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REGULAR ARTICLE

Fuzzy modeling of coffee productivity under different irrigation depths, water deficit and temperature

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EZG: conceptualization, supervision, experimental data collection, data custody, data analysis, literature review, writing the manuscript, manuscript review; FdeLC.: conceptualization, manuscript review, Supervision; LRAGF: literature review, writing the manuscript, manuscript review, data analysis. CPCG: literature review, data analysis, writing the manuscript, manuscript review.

Abstract

The coffee culture has great economic importance on the world stage, especially for Brazil. Considered one of the most traded commodities on the world's trading exchanges. Thus, the main objective of this study was to develop a system based on fuzzy rules to evaluate coffee productivity, using irrigation, soil water deficit and ambient temperature as the main production factors. The research was developed from searches of scientific data on the main variables for coffee production. The work was divided into two stages: the first in the scientific search for data collection and the second in the development of the fuzzy model. With this, it was parameterized that the input variables would be the temperature, the irrigation depth, and the water deficit of the soil and for the output variable the coffee productivity. Based on the model prediction, the fuzzy system showed which variable values are necessary for the best coffee productivity, by a set of rules involving the variation of water deficit (60%), temperature (30°C) and irrigation (300 mm), for a productivity of 24 sc ha^{-1}. The performance of the fuzzy system was tested by comparing it with articles on the subject that relate coffee production with irrigation, water deficit and temperature of the environment and in almost all cases the model was efficient, reinforcing the assessment of the strength of the scheme, the analysis was extended to several scenarios relating the same three input variables.

Keywords

Fuzzy logic. Irrigation. Water deficit. Temperature.

Introduction

The coffee crop (Coffea sp.) has great economic importance on the world stage, mainly for Brazil (Ramachandra; Bharath; Vinay, 2019). Considered one of the most traded commodities on the world's trading exchanges (Ronchi & Miranda, 2020).

According to the National Supply Company (CONAB), in the 2020/2021 harvest, coffee production in Brazil exceeded 47,000,000 processed bags, of which approximately 75.0% of production was arabica coffee and 25.0% conilon coffee or robust (CONAB, 2021).

These high productions confirm that Brazil is the main world producer (Silva et al., 2011). With great emphasis on the Southeast regions, especially the State of Minas Gerais, which is the largest national producer of the grain, having produced in the 2020/2021 harvest about 39,813 thousand bags of processed coffee, equivalent to approximately 84.0% of the national production (CONAB, 2021).

However, to achieve high productivity, the plant needs to have two important factors in its management from its development to production, such as water and temperature of the environment (Garcia et al., 2019). Therefore, correct management with irrigation is essential for the overall development of the plant (Assar et al., 2019), which without this factor can lead to losses in the plant in production and in the environment (soil), inhibiting absorption and translocation of nutrients, gas exchange with the environment to produce photosynthesis, among other important processes, mainly for coffee cultivation (Rodrigues et al., 2022).

In addition to this factor, another indicator has great representation in production, the water balance, which is characterized by the interaction between the soil-water-plant-atmosphere system, considering as a basis the inputs and outputs of water in this system (Batista et al., 2010). It can be monitored by the availability of water and the general characteristic of the soil, in addition to the rate of evaporation from the atmosphere and especially the ability of the crop to

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absorb water from the soil (Silva et al., 2019). In view of this, the agribusiness production chain tends to use technology tools to optimize production processes, a method used is fuzzy or fuzzy logic.

Fuzzy set theory was introduced by Lotfi Asker Zadeh in the 1960s, as a mathematical theory applied to fuzzy concepts (Zadeh, 1965). Since then, the research and application of this theory in information systems has grown more and more, (Godoy et al., 2020, Godinho; Caneppele; Gasparotto, 2021). What makes fuzzy logic increasingly used is that it approaches human thinking (Caneppele; Seraphim, 2013). In these cases, linguistic variables are represented by fuzzy sets, interpreting a linguistic variable as a variable whose values are words or sentences in natural language, in addition to the existence of variation in the options (Zadeh, 1965).

Thus, the main objective of this study was to develop a system based on fuzzy rules to evaluate coffee productivity, using irrigation, soil water deficit and ambient temperature as the main production factors.

Materials and methods

Experimental data

The experiment was installed in the greenhouse of State Agricultural College Adroaldo Augusto Colombo (CAEAAC), located in the municipality of Palotina/PR, latitude 25º02'29" South, longitude 54º15'45" West and altitude of 450 m.

