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MODELAGEM *FUZZY* PARA SUPORTE AO MANEJO DA IRRIGAÇÃO E USO DE COBERTURA MORTA EM CULTIVO DE RABANETE

ALEXSANDRO OLIVEIRA DA SILVA[1]; ANTONIO VANKLANE RODRIGUES DE ALMEIDA[1]

[1]Programa de Pós-Graduação em Engenharia Agrícola, Universidade Federal do Ceará, Rua Campus do Pici S/N - Bloco 804, 60440-554, Fortaleza – CE, e-mail: alexsandro@ufc.br , vanklaneprece@hotmail.com

1 RESUMO

A agricultura irrigada é fundamental para a produção de alimentos no mundo, porém o elevado uso da água torna-se um desafio, diante disto deve-se buscar soluções para amenizar os impactos demandados por tal uso, como uso de cobertura morta e um correto manejo da irrigação, além de ferramentas para um adequado suporte a decisão sobre produção das culturas com o uso da água. Este trabalho tem como objetivo desenvolver um sistema baseado em regras *fuzzy* (SBRF) para a modelagem matemática do manejo da irrigação e uso de cobertura morta na cultura do rabanete (*Raphanus Sativus*), a partir de um experimento agronômico realizado em campo, foi considerado como variáveis de entrada no SBRF o manejo da irrigação através de diferentes lâminas de água aplicada em função da evapotranspiração da cultura (ETc) (25, 40, 55, 70, 85 e 100% da ETc), e dos níveis de cobertura morta de bagana de carnaúba (0, 25; 50; 75 e 100% de bagana de carnaúba), enquanto que as variáveis de saída foram: número de folhas, massa fresca da parte aérea e a massa fresca da raiz. Após a definição das variáveis de entrada e saída, foi determinada a base de regras do sistema, e na inferência foi adotado método de Mamdani, e para a fuzzyficação adotou-se o método centróide. No modelo *fuzzy* para a variável massa fresca da raiz, observou-se que com o uso de 100% da ETc e 100% da cobertura morta obtém-se os maiores valores (52,2 g planta^{-1}) para esta variável, sendo considerada a parte comercial desta hortaliça. No presente estudo, evidenciou-se a modelagem *fuzzy* pode ser uma ferramenta interessante para suporte ao uso adequado da água com vistas ao manejo da irrigação e cobertura morta vegetal em hortaliças.

Palavras-chaves: *Raphanus Sativus*, uso eficiente da água, suporte a decisão.

SILVA, A. O. DA; ALMEIDA, A. V. R. DE
FUZZY MODELING TO SUPPORT IRRIGATION MANAGEMENT AND MULCH USE IN RADISH CULTIVATION

2 ABSTRACT

Irrigated agriculture is fundamental for food production in the world, but the high use of water becomes a challenge. In view of this, solutions must be sought to mitigate the impacts required by such use, such as the use of mulch and correct management irrigation, as well as tools for adequate decision support on crop production using water. Aiming to mitigate the impacts caused by the use of water in agriculture, this work aims to develop a system based on fuzzy rules (SBRF) for the mathematical modeling of irrigation management and the use of mulch in

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radish (Raphanus Sativus) cultivation based on an agronomic experiment carried out in the field, irrigation management through different applied water depths (25, 40, 55, 70, 85 and 100% of ETc) was considered as input variables in the SBRF, in which ETc represents crop evapotranspiration and mulch levels (0, 25; 50; 75 and 100% of carnauba bagana), while the output variables were the number of leaves, fresh mass of the aerial part and the fresh mass of the root. After defining the input and output variables, the system's rule base was determined, and the Mamdani method was adopted for inference, and the centroid method was adopted for fuzzyfication. The fuzzy model for the MFR variable, it is observed that with the use of 100% of ETc and 100% of mulch, the highest values (52.2 g plant^{-1}) for this variable are obtained, considering the commercial part of this vegetable. In the present study, it was demonstrated that fuzzy modeling can be an interesting tool to support the appropriate use of water with a view to irrigation management and mulch in vegetables.

Keywords: *Raphanus Sativus*, efficient use of water, decision support.

3 INTRODUCTION

Irrigated agriculture is an essential practice for food production worldwide, accounting for 44% of the world's agricultural area and approaching 310 million irrigated hectares across the globe (FAO, 2013), with the greatest concentration occurring on the Asian continent. However, the sustainability of irrigated systems has been questioned every year since irrigated agriculture is currently responsible for the consumption of approximately 70% of all water used in human activities (BERNARDO *et al.*, 2019; FAO, 2017).

To achieve more efficient water use, techniques that reduce evaporation and maintain adequate soil moisture are recommended to aid irrigation management in agriculture. In this sense, mulch made from plant material can be used (ALMEIDA *et al.*, 2020) to fulfill this function. Among the vegetable mulch (CMV) used in semiarid regions of northeastern Brazil, we can highlight carnauba bagana. Derived from the leaves of the carnauba palm (*Copernicia prunifera*), bagana is the result of the residue generated by the extraction of the wax present in its leaves. It is widely used as fertilizer and mulch, and its use, combined with proper irrigation management, can increase the productivity of vegetables such as radishes (ALMEIDA *et al*., 2020) and tomatoes (SILVA *et al*., 2019).

Irrigation practices depend primarily on crop, climate, and soil characteristics (SILVA *et al.*, 2020). Therefore, water management in irrigated systems must consider these factors to optimize crop production (MORRILO-VELARDE, 2010; GEERTS; RAES, 2009; SEPASKHAH; KAMGAR-HAGHIGHI, 1997). However, irrigation management associated with the use of CMV lacks information that allows for adequate decision-making regarding the amount of CMV to be used and the possible reduction in water use (SILVA *et al.,* 2019). To support this decision, mathematical modeling can be a viable alternative, since through models and various simulations with prognoses and considering uncertainties, satisfactory results can be obtained (SIMÕES; SHAW, 2007), supporting a correct decision.

Fuzzy logic modeling can be considered an important option for decision-making tasks, as individual variables are not defined in exact terms. Therefore, it is an option for planning irrigation management and CMV use, minimizing costs and consequently preserving natural resources. Giusti and Marsili-Libelli (2015), applying *fuzzy* logic, developed a model to determine the ideal water replenishment rate and thus optimize a region's water resources. Other applications aimed at efficient water use have already been studied, among which we can highlight works such as those by Putti *et al.* (2021), in which these authors demonstrated the possibility of using *fuzzy models* to support proper irrigation management.

