# Fuzzy Logic Expert System for Taxonomic Variation of Solonchaks

Samir Hadj-Miloud, Kaddour Djili

10.18805/IJARe.A-641


## ABSTRACT

**Background:** The main objective of this research is to apply fuzzy logic to four Solonchaks, in order to determine their degree of remoteness or rapprochement with their central taxonomic concept. Therefore, we identify their possible seasonal taxonomic variation on the criteria established by world reference base (WRB).

**Methods:** We have studied the seasonal evolution of salinity in a region of Algeria (Case of Rélizane), during two years 2012 and 2013 by applying fuzzy logic on the four soils.

**Result:** The results reveal that the salinity increased during the dry period for all soils and it decreased during the wet period. On the taxonomic level, the application of fuzzy logic on the four soils revealed that the Solonchaks indices (Is) are always significantly higher than those of Calcisols indices (Ic). The four profiles have a similar behavior regarding the variation of Is. Indeed, when the salinity increases the soils come closer to the central taxonomic concept of the Solonchaks. Likewise, when the salinity decreases the soils move away from their central taxonomic concept. Consequently, they approach the central taxonomic concept of Calcisols. Thus, the variation of Isis closely related to the seasonal variation of salinity. Fuzzy logic, exhibited high precision concerning the membership value between soils over time. The application of fuzzy logic for other soil classifications in the world is possible.


**Key words:** Calcisol, Classification, Fuzzy logic, Salinity, Solonchak.

## INTRODUCTION

Fuzzy logic has spread widely in recent years,entering many scientific fields, including soil science (McBratney and Odeh 1997; Hadj Miloud *et al.* 2018). It aimed to deal with the uncertainty due to imprecision (Zimmermann, 2001). Moreover, the introduction of the fuzzy logicmodel would give some solutions for reducing indicatoruncertainty (Chunsheng *et al.* 2019). Nowadays, the principles of fuzzy logic applied in environmental science have become an important and sophisticated statistical instrument(Haidara, 2019; Demicco and Klir, 2003). In addition, use of fuzzy logic is worthwhile in view of the added level of detail, as compared to the very large and poorly defined units of upland soils in conventional soil mapping (Ruamporn *et al.* 2020). Fuzzy logic has the potential for reducing inconsistency and costs associated with the traditionalsoil mapping processes, as mapping can be carried out with a relatively low density of soil samples (Ruamporn *et al.* 2020).

Therefore, fuzzy logic development possesses a number of methods inferences systems. The most well known fuzzy inference system methods are fuzzy Mamdani (1977) and Takagi and Sugeno (1985). Many studies have been successfully used based on this method. The level for the system sensitivity Mamdani is by 94.4% (Wahyuni *et al.* 2016).

There are several fuzzy inference systems that were used in different applications, the most commonly used is the Mamdani fuzzy inference system (MFIS), which will be used in this research. The advantages of MFIS are known as intuitive; it is the most widespread acceptance and better suited to human knowledge (Mamdani, 1977; Yuanyuan *et al.* 2009).

MFIS can identify a possible variation in the degree of belonging of soils in relation to their central taxonomic concept, especially when it comes to salty soils such as Solonchaks. Their degree of salinity is subject to seasonal variations, this could cause a possible taxonomic change in the soils.

Soils salinity presents a strong spatio-temporal variability and a marked seasonality (FAO, 2002; Sabareshwari and Ramya, 2018). Salinity evolution is influenced by climate, irrigation water quality, poor drainage and by groundwater piezometric level. Soil salinity increases when soil dries up (FAO, 2002; Morgan *et al.* 2018; Mahesh and Ramovatar, 2019). Temporal variation of soils salinity could cause a change in their taxonomy, especially if they contain in addition other salts such as calcium carbonate.

Ecole Nationale Supérieure Agronomique (ENSA, ES1603), El-Harrach, Algeria.

**Corresponding Author:** Samir Hadj-Miloud, Ecole Nationale Supérieure Agronomique (ENSA, ES1603), El-Harrach, Algeria.
Email: samir.hadjmiloud@edu.ensa.dz

**How to cite this article:** Hadj-Miloud, S. and Djili, K. (2022). Fuzzy Logic Expert System for Taxonomic Variation of Solonchaks. Indian Journal of Agricultural Research. 56(1): 57-64. DOI: 10.18805/IJARe.A-641.