The Coffea arabica species of Catuaí Vermelho IAC 44 variety was used, in an area of 1 hectare, where it had 7,000 feet of dimensions of 70 cm between plants and 2.5 meters between lines.

A chemical analysis was carried out on the soil for possible corrections with limestone and specific use of a fertilizer. The experiment was set up in a completely randomized design with five treatments and three replications. The treatments consisted of the use of drip irrigation on each foot, with irrigation opening every 7 days in an interval of 10 in 10 days, where MB = very low irrigation up to 100 mm, B = low irrigation between 101 and 200 mm, Me = medium irrigation between 201 and 300 mm, A = high irrigation between 301 and 400 mm and MA = very high irrigation between 501 and 600 mm.

The article was based on detailed readings of scientific articles on topics related to irrigation, water deficit and temperature for arabica coffee productivity (Garcia et al., 2019, Arêdes; Pereira; Santos, 2010, Silva et al., 2011, Lenzi; Marvasi; Baldi, 2021, Tavares et al., 2013, Wakeyo; Gardebroek, 2017, Ren; Yang; Zhang, 2019).

Fuzzy controller

Fuzzy rules were developed based on four main components: an input processor also called input, a set of linguistic rules, a fuzzy inference method and an output processor, generating a real number as output (Caneppele et al., 2021).

In this way, it was possible to build the membership functions for the input variables, such as irrigation, in the form of water depth (mm), water deficit (%) and temperature (°C) and for output the productivity of the coffee (sc ha^{-1}) according to Figure 1.

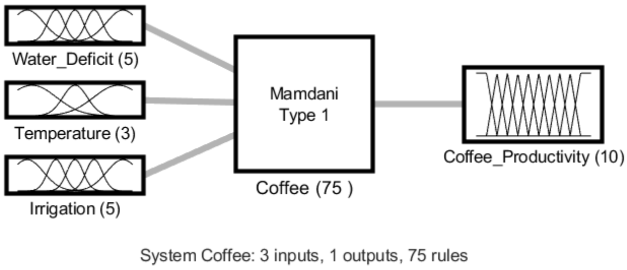

Figure 1. *Fuzzy* set membership functions of the Mineral Fertilizer *input* variables.

For each input variable, the fuzzy sets associated by the linguistic variables were defined. For temperature, the variables were defined as follows: “Low” (B), “Medium” (M) and “High” (A), with a range value between 20 and 40°C [20 – 40], as shown in Figure 2.

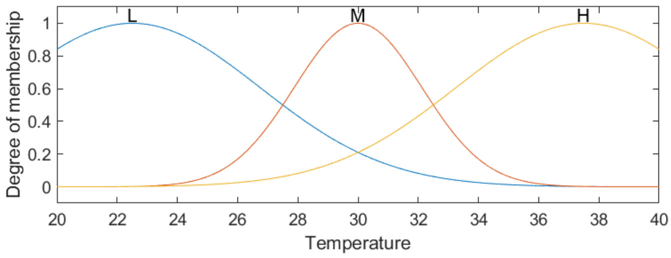

Figure 2. *Fuzzy* set membership functions of the Mineral Fertilizer *input* variables.

In the water deficit variable, the pertinence functions were defined: “Very Low” (MB), “Low” (B), “Medium” (M), “High” (A) and “Very High” (MA) with a range value between 0 and 120% [0 – 120], as shown in Figure 3.

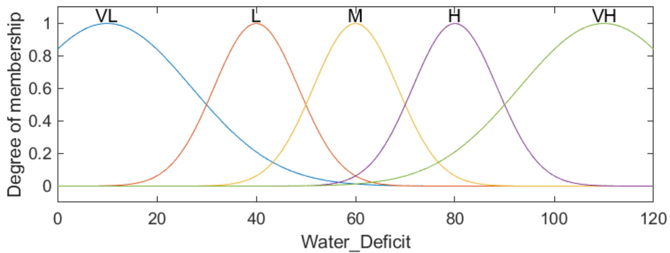

Figure 3. Fuzzy set membership functions of the Mineral Fertilizer input variables.

For the irrigation variable, the pertinence functions were defined: “Very Low” (MB), “Low” (B), “Medium” (M), “High” (A) and “Very High” (MA) with a range between 0 and 600mm [0 - 600], as shown in Figure 4.