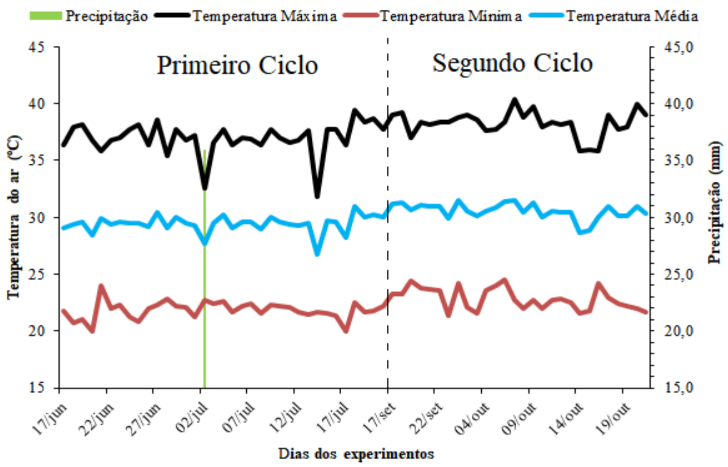
Given the above, the objective of this work was to develop a system based on *fuzzy rules* (SBFRs) to mathematically model the effects of irrigation depth and the use of mulch in irrigated radish production, with the aim of supporting decision-making.

4 MATERIALS AND METHODS

4.1 Experimental description

To prepare the proposed SBRF, an agronomic experiment was carried out in the field in the region of Pentecoste-CE. The experiment was conducted from June 17 to October 21, 2018, in an area belonging to the Cooperative Cell Education Program (PRECE) in the municipality of Pentecoste, Ceará State, with geographic coordinates of 39°12'46" west longitude, 03°55'20" south latitude, and 56 m above sea level. The region has a climate according to the Köppen classification of the BSw'h'h' type, hot and semiarid, with irregular rainfall distributed from February to May, an average annual rainfall of 860 mm, an evaporation of 1,475 mm (Piche evaporimeter), an average annual temperature of approximately 26.8°C and an average relative humidity of 73.7%. The daily precipitation and temperature data collected during the experiments are presented in Figure 1, where the average temperature during the first cycle was 28.6°C and 29.7°C during the second cycle, and the average relative humidity was 50.9% during the first cycle and 59.8% during the second cycle.

Figure 1. Data on the maximum, average and minimum temperatures and precipitation recorded in the two production cycles of the experiment.

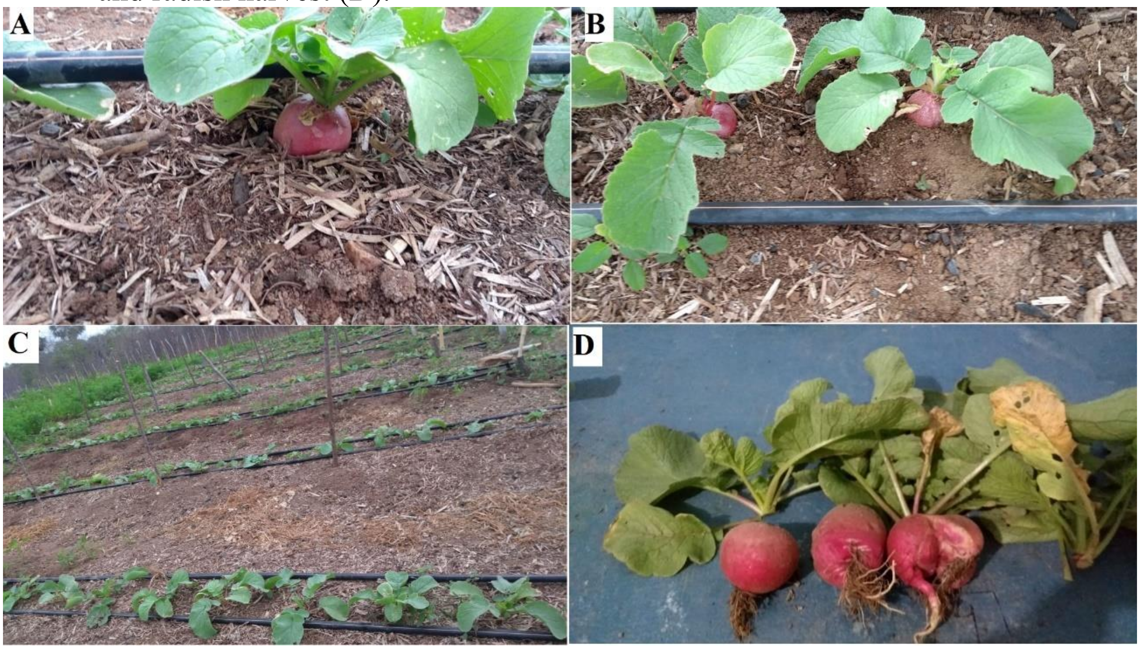


Source: Author (2021)

The experiment was carried out in a randomized block design with split plots and consisted of four replicates with five primary treatments, comprising the plots, and five secondary treatments, which were arranged in the subplots, for a total of 100 experimental plots. The primary treatments consisted of irrigation depths of 50%, 75%, 100%, 125% and 150% of crop evapotranspiration (ETc), and the secondary treatments consisted of five different levels of mulch: carnauba bagana (0%, 25%, 50%, 75% and 100%). The experimental plots with bagana (Figure 2A) and without bagana, as well as the experimental unit (Figure 2C) and harvest (Figure 2D), are shown in Figure 2. Notably, the 100% level is equivalent to 16 t ha $^{-1}$ (SOUSA *et al*., 2017).

The experimental plot was 6.0 ^{m2} (1.0 m × 6.0 m), and the subplot was 1.20 m² (1.0 m × 1.20 m), with a spacing of 0.15 m between plants and 0.2 m between rows. Each subplot had 18 plants, where the nine plants in the center of the subplots served as samples for determining the variables.

Figure 2. Experimental view of irrigated radish in the experiment: treatment with carnauba bags (A), treatment without carnauba bags (B), general view of the experiment (C) and radish harvest (D).



Source: Author (2021)

The plots and subplots were arranged in ridges 20 m long, 0.7 m wide, and spaced 0.30 m apart. To prepare the area, cleaning was carried out, and all plant debris was removed. Thirty days before the installation of the experiment, 20 kg m² of organic compost (Table 1) was incorporated into the soil ^{at} a depth of 0–0.30 m.