**Submitted:** 31-03-2021 **Accepted:** 10-06-2021 **Online:** 29-07-2021

In arid and semi-arid environments of North Africa, calcium carbonateaccumulations are frequently associated with those soluble salts (Djili, 2000). In many cases, soils are at the same time saltyand calcareous (Halitim, 1988; Djili, 2000). As a result, using WRB may not reflect sometimesthe field reality, especially when the similarity between two soils groups is strong, as is the case between Solonchaks and Calcisols (Hadj Miloud, 2019). Indeed, soil salinity seasonal modification can possibly constitute a modification of their degree of belongingwith respect totheir central taxonomic concepts. As a result, Solonchaks can move towards or away from their central taxonomic concept over the seasons.

The objective of this research is the application of MFIS to the Solonchaks to identify a possible variation in their degree of belonging membership to their central taxonomic concept, as defined by IUSS Working Group WRB (2015). This could occur during wet and dry seasons. This seasonal variation of the central taxonomic concept of the Solonchaks can affect the degree of belonging of the Solonchaks to the Calcisols, because these soils are at the same time salty and calcareous (Hadj Miloud, 2019). In order to meet this objective, we studied the seasonal variation of salt profiles of four Solonchaks in a region of Rélizane (Algeria). After that, we applied MFIS to these soils at the end of the wet season and at the end of the dry season of two consecutive years.

## MATERIALS AND METHODS

The soils studied are located in the irrigated perimeters of the plains of Mina and Bas Cheliff in the region of Relizane (Fig 1 and Table 1). The climate is semi-arid characterized by 253 mm rain/year and a very strong potential evapotranspiration (ETP = 1500 mm/year) calculated by Penman equation (1948). The maximal summer and winter temperatures are respectively 34°C and 12.2°C. Using IUSS Working Group WRB (2015) criteria, these soils are classified as Solonchaks. These Solonchaks are représented by four (4) profiles reférences identifed by Hadj Miloud (2010).

The profiles are moderately calcareous (18.5% < $CaCO_3$ < 20.2%) and very saline in most of their horizons (2.61 $dSm^{-1}$ < EC < 165.8 $dSm^{-1}$). The four Solonchaks locations are shown in Table 1.

Methodology adopted for this research comprises two stages, the study of the seasonal salt profile variation and then the application of MFIS.

### Seasonal salt profile variation

Four sampling campaigns were carried out at the end of the wet season (January) and at the end of the dry season (August) each year, during 2 years (2012 and 2013). The samples (from each horizon) are analyzed to determine their saturated paste extract salinity (EC) at 25°C. Thus, we determined the salinity of 74 samples (19 horizons × 4 intervals). This study was conducted at the Ecole Nationale Supérieure Agronomique, El-Harrach, Algeria. January, 2015.

### Application of MFIS

It is a question of classifying the four profiles by MFIS. This classification system was applied to studied soils, taking into account the seasonal modification of some their diagnostic criteria established by IUSS Working Group WRB (2015) (Table 2). These diagnostic criteria are evaluated at the end of the two wet seasons and at the end of the two dry seasons of the years 2012 and 2013 for the references of Solonchaks and Calcisols according to the WRB concepts.

MFIS requires three steps, fuzzification, inference and defuzzification (Fig 2).