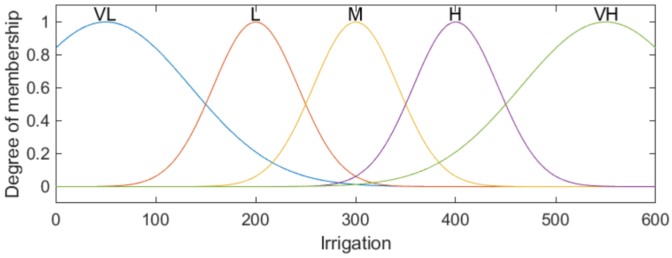

Figure 4. Fuzzy set membership functions of the Mineral Fertilizer input variables.

Thus, the membership functions for the *output* variable in coffee productivity (sc ha^{-1}), were defined between 0 and 33, that is, [0 – 33]. The functions were given between values at the midpoint (3; 6; 9; 12; 15; 18; 21; 24; 27 and 30), where production responses were collected in several scientific documents (Silva et al., 2006; Valadares et al., 2013 and Moreira et al., 2019), where language settings PROD1 to PROD10 were applied, as shown in Figure 5.

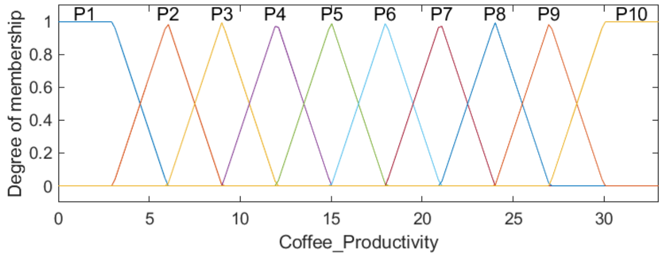

Figure 5. Fuzzy set membership functions of the Mineral Fertilizer input variables.

Results and discussion

Productivity

From the reading of scientific data (Arêdes; Pereira; Santos, 2010; Assar et al., 2019; Batista et al., 2010; Ren; Yang; Zhang, 2019; Rodrigues et al., 2022; Ronchi; Miranda, 2020; Silva et al., 2019) based on topics related to the use of irrigation in coffee, it was possible to outline the rule base (Table 1).

Table 1. Definition of parameters of triangular relevance functions for the *output* variable.

Id.	DH	Temp.	Irr.	Prod.	Id.	DH	Temp.	Irr.	Prod.
1	MA	B	MB	P1	**39**	M	M	A	P9
2	MA	B	B	P2	**40**	M	M	MA	P9
3	MA	B	M	P3	**41**	M	A	MB	P6
4	MA	B	A	P7	**42**	M	A	B	P6
5	MA	B	MA	P8	**43**	M	A	M	P8
6	MA	M	MB	P1	**44**	M	A	A	P9
7	MA	M	B	P1	**45**	M	A	MA	P9
8	MA	M	M	P2	**46**	B	B	MB	P5
9	MA	M	A	P2	**47**	B	B	B	P5
10	MA	M	MA	P3	**48**	B	B	M	P6
11	MA	A	MB	P1	**49**	B	B	A	P7
12	MA	A	B	P1	**50**	B	B	MA	P8
13	MA	A	M	P3	**51**	B	M	MB	P6
14	MA	A	A	P5	**52**	B	M	B	P7
15	MA	A	MA	P8	**53**	B	M	M	P8
16	A	B	MB	P3	**54**	B	M	A	P8
17	A	B	B	P3	**55**	B	M	MA	P9
18	A	B	M	P3	**56**	B	A	MB	P4
19	A	B	A	P5	**57**	B	A	B	P4
20	A	B	MA	P5	**58**	B	A	M	P8
21	A	M	MB	P5	**59**	B	A	A	P8
22	A	M	B	P2	**60**	B	A	MA	P9

23	A	M	M	P2	**61**	MB	B	MB	P10
24	A	M	A	P5	**62**	MB	B	B	P9
25	A	M	MA	P4	**63**	MB	B	M	P8
26	A	A	MB	P2	**64**	MB	B	A	P8
27	A	A	B	P2	**65**	MB	B	MA	P8
28	A	A	M	P4	**66**	MB	M	MB	P9
29	A	A	A	P6	**67**	MB	M	B	P10
30	B	A	MA	P7	**68**	MB	M	M	P10
31	M	B	MB	P3	**69**	MB	M	A	P9
32	M	B	B	P3	**70**	MB	M	MA	P9
33	M	B	M	P5	**71**	MB	A	MB	P7
34	M	B	A	P5	**72**	MB	A	B	P9
35	M	B	MA	P8	**73**	MB	A	M	P9
36	M	M	MB	P6	**74**	MB	A	A	P7
37	M	M	B	P6	**75**	MB	A	MA	P8
38	M	M	M	P8					

DH – Water Deficit; Temp. – Temperature; Irr. – Irrigation. MB – Very low; B – Low; M – Average; The high; MA – Very high, for the *input* membership data.