Table 1. Chemical composition of the organic compounds used

pH	P	K	Here	Mg	In the	Faith	As s	Zn	Mn
H_2O	mg kg $^{-1}$	mg dm $^{-3}$	------------ cmolc dm $^{-3}$ -------			------------ mg dm $^{-3}$ ------			
6.9	314.7	1690	14.0	9.20	1.14	26.9	0.4	20.4	100.3

To determine ETc, daily reference evapotranspiration (ETo) data estimated from the Class “A” tank were initially obtained according to the following equation:

$$ETo = ECA \times Kp \qquad (1)$$

where ETo represents the reference evapotranspiration (mm.day $^{-1}$), ECA represents the tank evaporation (mm.day $^{-1}$), and Kp represents the Class A tank coefficient.

Crop evapotranspiration was determined via the crop coefficient (Kc) according to Doorenbos and Pruitt (1997) and by fractioning the applied depth according to the treatment according to the following equation:

$$ETc = ETo \times Kc \times f \quad (2)$$

where ETc represents the crop evapotranspiration (mm.day $^{-1}$), ETo represents the reference evapotranspiration (mm.day $^{-1}$), Kc represents the crop coefficient (und), and f represents the fraction of the water depth to be applied (%), with values of 50, 75, 100, and 125, with 150% used in this work.

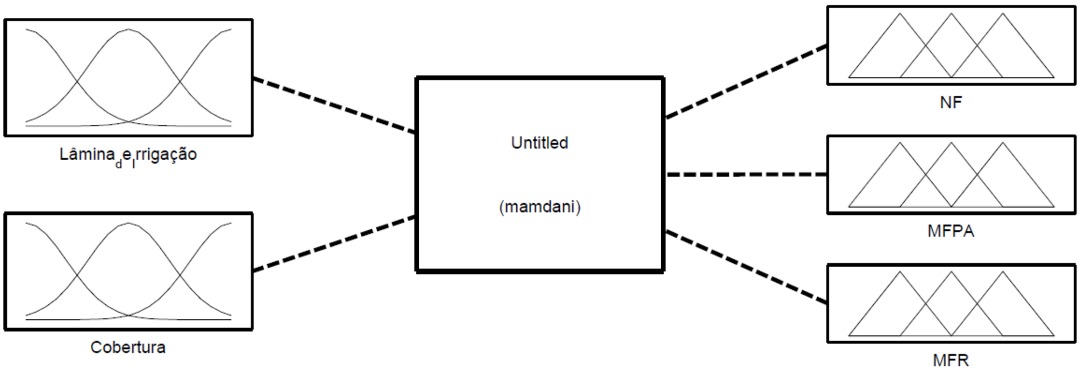
The irrigation system used was drip irrigation with 16 mm drip tape-type self-compensating emitters spaced 0.20 m apart, with a flow rate of 2.20 L h $^{-1}$ and a working pressure of 98 kPa.

At 30 days after sowing (DAS) for each experimental cycle, the plants were harvested, and the following production variables were evaluated: number of leaves (NF), counted manually in each experimental plot; fresh mass of the aerial part (MFPA); and fresh mass of the root (MFR), in g plant $^{-1,}$ weighed immediately after harvest. on a scale with an accuracy of 0.01 g.

4.2 fuzzy model

The *fuzzy inference method* and an output processor (or defuzzifier) were defined, generating a real number as the output (Figure 3).

Figure 3. *Fuzzy* rule-based system proposed for mathematical modeling of the effects of irrigation and mulch depth on radish (*Raphanus sativus*) crops with two input variables (irrigation and mulch depth) and three output variables (number of leaves (NF), fresh shoot mass (MFPA) and fresh root mass (MFR)).



Source: Author (2021)

This SBRF represents a function:

$$F: \{50{,}150\} \times [0, 100] \rightarrow \mathbb{R}^3, F(x,y) = (f_1(x,y), f_2(x,y), f_3(x,y)) \quad (3)$$

The Cartesian product that constitutes the domain represents the irrigation depth ({50,150}, where each point in the interval represents a percentage of the ETc associated with the irrigation performed) and the CMV ([0, 100], where each point in the interval represents a percentage of the CMV applied). The codomain $\mathbb{R}^3$ represents the three response variables evaluated: the number of leaves (NF), fresh mass of the aerial part (MFPA, g plant [-1]) and fresh mass of the root (MFR, g plant [-1]).

The results are presented in three-dimensional graphs, which are subdivided into 3 groups, with each group representing an effect of the response variables, where the graphs of the functions are represented by the following: $F_L^C: [50,150] \times [0, 100] \to \mathbb{R}, F_L^C(x,y) = f_1(50,0), f_2(50,25), f_3(50,50), f_4(50,75), \ldots f_{25}(150,100)$, in which the codomains are related to the number of leaves (NF) (Group 1); the fresh mass of the aerial part (Group 2); and the fresh mass of the root (Group 3).

To establish the input processor, it is necessary to define the *fuzzy sets* in the domains of each input variable: irrigation depth (L) and mulch (C).

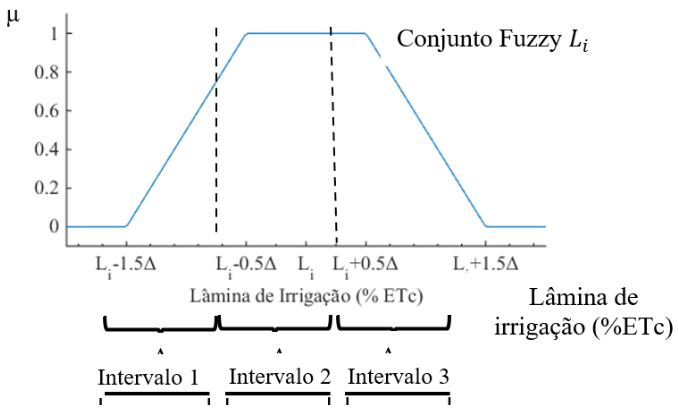
For each input variable "irrigation level", five *fuzzy sets* were considered $L_i, 1 \leq i \leq 5\ e\ C_i, 1 \leq i \leq 5)$. This definition is because, in the agronomic experiment, there were five irrigation levels and five mulch levels, which were sized according to the ETc rates: $(10 + 15i)\%, 1 \leq i \leq 5$ and carnauba bagana $(25 + 25i)\%, 1 \leq i \leq 5$. The (trapezoidal) membership functions of the sets $L_i\ e\ C_i$ are defined so that each rate has a membership degree of 1 to its respective *fuzzy set* $\left(u_{L_i}(10 + 15i) = 1\right)\ ou\ \left(u_{C_i}(25 + 25i) = 1\right)$ and that its support has three intervals of the same amplitude Δ, as exemplified for figure, with the following delimiters:

$$[L_i - 1{,}5\Delta\ ; L_i - 0{,}5\Delta\ ; L_i + 0{,}5\Delta\ ; L_i + 1{,}5\Delta\ ] \to \textit{Lâminas de irrigação} \quad (4)$$

$$[C_i - 1{,}5\Delta\ ; C_i - 0{,}5\Delta\ ; C_i + 0{,}5\Delta\ ; C_i + 1{,}5\Delta\ ] \to \textit{Cobertura morta,} \quad (5)$$

Considering that $Li\ ou\ Ci$ is the midpoint of the support of the membership function associated with the *fuzzy set* that belongs to degree 1 (Figure 4).

