 35 DAT, the range between 1 and 2 dS m^{-1} increased NL compared to the other levels. From 35 to 45 DAT, NL increased, especially for salinity levels between 0 and 1 dS m^{-1}. During this period, there is a reduction in NL due to the increase in electrical conductivity. This reduction in NL may be due to a physiological response of plants to salt stress. Increased salinity of irrigation water increases soil osmotic potential, hindering water and nutrient uptake by plant roots. As a response mechanism, plants reduce leaf area and transpiration surface (Tester & Davenport, 2003). Other cucurbits, such as watermelon, gherkin, and melon, have shown similar responses (Costa et al., 2012; Oliveira et al., 2014; Porto Filho et al., 2006).

From 21 to 39 DAT, NF was maximum for salinity levels between 1 to 2 dS m^{-1} (Figure 6b). Moreover, the regions where DAT is less than 20 and where greater than 40 demonstrate respectively the pre-flowering and senescence periods, with salinity effects not evident. Other studies have shown decreases in NF as a plant physiological response to salt stress, such as in common beans (Furtado et al., 2014) and melon (Aragão et al., 2009; Terceiro Neto et al., 2013). According to Larcher (2006), plants under saline (or water) stress at the flowering show a drop in flower number, therefore compromising crop yield. Fruit number per plant may also reduce due to abortion of flowers and/or fruits, as pointed out by Del Amor et al. (1999) for melon.

Salinity above 3 dS m^{-1} had an increasing effect on LFM and LDM. After 21 DAT, such an increase was observed 2 dS m^{-1} onwards. This effect intensifies between 26 and 35 DAT for LFM, and from 36 to 45 DAT for LDM (Figures 6c and 6d). These results corroborate those of Porto Filho et al. (2006) for melon.

The three distinct salinity intervals had little influence on SFM from 15 to 27, 27 to 35, and 35 to 40 DAT, respectively (Figure 6e). However, this variable decreased throughout the crop cycle at the following salinity intervals 0 to 1, 2 to 3 and 4.5 to 5 dS m^{-1}. At other salinity levels (1 to 2 and 3 to 4.5 dS m^{-1}), SFM decreased until 35 DAT, and afterwards, it increased.

From 21 DAT onwards, SL increased at conductivities above 2 dS m^{-1}, which was accentuated between 40 and 45 DAT for salinity above 3 dS m^{-1} (Figure 6f). Similar results were observed by Oliveira et al. (2011)

Salinity reduced RFM (Figure 6g) at conductivities from 1 dS m^{-1} onwards. Root development was delayed when compared to conductivities below 1 dS m^{-1}, with mass peaking at 30 DAT. For conductivities above 1 dS m^{-1}, maximum values were reached between 40 and 45 DAT. According to Carillo et al. (2019), saline water irrigation can change plant metabolism due to salt concentrations within the root zone of plants considered sensitive to salinity. This reduces water absorption and contributes to stomatal closure, decreasing CO_2 uptake, restricting photosynthesis, and therefore inhibiting cell division.

Regarding RL, intermediate electrical conductivities (2 to 3 dS m^{-1}) provided the best responses from 20 to 45 DAT (Figure 6h). Between 35 and 45 DAT, salinity levels between 1 and 2 dS m^{-1} promoted the same RL values as those between 2 and 3 dS m^{-1}.

Table 5 displays the fuzzy model validation and shows that its estimates had no significant differences with the field data for all output variables. Data distributions (collected and mathematically modelled) did not show normal distribution, which implies the use of the non-parametric Wilcoxon test.

TABLE 5. Comparison between data obtained using the fuzzy model and data collected in fields using the nonparametric Wilcoxon test.