Table 1 presents the basic rules of the system, which was elaborated from linguistic data of fuzzy logic. Where: If (water deficit is “MA”) (temperature is “B”) (irrigation is “MB”) then (productivity “P1”); If (water deficit is “MA”) (temperature is “B”) (irrigation is “B”) then (productivity “P2”); If (water deficit is “MA”) (temperature is “B”) (irrigation is “Me”) then (productivity “P3”); If (water deficit is “MA”) (temperature is “B”) (irrigation is “A”) then (productivity “P7”); If (water deficit is “MA”) (temperature is “B”) (irrigation is “MA”) then (productivity “P8”); If (water deficit is “MA”) (temperature is “Me”) (irrigation is “MB”) then (productivity “P1”); If (water deficit is “MA”) (temperature is “Me”) (irrigation is “B”) then (productivity “P1”); If (water deficit is “MA”) (temperature is “Me”) (irrigation is “Me”) then (productivity “P2”); If (water deficit is “MA”) (temperature is “Me”) (irrigation is “A”) then (productivity “P2”); If (water deficit is “MA”) (temperature is “Me”) (irrigation is “MA”) then (productivity “P3”); If (water deficit is “MA”) (temperature is “A”) (irrigation is “MB”) then (productivity “P1”); If (water deficit is “MA”) (temperature is “A”) (irrigation is “B”) then (productivity “P1”); If (water deficit is “MA”) (temperature is “A”) (irrigation is “Me”) then (productivity “P3”); If (water deficit is “MA”) (temperature is “A”) (irrigation is “A”) then (productivity “P5”); If (water deficit is “MA”) (temperature is “A”) (irrigation is “MA”) then (productivity “P8”) and the other lines are interpreted analogously.

From there, it was possible to develop response surfaces for coffee productivity and their contour maps to verify the real inference of the use of irrigation depth, water deficit and temperature on coffee productivity.

The model based on fuzzy rules verified all combinations between the variables, being for water deficit (5 levels), temperature (3 levels) and irrigation depth (5 levels) resulting in a combination of 5 x 3 x 5, that is, 75 possible combinations.

With this, the models of diffuse response surfaces in Figures 6 to 8 were developed.

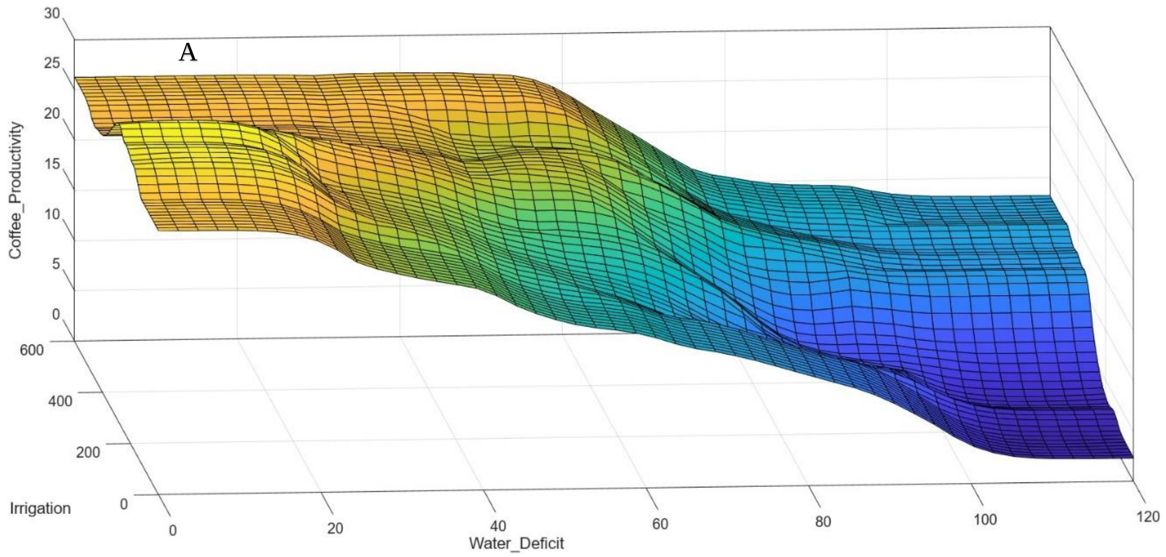

Figure 6. Response surface model of coffee productivity in response to water deficit x irrigation.