Figure 4. Generic membership function for determining *fuzzy sets* for the irrigation depth variable.



Source: Author (2021)

Owing to the amplitude Δ being the same for all supports of all membership functions of the *fuzzy sets* L_I (Figure 5), we have the following:

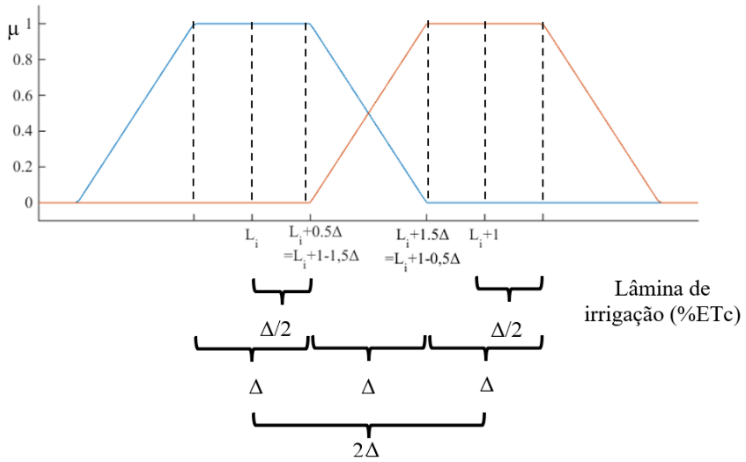
$$L_{i+1} - L_i = 2\Delta \Rightarrow [10 + 15\,(i+1)] - [10 + 15i] = 2\Delta \Rightarrow 15\,[(i+1) - i] = 2\Delta \Rightarrow 5 = 2\Delta \Rightarrow \Delta = 7{,}5. \quad (6)$$

Or

$C_{i+1} - C_i = 2\Delta \Rightarrow [25 + 15\,(i + 1)] - [25 + 15i] = 2\Delta \Rightarrow 25\,[(i + 1) - i] = 2\Delta \Rightarrow 25 = 2\Delta \Rightarrow \Delta = 12{,}5$. (7)

This calculation allows us to establish the definition of all the membership functions of *fuzzy sets* for both $L_i$exemplified in Figure 5, as for C_i.

Figure 5. Generic intersection of the membership functions of the irrigation depth variable.



Source: Author (2021)

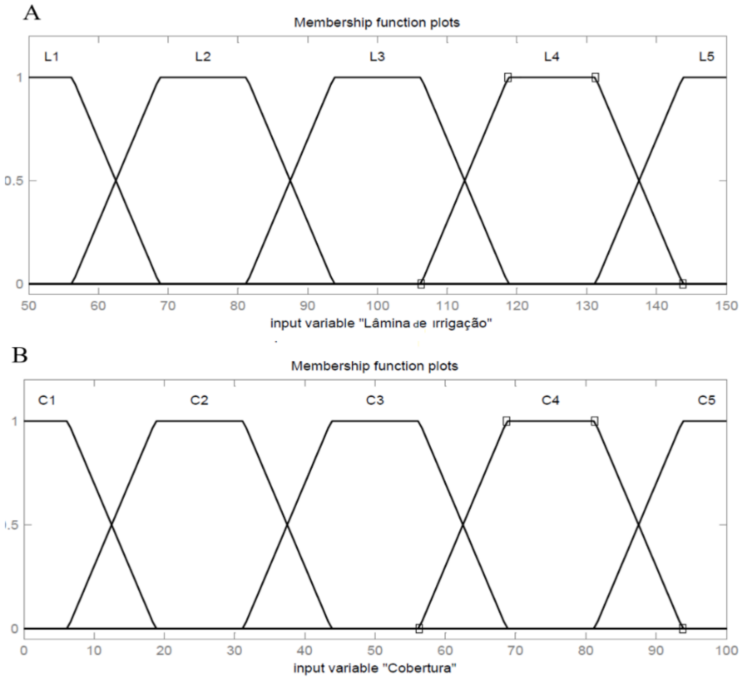
The delimiters of the membership functions can be seen in Table 2. The proposed methodology followed the guidelines of Putti *et al.* (2021) for datasets related to orange production under different doses of sewage sludge and wastewater, adapting it for use at the level of vegetation cover.

Table 2. Delimiters of the trapezoidal membership functions of the *fuzzy sets* $\boldsymbol{L_i}$ $\boldsymbol{ou}$ $\boldsymbol{C_i}, \mathbf{1 \leq i \leq 5}$ for the input variables "irrigation depth" and "mulch".

Set *Fuzzy*	Type	Delimiters
L 1	Trapezoidal	[50-1.5Δ; 25-0.5Δ; 50+0.5Δ; 25+1.5Δ]=[31.25; 43.75; 56.25; 68.75]
L 2	Trapezoidal	[75-1.5Δ; 40-0.5Δ; 75+0.5Δ; 40+1.5Δ]=[56.25; 68.75; 81.25; 93.75]
L 3	Trapezoidal	[100-1.5Δ; 55-0.5Δ; 100+0.5Δ; 55+1.5Δ]=[81.25; 93.75; 106.25; 118.75]
L 4	Trapezoidal	[125-1.5Δ; 70-0.5Δ; 125+0.5Δ; 70+1.5Δ]=[106.25; 118.75; 131.25; 143.75]
L 5	Trapezoidal	[150-1.5Δ; 85-0.5Δ; 150+0.5Δ; 85+1.5Δ]=[131.25; 143.75; 156.25; 168.75]
C1	Trapezoidal	[0-1.5Δ; 0-0.5Δ; 0+0.5Δ; 0+1.5Δ]=[-18.75; -6.25; 6.25; 18.25]
C2	Trapezoidal	[25-1.5Δ; 25-0.5Δ; 25+0.5Δ; 25+1.5Δ]=[6.25; 18.25; 31.25; 43.75]
C3	Trapezoidal	[50-1.5Δ; 50-0.5Δ; 50+0.5Δ; 50+1.5Δ]=[31.25; 43.75; 56.25; 68.75]
C4	Trapezoidal	[75-1.5Δ; 75-0.5Δ; 75+0.5Δ; 75+1.5Δ]=[56.25; 68.75; 81.25; 93.75]
C5	Trapezoidal	[100-1.5Δ; 100-0.5Δ; 100+0.5Δ; 100+1.5Δ]=[81.25; 93.75; 106.25; 118.75]

Figure 6 shows the relevance graphs generated through the input values (Table 2) generated by the delimiters of the relevance functions for the variables irrigation depth (Figure 6A) and mulch (Figure 6B).