Fuzzification is a process of converting numeric values (or physical parameters of the diagnostic criteria) of each group of soil (Table 2) into fuzzy variables. Fuzzification of all physical variables has been applied using the Gaussian

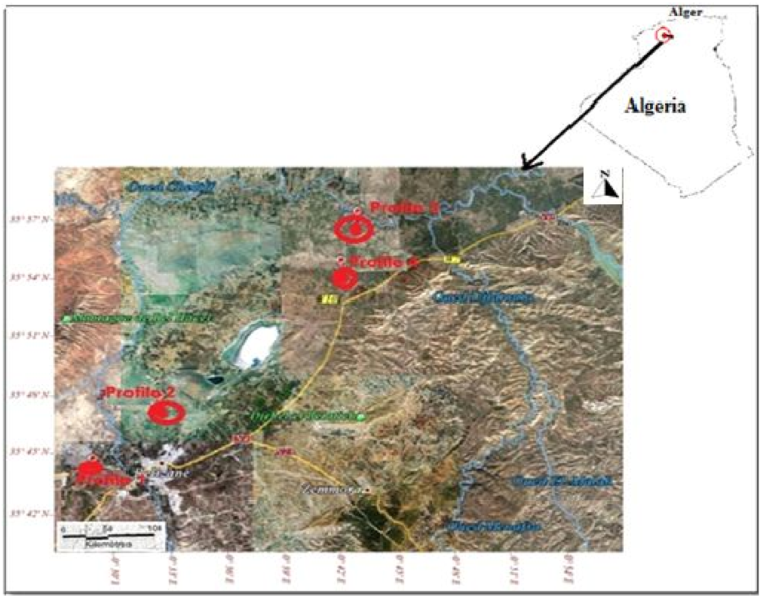


**Fig 1:** Profiles location map (red spots).

**Table 1:** Profiles location.

| Profiles | Longitude | Latitude | Location |
|---|---|---|---|
| 1 | 0° 29′ 31.2″ E | 35° 44′ 17.0″ N | Mina |
| 2 | 0° 33′ 22.0″ E | 35° 47′ 44.33″ N | Mina |
| 3 | 0° 44′ 59,6″ E | 35° 57′ 47,5″ N | Bas Chéliff |
| 4 | 0° 74′ 50.0″ E | 35° 92′ 49″ N | Bas Chéliff |

**Table 2:** Diagnostic criteria of soil groups recommended by WRB.

| Soil groups (output variables) | Variables used (WRB) (input variables) |
|---|---|
| Solonchaks | - EC (dS $m^{-1}$)- E (cm)- (EC × E) |
| Calcisols | - CE (%) - E (cm)- SC (%) |

E: Thickness of diagnostic horizons, EC: Electrical conductivity, SC: Secondary carbonate, CE: Calcium carbonate equivalent.

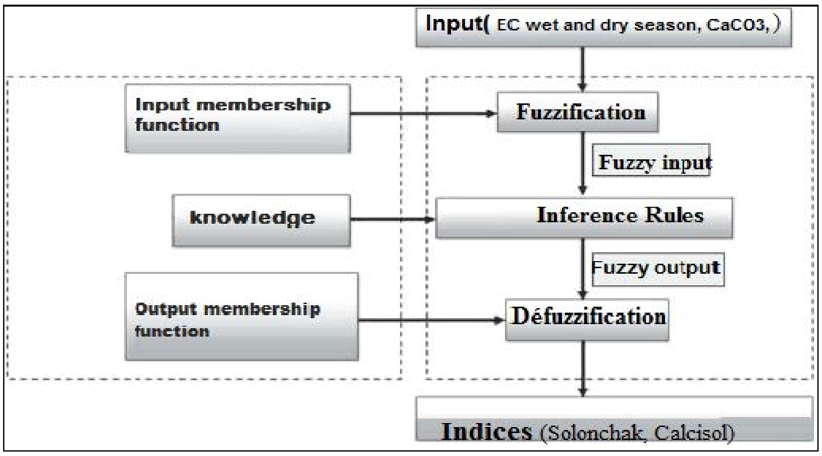


**Fig 2:** Block diagram of MFIS.

belonging function and the fuzzy set. The fuzzy variables (input) were divided into three subsets using linguistic variables, little value (L), medium value (M), and great value (G). The importance of input variables in the fuzzy logic approach can be weighted by using expert judgement (Shi *et al.* 2009).

During this step, we firstly defined the membership function of all variables, and then, we proceeded to the passage from the physical quantities to the linguistic variables. Fuzzy logic does not use binary logic, *i.e.* that a certain value is either "great" or "little" (called crisp data). Instead, memberships for all classes are inferred by indices.