The regions where they are indicated with the letter "B" illustrated in Figure 6, represent unfavourable conditions for coffee, due to values that may be above or below what is necessary for high productivity, in addition to not providing ideal conditions for the growth and development of this specific culture. On the other hand, region "A" is characterized by being an area that presents the best indicators for coffee productivity correlating water deficit between 3 and 20% with irrigation depth between 180 and 280mm.

Observing the results presented in Fig. 6, the authors obtained good results when comparing irrigation and water deficit. Reinforcing the good results Giusti & Marsili-Libelli (2015), presented similar results when applied modeling relating water deficit x irrigation.

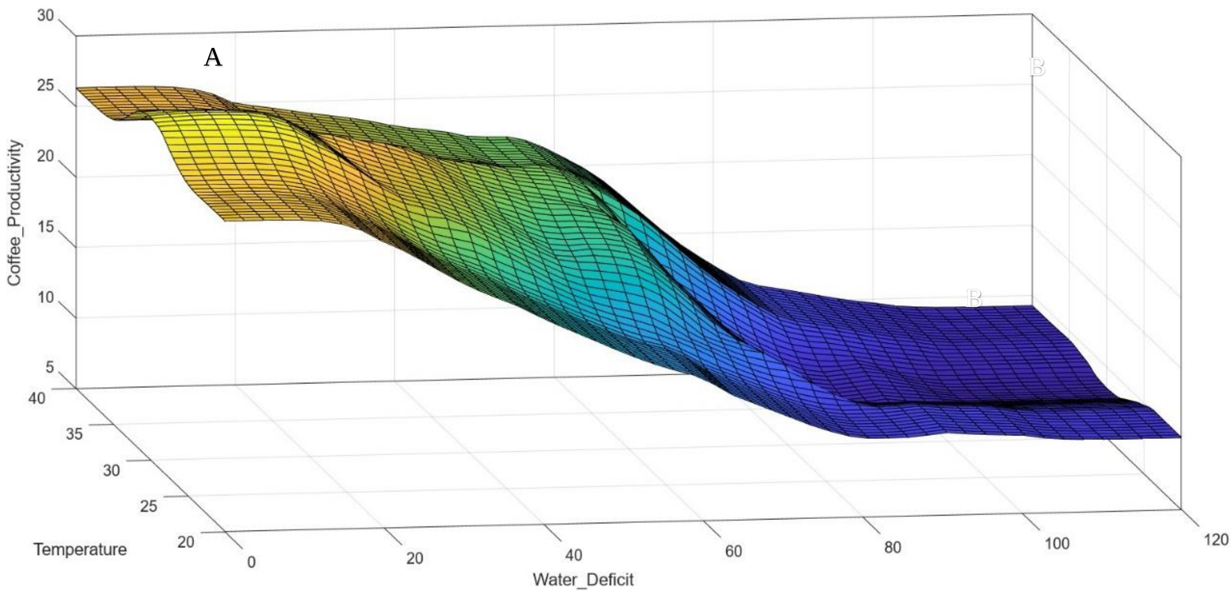

Figure 7 - Response surface model of coffee productivity in response to water deficit x temperature.

The region presented in indicator "A", corresponds to the best points to obtain high productivity in coffee, analyzing the water deficit with temperature, having intervals between 3 and 20% and 28 to 31°C, respectively. In region "B", the conditions of both variables do not present responses that could have high coffee productivity.

Batista et al. (2010), presents satisfactory results in relation to the relationship between coffee production and water deficit, where they mapped the interval of lack of water in the foot that could harm the final production of the coffee plantation. These results reaffirm the applicability of an optimization model that presents water, water deficit and irrigation relationships for coffee, as it is observed that even with a water deficit at certain levels it does not interfere with coffee productivity.

Armoa Báez et al. (2020), demonstrated results on the influence of different irrigation levels and meteorological conditions on water balance, the soybean cycle, morphological characteristics, and their yield components, concluded that there was a reduction in grain yield with increasing deficit water between 11.5% and 42.0% in the two years of analysis. Reinforcing the applicability of modelling to seek to optimize the processes that involve the production of cultures, mainly the coffee culture of great expression in the world.

Ronchi & Miranda (2020), working with coffee relating water deficit versus production, concluded that deficits of 4 to 6 days tend to significantly interfere with coffee productivity. In contrast, Fernandes et al. (2016), obtained opposite results regarding the water deficit in relation to coffee production in the Cerrado Mineiro region.