Figure 6. Graphs of the membership functions of the *fuzzy sets* $\boldsymbol{Li}$ $\boldsymbol{e}$ $\boldsymbol{C_i}, \mathbf{1} \leq \boldsymbol{i} \leq \mathbf{5}$ of the input variables: Irrigation Blade (A), in the interval [50,150] and Mulch [0,100].



Source: Author (2021)

For each output variable, i.e., the number of leaves (NF), fresh mass of the aerial part (MFPA) and fresh mass of the root (MFR), 25 *fuzzy sets* were defined $F_n, 1 \leq n \leq 25$.

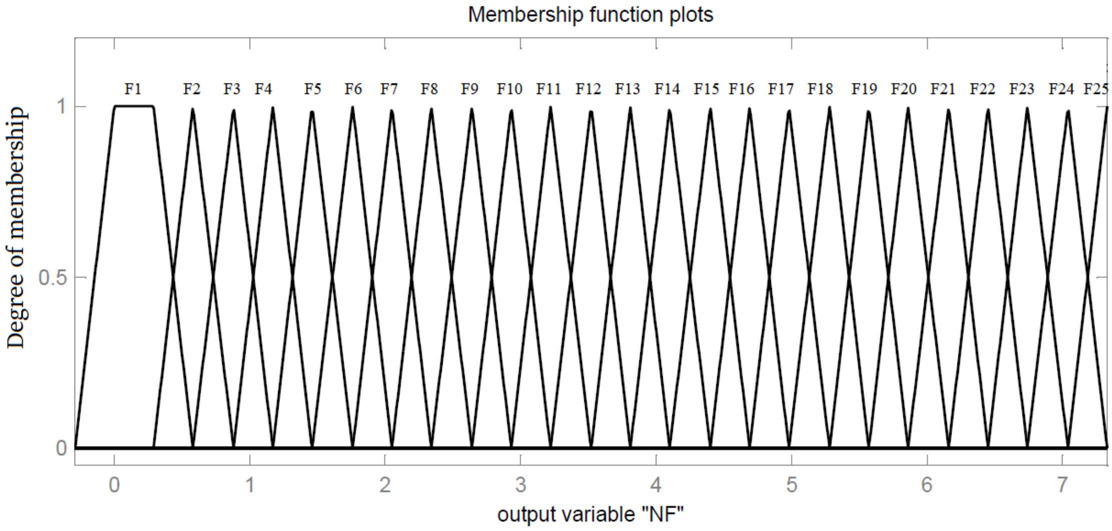
To generalize the methodology of the output variables for constructing *fuzzy sets* and their respective membership functions, the use of 25 *fuzzy sets* was adopted $F_n 1 \leq n \leq 25$. For this purpose, it was necessary to calculate several delimiters that made it possible to define the triangular form of each membership function of each *fuzzy set* F_n $2 \leq n \leq 24$ and the trapezoidal form of the membership functions of the *fuzzy sets* F_1 and F_{25}.

Membership functions require the calculation of delimiters, which we define in this work as percentiles of the measured data sets for each output variable. These percentiles in $x\%$, denoted by $P(x\%)$, depend on a constant k since the required delimiters are of the form $P(mk)$, $0 \leq m \leq 25$. The constant k is calculated as:

$$25k = 100\% \Rightarrow k = \frac{100\%}{25} \Rightarrow k = 4{,}00\%. \quad (8)$$

Figure 7 presents the proposed methodology for creating membership functions for the output variables. The trapezoidal membership functions F_1 are highlighted F_{25}, in which, for each of them, the two disjoint intervals of the support whose point does not have a membership degree of 1 are defined by the same amplitude.

Figure 7. Relevance functions of the output variables according to the methodological proposal of using percentiles.



Source: Author (2021)

To obtain the rule base of the *fuzzy system, 25 (5 × 5) combinations between the fuzzy sets* of the two input variables $lâmina\ de\ irrigação\ x\ cobertura\ morta$ were considered. Thus, 25 pairs of the form () were created according to the methodology developed in Cremasco, Gabriel Filho and Cataneo (2010) and applied in Putti *et al.* (2021).

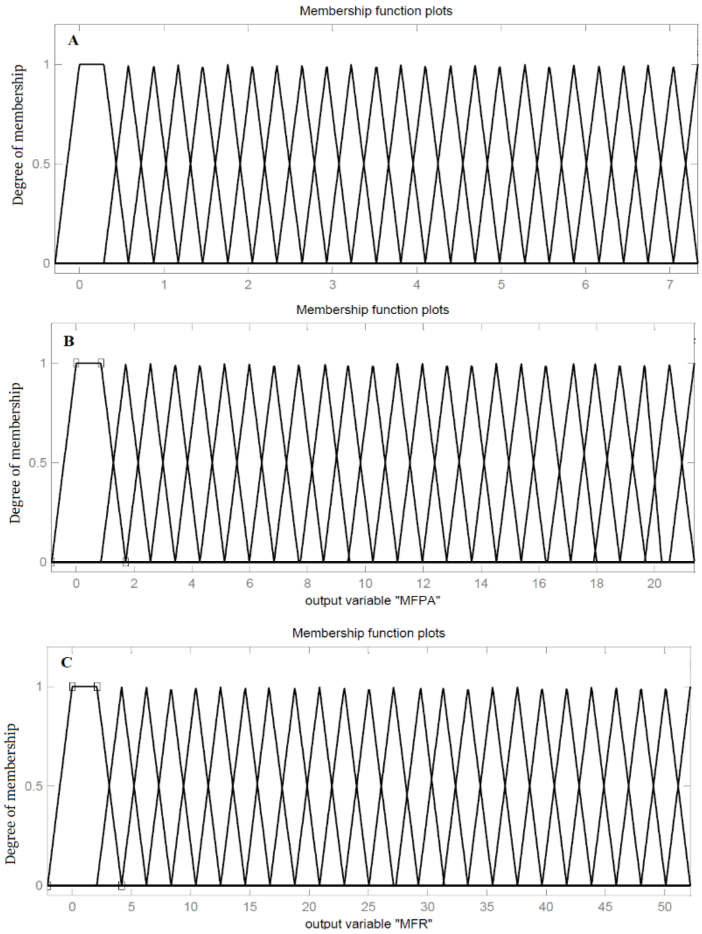
For each type of vegetation cover and each *fuzzy set* for the input factor "irrigation depth," which is associated with the statistically calculated value of the output variable, this value should be associated with the *fuzzy set* with the highest degree of relevance. Thus, for each combination, three *fuzzy sets were associated*, each related to the output variables.