The membership functions describe the membership degree of a fuzzy variable (EC in this case) to a fuzzy sub set A (little, medium, or great EC value) and it is noted as $\mu_A$ (x) where,

$$\mu_A(\chi) = [0\ 1] \text{ si } \chi \in A \text{ et } \mu_A(\chi) = 0 \text{ si } \chi \notin A$$

Compared to other numerical classifications as distance metrics method (Carré and Jacobson, 2009), neither crisp data (non fuzzy) nor model assumptions are required (Mamdani, 1974 ; Ahumada *et al.* 2015), which is considered as one of the major advantages of fuzzy logic.

Inference rules were developed using the 5 input data (diagnostic criteria or physical variables) (Table 2) previously divided into three sub groups that represent Solonchak, and Calcisol, respectively. The soil was classified Solonchak if all its diagnostic criteria were great (G). The same was applied for Calcisol. For example, if soil presented L (CE) and L (SC) (that characterize Calcisol) and GEC (that characterize Solonchak), the soil will be classified as Solonchak. These rules are expressed as single conditions (IF) or combined with other conditions (AND, OR) to achieve a linguistic result. Each rule consists of an antecedent part (condition or input) expressed by IF and a substantial portion (conclusion or output) expressed by THEN. For example, IF EC is L AND (EC × E) is L AND E is L (Solonchak criteria), AND calcium carbonate equivalent is G AND SC is G (Calcisol criteria) THEN Solonchak is L, Calcisol is G.

In this study, the degree of belonging between the soils studied was highlighted using 5 physical variables (two for each soil) and 3 linguistic variables (Little, Medium and Great). In total, 45 inference rules (equation 1) which represent all diagnostic criteria combinations. Under our conditions, we selected only 21 inference rules were retained high significant correlation (n = 194, p<0.05) between the different Solonchaks (Is) and Calcisol (Ic) indices and WRB diagnostic criteria (except for diagnostic horizon thickness criteria) (Hadj Miloud *et al.* 2018) (Table 3).

$$\left(3 \times C_2^1 + 3 \times C_2^2\right) \times 5 = 45 \text{ where C is combination} \quad (1)$$

Correlations between Is and Ic and diagnostic criteria are shown in Table 3.

Defuzzification is the transformation of fuzzy information into measured information. A centroid (Z) method was used (Ross, 1995). The expression of Z is given by the following equation:

$$Z = \frac{\int_D y \times \mu_{res}(y) \times dy}{\int_D \mu_{res}(y) \times dy}$$

μres (y): Inference methods provide membership function for the output variable "y".
Variable "y": Solonchak and Calcisol.

In this study, Z represents the Solonchak indices (Is), or Calcisol indices (Ic) obtained by MFIS.

Interpretation of Indices: Classification by MFIS is in favor of the higher indices. Thus, we can interpret the evidence as follows:

-Is approaches the value 1: Solonchak approaches the central taxonomic concept.
-Is moving away from the value 1: Solonchak moving away from the central taxonomic concept.
-If Is > Ic, then the soil is classified Solonchak.
-If Ic > Is, the soil is classified Calcisol.

## RESULTS AND DISCUSSION

### Classification of soils by MFIS

The Is and Ic determination of each soil for each measurement period allows to analyze the remoteness or the approach of the salic horizon of the central taxonomic concept of Solonchaks.The results of the calculation of Is and Ic and statistical results are mentioned in Tables 4 and 5. show that values of Is and Ic vary differently. Indeed, variations of Ic values across the seasons are small (CV = 9%). This finding suggests that the values of Ic are relatively stable over time and consequently, the diagnostic criteria for Calcisols is little affected by the impact of seasonal changes on soil characteristics. On the other hand, variation of Is values is relatively high (CV = 33%) and suggest that diagnostic criteria relating to Solonchaks are impacted by seasonal climatic characteristics.