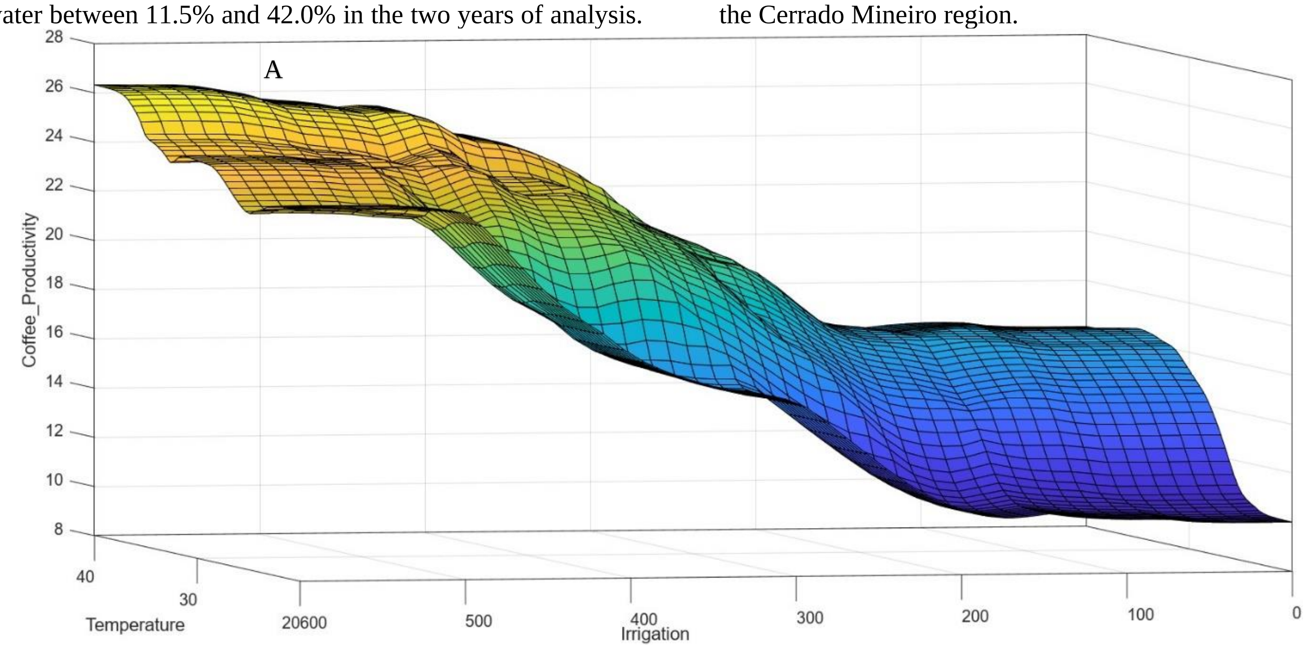

Figure 8 - Coffee productivity response surface model in response to temperature x irrigation.

Region “B” illustrated in Figure 8 represents an unfavourable coffee productivity condition due to the low use of irrigation with low temperatures, which do not provide ideal conditions for the growth and development of this specific crop. On the other hand, region “A” is characterized by being an area that presents specific indicators of irrigation depth at 400 to 600mm with temperatures between 31 and 40°C, which provides a suitable region condition for high coffee productivity.

In this research, a strong relationship was observed between the three analysed variables (water deficit, temperature, and irrigation depth) obtaining coffee productivity as a response. Which demonstrates that coffee responds well to these specified values.

From there, it resulted in an application of the Mandani inference method (Gabriel Filho et al., 2011, Gabriel Filho et al., 2015, Gabriel Filho et al., 2016) for coffee productivity, as shown in Figure 9.