The inference method used to calculate the numerical value of the output variables, according to the rule base, was Mamdani's (MAMDANI; ASSILIAN, 1975). With the help of the *Fuzzy* Logic Toolbox in MATLAB®*, it was possible to create a fuzzy* logic-based system computationally, and a three-dimensional graph and a contour map of the associated system representation function were also determined.

5 RESULTS AND DISCUSSION

Figure 8 shows the membership functions of the output sets for the variables “number of leaves (NF)”, “fresh mass of the aerial part (MFPA)” and “fresh mass of the root (MFR)”. By developing percentiles to calculate the delimitators of the membership sets, it was possible to model the output variables.

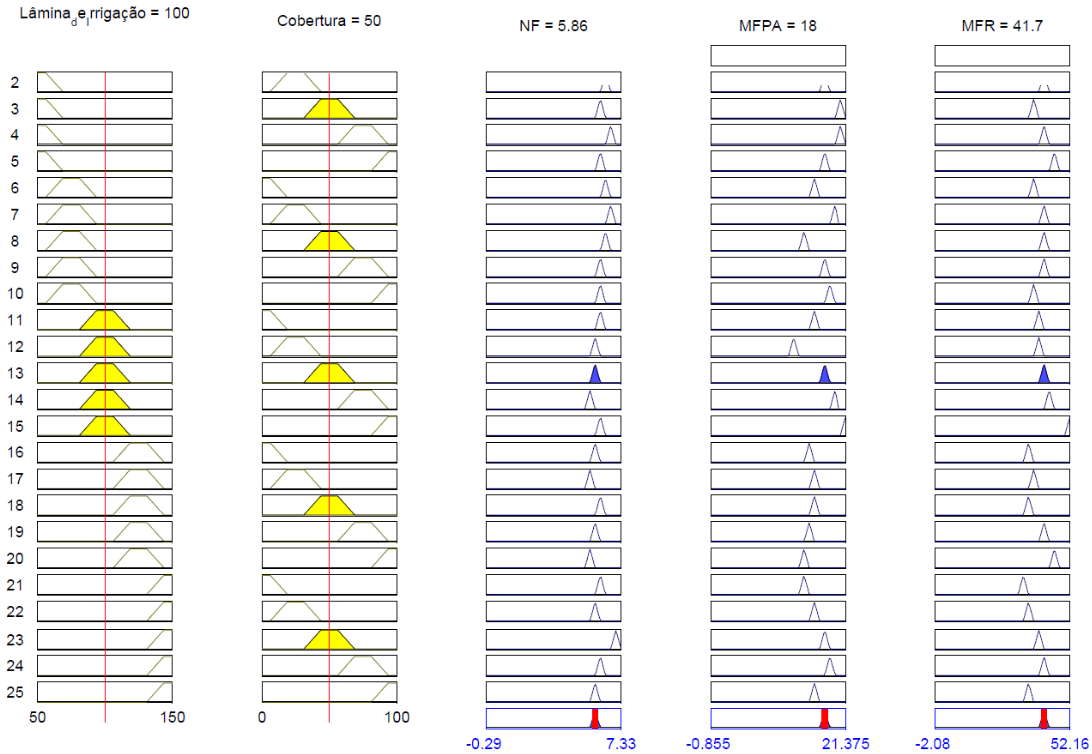
Figure 8. Membership functions of the *fuzzy sets* of the output variables: (A) number of leaves (NF), (B) fresh mass of the aerial part (MFPA, g plant $^{-1}$), and (C) fresh mass of the root (MFR, g plant $^{-1}$) for the radish crop subjected to different irrigation and mulch depths.



Source: Author (2021)

Through the model generated by means of the rules, the estimates of the variables analyzed with the use of 100% ETc and 50% mulch yielded values of 5.86 for NF, 18 g plant $^{-1}$ for MFPA and 41.7 g plant $^{-1}$ for MFR (Figure 9).