Variables	p-value
NL * NL Fuzzy	0.21^{ns}
NF * NF Fuzzy	0.07^{ns}
LFM * LFM Fuzzy	0.949^{ns}
LDM * LDM Fuzzy	0.073^{ns}
SFM * SFM Fuzzy	0.847^{ns}
SL * SL Fuzzy	0.436^{ns}
RFM * RFM Fuzzy	0.804^{ns}
RL * RL Fuzzy	0.385^{ns}

Caption: ns - not significant.

Using the fuzzy model, we could verify different DAT × Salinity conditions established in a computational mathematical system. Therefore, this tool can help the management of pumpkin crops subjected to different levels of salinity.

Using the fuzzy model and field data, we could build a Receiver Operating Characteristic (ROC) curve (Figure 7). This curve allowed us to verify the relationship between true-positive versus false-positive (sensitivity versus specificity) for the model's classification outputs. The ROC curve also enabled us to assess model accuracy by analysing the area of the curve, which represents the probability of a model being reliable. The curve area was 0.908 (90% CI - 0.87 to 0.94); thus, the model was reliable.

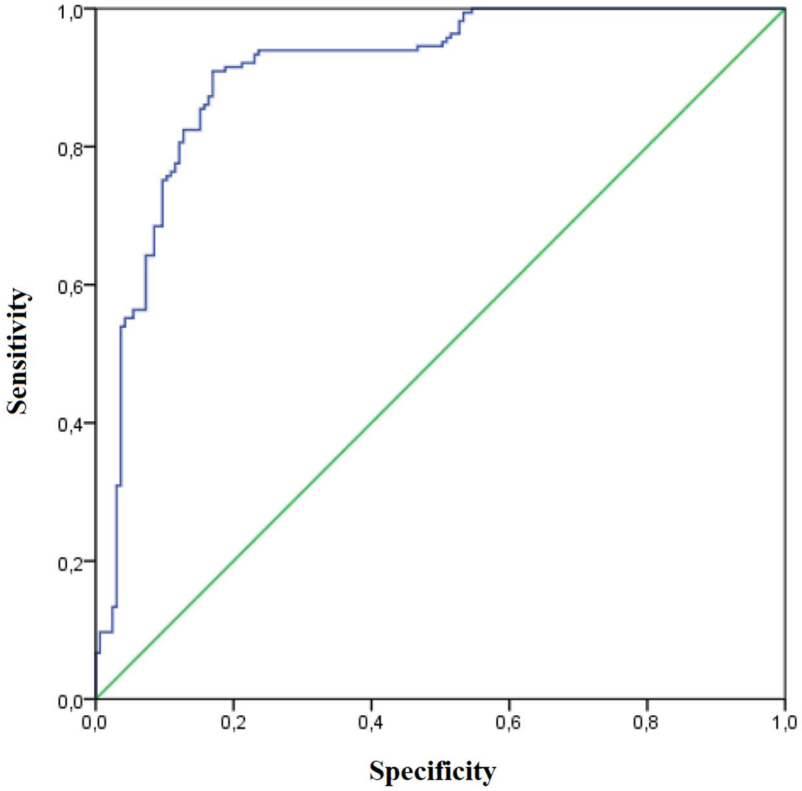

FIGURE 7. ROC curve for evaluating the proposed fuzzy model and collected data.

CONCLUSIONS

Pumpkins are sensitive to soil salinity. Its leaf fresh mass and area are affected most severely at the end of the crop cycle.

The fuzzy model provides a generalization of pumpkin biometric variables for the five salinity levels (from 0 to 5 dS m^{-1}) and three evaluation times (between 15 and 45 DAT) assessed. Therefore, our results can be used in further studies since such data were not available in the literature until now.

The model validation carried out using statistical methods enabled the eight fuzzy mathematical sub-models developed to have credibility for such further use in assessing salinity effects on pumpkin development.

ACKNOWLEDGEMENTS

This work was supported by the National Council for Scientific and Technological Development (CNPq) for the research productivity grants awarded (Process #303923/2018-0 (FFP) and #315228/2020-2 (LRAGF)).

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