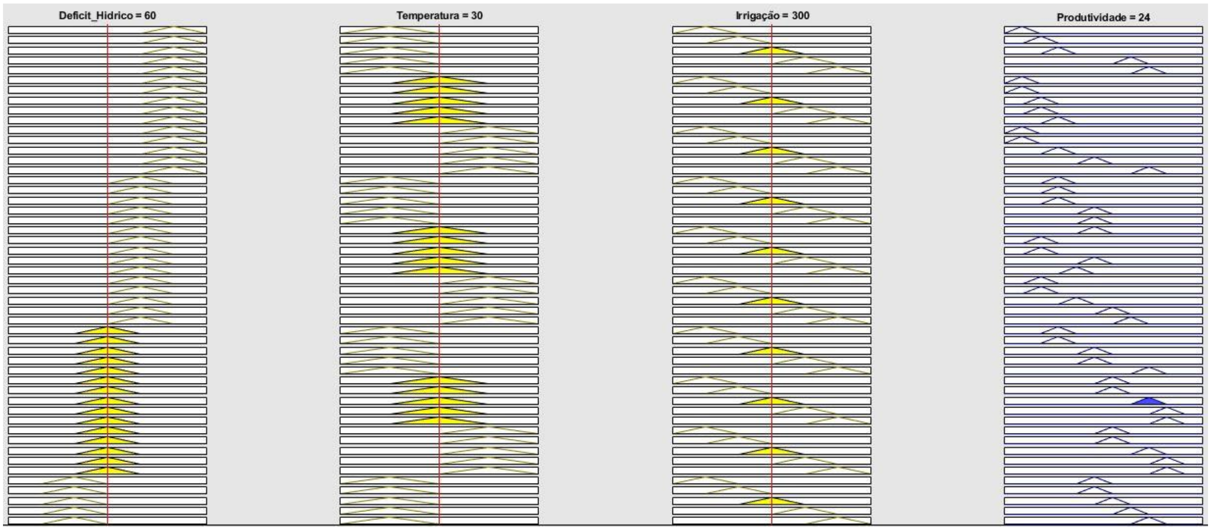

Figure 9 - Mandani inference method for water deficit = 60%, temperature = 30°C and irrigation depth = 300mm, with coffee productivity = 24.0 sc ha^{-1}.

The best point found is within an intermediate condition for both *input* variables, which results in an approximate yield of 24 sc ha^{-1}. When analysing the degree of pertinence of the *fuzzy* set, a maximum point (1.0) is observed in productivity, which may consider the maximum productivity in relation to the management of the *input* variables.

Conclusions

This article presented a decision support system for the use of variables (water deficit x irrigation depth x temperature), based on a *fuzzy* inference system, which incorporates a *fuzzy* model for coffee productivity. Its development was motivated by developing a better result in coffee production based on data from scientific articles with topics related to coffee irrigation.

Based on the model prediction, the *fuzzy* system decides which variable values are necessary for the best coffee productivity, by a set of rules involving the water deficit variation (60%), temperature (30°C) and irrigation (300mm), for a productivity of 24 sc ha^{-1}.

The performance of the *fuzzy* system was tested by comparing it with articles on the subject that relate coffee production to irrigation, water deficit and medium temperature and in almost all cases the model was efficient. To assess the strength of the scheme, the analysis was extended to several scenarios relating the three *input* variables.

The next steps should increasingly restrict the range of variables so that the results are closer to real values.

References

Arêdes, A. F. de, Pereira, M. W. G., & Santos, M. L. dos. (2010). A irrigação do cafezal como alternativa econômica ao produtor. *Acta Scientiarium Agronomy*, Maringá, 32(2), 193-200. https://doi.org/10.4025/actasciagron.v32i2.1624.

Armoa Báez, M. S. et al. (2020). Balanço hídrico e produtividade da soja cultivada sob diferentes níveis de déficit hídrico no Sul do Brasil. *Investigación Agraria*, 22 (1), 3-12. https://doi.org/10.18004/investig.agrar.2020.junio.03-12.

Assar, W. et al. (2019). Assessing the agricultural drainage water with water quality indices in the El-Salam Canal Mega Project, Egypt. *Water* (Switzerland), 11(5), 1-21. https://doi.org/10.3390/w11051013.

Batista, L. A. et al. (2010). Anatomia foliar e potencial hídrico na tolerância de cultivares de café ao estresse hídrico. *Revista Ciência Agronômica*, 41(3), 475-481. https://doi.org/10.1590/S1806-66902010000300022.

Caneppele, F. D. L. et al. (2021). Aplicação da lógica *fuzzy* no desenvolvimento do morango no Oeste do Paraná. *Revista Sodebras*, 16(184), 6-9. https://doi.org/10.29367/issn.1809-3957.16.2021.184.06.

Caneppele, F. D. L., & Seraphim, O. J. (2013). Madeireiras através da lógica *fuzzy*. *Revista Energia na Agricultura*, 28(2), 95-102. https://doi.org/10.17224/EnergAgric.2013v28n2p95-102.

CONAB, Companhia Nacional de Abastecimento. Acompanhamento da safra brasileira: café, v.8, n.3 (2021) Brasília: Conab, 2021.