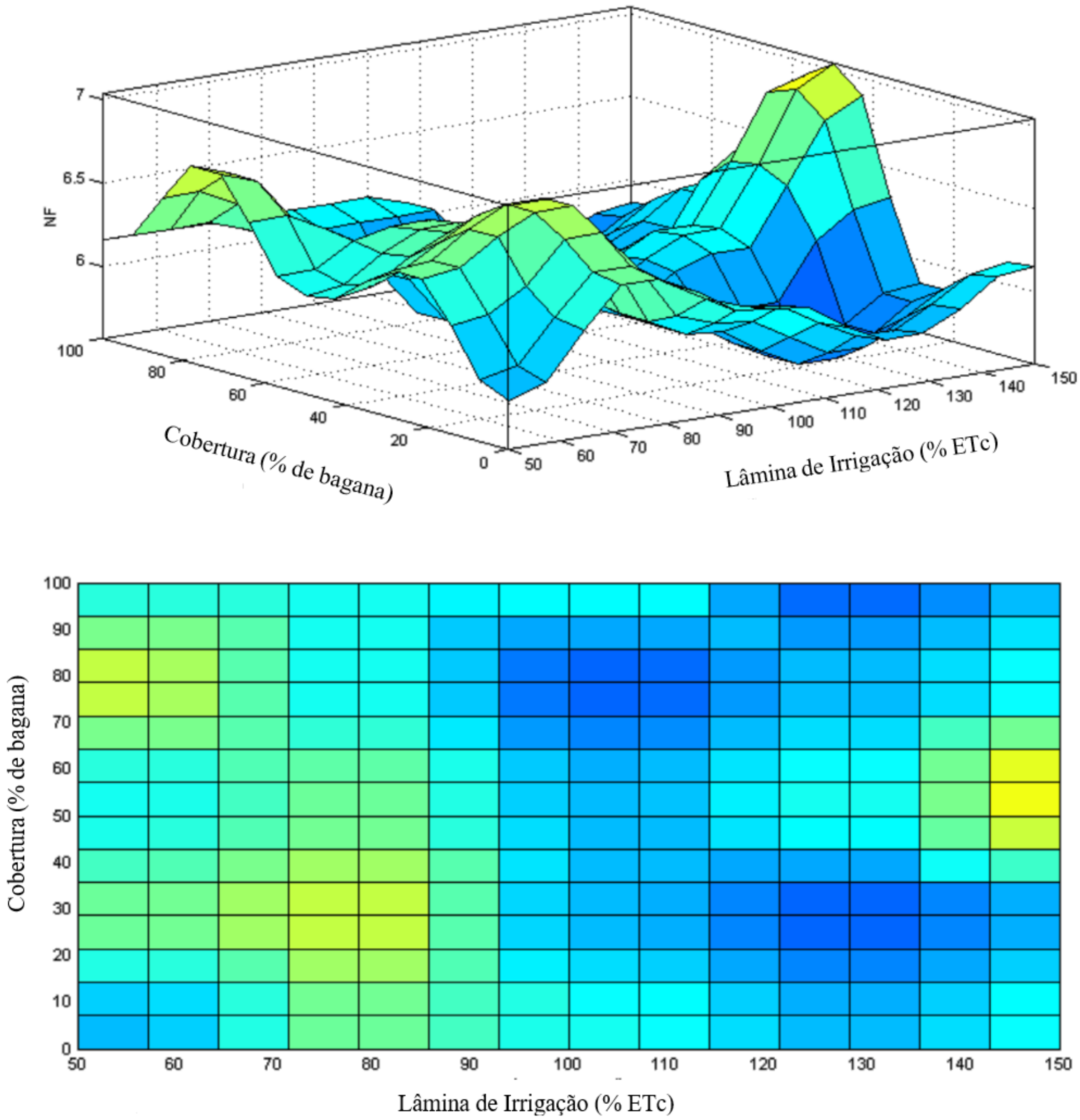
Figure 9. Visualization of the rules of the generated *fuzzy model* in relation to the response variables



Source: Author (2021)

For the NF variable, Figure 10 shows the adjustment of the *fuzzy model* for decision support. High irrigation depths (greater than 100% of ETc) increased the crop's NF, together with the use of 40 to 60% mulch. In other words, greater water availability can lead to an increase in NF. However, when water conservation is necessary, the use of 50 to 60% of ETc with 70 to 80% mulch can provide benefits, especially in water-scarce regions such as semiarid regions. Almeida *et al.* (2020) demonstrated that the use of carnauba bagasse can increase radish productivity. Other vegetables studied also demonstrated potential increases in their variables with increasing irrigation depth. Among these studies, the work of Silva *et al.* (2021) with tomato crops stands out.

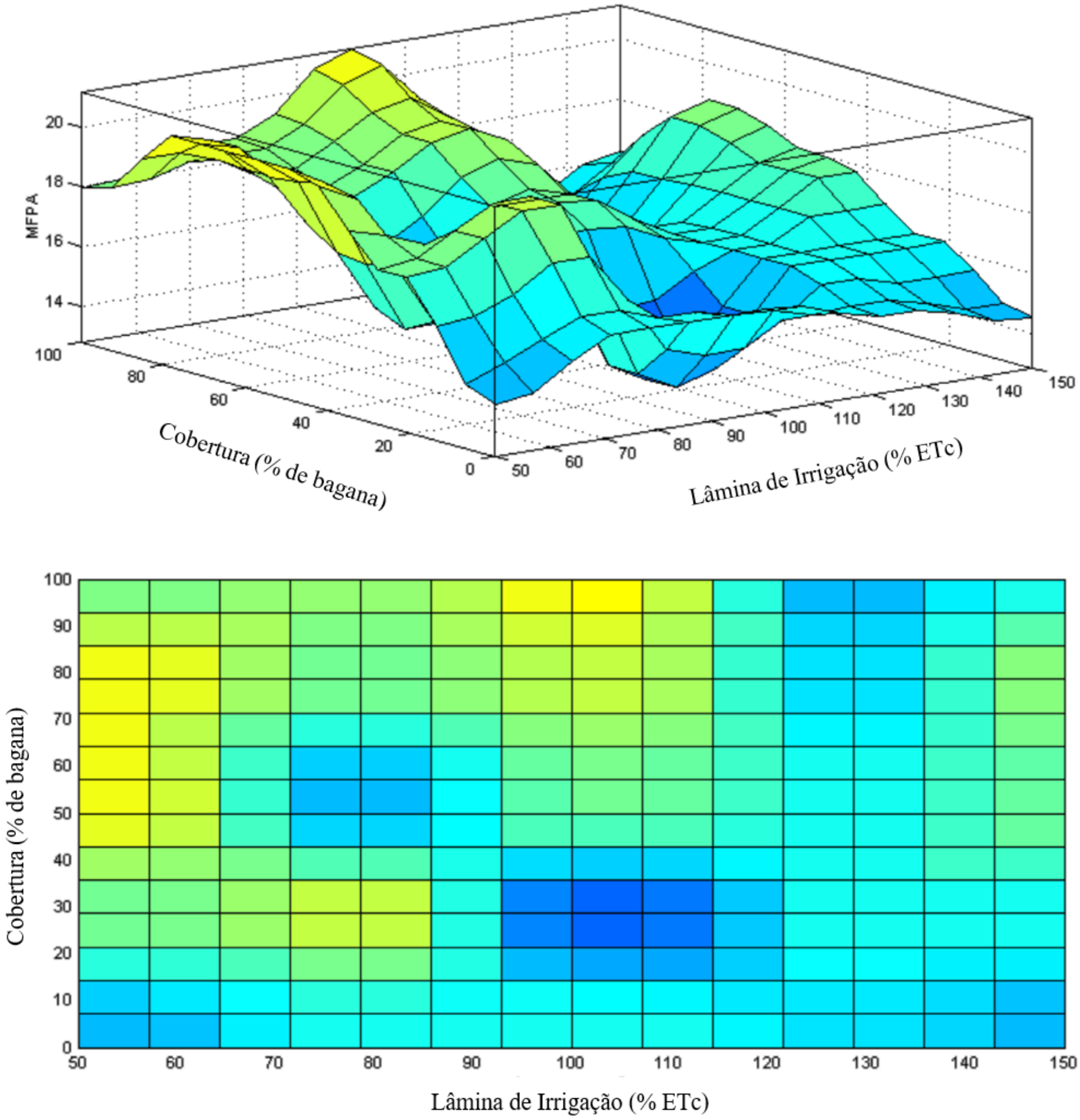
Figure 10. *Fuzzy* model for the variable number of leaves (NF) as a function of different irrigation depths (%ETc) and mulch for the radish crop.