Fernandes, A. L. T. et al. Viabilidade técnica e econômica da irrigação localizada do cafeeiro, nas condições climáticas do planalto de Araxá, MG. *Coffee Science*, 11: 346-57, 2016. https://doi.org/10.1590/1983-21252020v33n121rc.

Garcia, F. H. S. et al. (2019). Análise fisiológica em mudas de cafeeiro com cercosporiose submetida a diferentes lâminas de irrigação. *Summa Phytopathologica*, Botucatu, 45(1), 83-88. https://doi.org/10.1590/0100-5405/185711.

Giusti, E., Marsili-Libelli, S. (2015). A Fuzzy Decision Support System for irrigation and water conservation in agriculture. *Environmental Modelling & Software*, 63, 73-86. https://doi.org/10.1016/j.envsoft.2014.09.020.

Godinho, E. Z., Caneppele, F. D. L., & Gasparotto, H. V. (2021). Utilização da lógica *fuzzy* para otimizar aplicação de fertilizantes no rabanete. *Revista Brasileira de Engenharia de Biossistemas*, 15(2), 270-282. https://doi.org/10.18011/bioeng2021v15n2p270-282.

Godoy, F. O. de et al. (2020). Utilização da lógica *fuzzy* aplicada à energia solar. *Cadernos de Ciência & Tecnologia*, 37(2), e26663. http://dx.doi.org/10.35977/0104-1096.cct2020.v37.26663.

Lenzi, A., Marvasi, M., & Baldi, A. Agronomic practices to limit pre-and post-harvest contamination and proliferation of human pathogenic Enterobacteriaceae in vegetable produce. *Food Control*, 119, e107486. https://doi.org/10.1016/j.foodcont.2020.107486.

Moreira, P. et al. (2019). Produtividade e economia de fatores de produção na cafeicultura brasileira. *Revista de Política Agrícola*, 28(2), 6-21.

Ramachandra, T. V., Bharath, S., & Vinay, S. (2019). Visualisation of impacts due to the proposed developmental projects in the ecológically fragile regions-Kodagu district, Karnataka. *Progress in Disaster Science*, 3, e100038.

Ren C, Yang J, & Zhang H (2019). Um modelo de programação fracionária inexata para alocação ideal de recursos hídricos de irrigação sob múltiplas incertezas. *PLoS ONE*, 14(6): e0217783. https://doi.org/10.1371/journal.pone.0217783.

Rodrigues, R. N. et al. (2022). Soil enzymatic activity under coffee cultivation with different water regimes associated to liming and intercropped brachiaria. *Ciência Rural*, Santa Maria, 52(3), e20200532. https://doi.org/10.1590/0103-8478cr20200532.

Ronchi, C. P., & Miranda, F. R. (2020). Flowering percentage in arabica coffee crops depends on the water deficit level applied during the pre - flowering stage. *Revista Caatinga*, Mossoró, 33(1), 195-204. https://doi.org/10.1590/1983-21252020v33n121rc.

Silva, A. H. et al. (2006). Produtividade de cultivares de café (*Coffea arabica* L.) sob espaçamentos adensados. *Revista Ceres*, Viçosa, 53(308). 539-547.

Silva, A. C. da et al. (2011). Evapotranspiração e coeficiente de cultura do cafeeiro irrigado por pivô central. *Revista Brasileira de Engenharia Agrícola Ambiental*, 15(2), 1215-1221. https://doi.org/10.1590/S1415-43662011001200001.

Silva, B. M. et al. (2019). Soil moisture associated with least limiting water range, leaf water potential, initial growth and yield of coffee as affected by soil management system. *Soil and Tillage Research*, 189, 36-43. https://doi.org/10.1016/j.still.2018.12.016.

Tavares, L. C. et al. (2013). Desempenho de sementes de soja sob deficiência hídrica: Rendimento e qualidade fisiológica da geração F1. *Ciência Rural*, 43(8), 1357-1363. https://doi.org/10.1590/S0103-84782013000800003.

Valadares, S. V. et al. (2013). Produtividade e bienalidade da produção de cafezais adensados, sob diferentes doses de N e K. *Pesquisa Agropecuária Brasileira*, 48(3), 296-303. https://doi.org/10.1590/S0100-204X2013000300008.

Wakeyo, M. B.; & Gardebroek, C. (2017). Share of irrigated land and farm size in rainwater harvesting irrigation in Ethiopia. *Journal of Arid Environments*, 139, 85-94. https://doi.org/10.1016/j.jaridenv.2017.01.002.

Zadeh, L. A. (1965). *Fuzzy* Sets. *Information and Control*, 8, 338-353.