Source: Author (2021)

The *fuzzy* model generated for the MFPA variable is shown in Figure 11. The combination of 100% ETc and 100% carnauba bagasse yielded the highest values (21.4 g plant $^{-1}$) observed for the MFPA variable. However, to reduce water use, the model indicates the use of 50% or 60% ETc with 80% mulch. This decision does not drastically affect MFPA production in plants, reducing water consumption by half. Frizzone (2007) demonstrated that irrigation planning should prioritize the optimal depth to be applied, aiming for maximum yield and input savings. In this sense, *fuzzy modeling* can serve to support rural producers in ensuring proper water use.

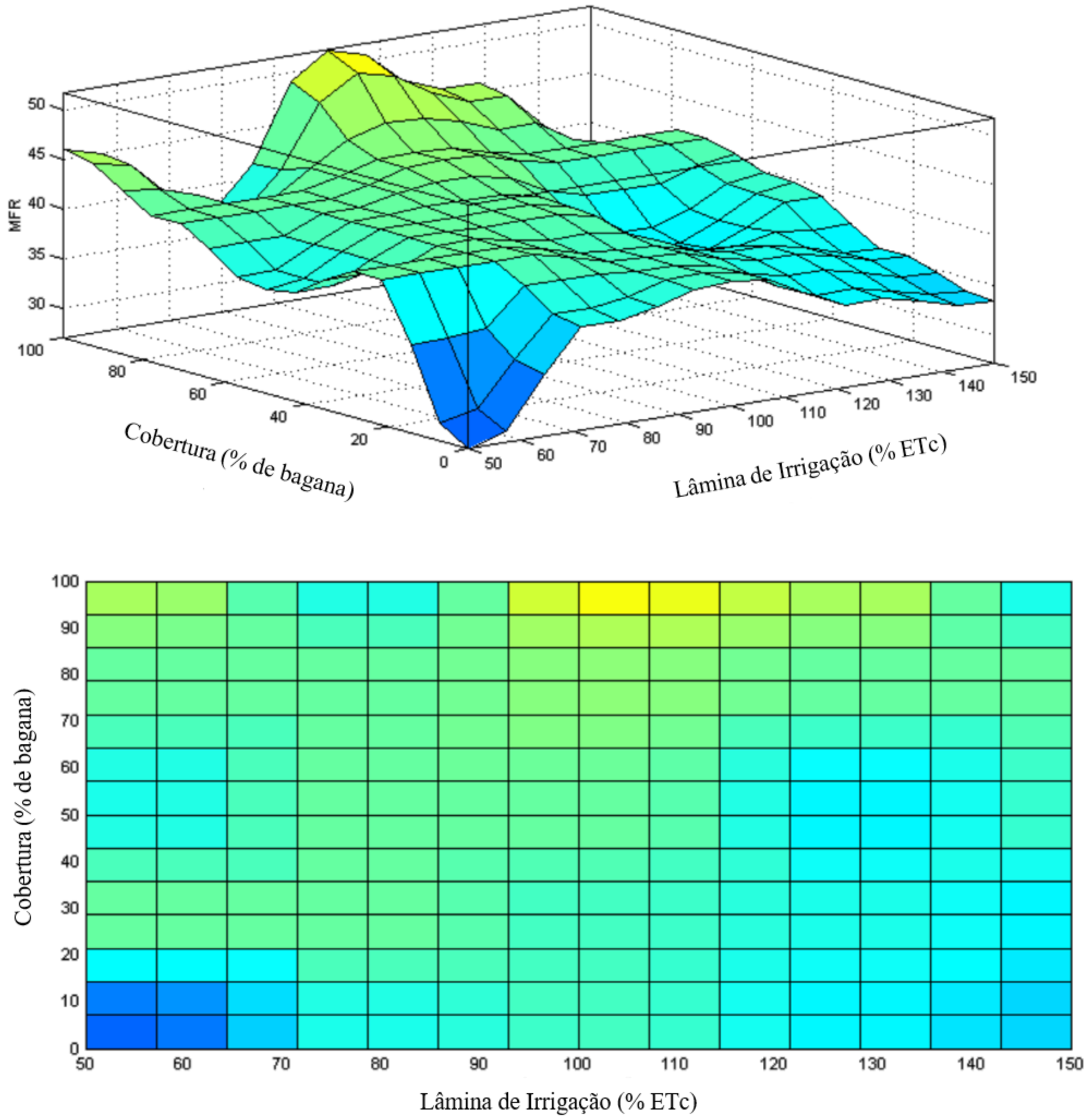
Figure 11. *Fuzzy* model for the variable fresh mass of the aerial part (MFPA, g plant $^{-1}$) as a function of different irrigation depths (%ETc) and mulch for the radish crop.



Source: Author (2021)

With respect to the *fuzzy model* for the MFR variable (Figure 12), the use of 100% ETc and 100% mulch yields the highest values (52.2 g plant $^{-1}$) for this variable, considering the commercial portion of this vegetable. With respect to water use management, it is possible, according to the proposed method, to reduce the applied water depth by 10% (90% ETc) in combination with 100% mulch, resulting in values of 45.6 g plant $^{-1}$. Despite the reduction in production, the 10% savings in water use can reach values of up to 10 m³ of water per month for areas greater than 0.5 ha, thus helping small producers increase water use efficiency in agriculture, despite the reduction in crop productivity. Peji ć *et al.* (2011), Mohammadian *et al.* (2008) and Katerji *et al.* (1997) reported that stress caused by a lack of water and excess salts leads to a reduction in production variables, as well as in the physiological characteristics of plants. However, according to Almeida *et al.* (2020) and Silva *et al.* (2021), reducing water use is a necessary strategy in irrigated agriculture, especially in regions with low water availability.

Figure 12. *Fuzzy* model for the variable fresh root mass (MFR, g plant $^{-1}$) as a function of different irrigation depths (%ETc) and mulch for the radish crop.



Source: Author (2021)

6 CONCLUSIONS

In the present study, fuzzy modeling was shown to be an interesting tool to support the adequate use of water with a view to managing irrigation and mulching in vegetables.

Using *fuzzy modeling*, it was possible to determine that the production of radish crops using irrigation depths of 80 to 90% of the ETc and 100% of the vegetation cover was satisfactory, thus increasing water use efficiency.

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