### Seasonal classification of profiles

Seasonal classification of profiles is illustrated by Fig 3 which reveals the following facts:

Whatever the year and the season considered, Is is always clearly stronger than Ic. Likewise, the variation of Is values is higher during the dry seasons compared to the wet seasons. The maximum of Is values is 0.83 and 0.78 for the dry season of 2012 and 2013 and they are 0.5 and 0.47 for the wet season for the same years (Table 4). This result is explained by the fact that Is varies as a function of EC, the thickness of the diagnostic horizon and the product of these two parameters. The latter are higher during the dry season, hence an increase in Is during this period.

Seasonal variation in the salinity of the horizons of profiles 1, 2, 3 and 4 are shown by Fig 4, 5, 6 and 7. These figures show that the salinity seasonal dynamic is practically similar in the four soils. In general, it grows during the dry season and it decreases during the wet season, but with different intensities between horizons and between years. Indeed, the gaps in EC between seasons, for the same horizon can be very important (133.13 dS $m^{-1}$) and sometimes, very small (2.7 dS $m^{-1}$). However, some horizons (horizon 1 profile 2 (H1P2), H5P3 and H1P4) are exceptions and depart from a rule in 2012 with salinities which regressed during the dry period, probably because of localized strom. However, Fig 4, 5, 6 and 7 show clearly that the dry season EC is in most cases stronger than those of the wet season.

These results explains the higher values of Is (Is = 0.83 dry season 2012; Is = 0.51 dry season 2013) during the dry season comparing to those of the wet season (Is = 0.43 wet

**Table 3:** Correlations between indices Is and Ic and diagnostic criteria.

| Relations | df | r |
|---|---|---|
| Is, EC | 192 | 0.76* |
| Is, E | 192 | 0.05 |
| Is, (E × EC) | 192 | 0.49* |
| Ic, E | 192 | 0.05 |
| Ic, calcium carbonate equivalent (CE) | 192 | 0.7* |

Note. *Significant at probability p<0.05; r: Coefficient of correlation; df: Degree of freedom.

**Table 4:** Results obtained by MFIS.

| Years | Seasons | Profiles | Is | Ic |
|---|---|---|---|---|
| 2012 | Wet season | P1 | 0.43 | 0.25 |
| | | P2 | 0.50 | 0.20 |
| | | P3 | 0.43 | 0.21 |
| | | P4 | 0.27 | 0.18 |
| | Dry season | P1 | 0.83 | 0.21 |
| | | P2 | 0.78 | 0.20 |
| | | P3 | 0.49 | 0.18 |
| | | P4 | 0.80 | 0.18 |
| 2013 | Wet season | P1 | 0.47 | 0.21 |
| | | P2 | 0.44 | 0.23 |
| | | P3 | 0.29 | 0.18 |
| | | P4 | 0.39 | 0.20 |
| | Dry season | P1 | 0.51 | 0.21 |
| | | P2 | 0.78 | 0.20 |
| | | P3 | 0.49 | 0.18 |
| | | P4 | 0.52 | 0.20 |

P: Profile.

**Table 5:** Statistical parameters of Is and Ic.

| Parameters | Is | Ic |
|---|---|---|
| Maximum | 0.83 | 0.25 |
| Minimum | 0.27 | 0.18 |
| S-D | 0.18 | 0.02 |
| Mean | 0.53 | 0.2 |
| CV (%) | 33 | 9 |

season 2012; Is = 0.47 wet season 2013) (Table 4). Therefore, these profiles approaches the central taxonomic concept of the Solonchaks during the dry season and moves away from their concept during the wet season.

Concerning Ic, this indice vary slightly during the different seasons. The maximum values of Ic for the wet season are 0.25 and 0.23 respectively for 2012 and 2013 (Table 4) and 0.21 for the dry seasons for the same years. This small variation of Ic over time is due to the fact that the criteria inherent in the calculation of Ic by MFIS are relatvely constant.

Results (Table 4) show that MFIS is in favor of Solonchaks because Isis greater than Ic in all cases. This results suggest also that Solonchaks studied have a certain degree of belonging with Calcisols (0.27 < Is < 0.83; 0.18 < Ic < 0.25) which is greater during the wet seasons (0.27 < Is < 50; 0.18 < Ic < 0.25) (Fig 3). This is due to the decrease in salinity during the wet season. Consequently, Solonchaks move away a little from their central taxonomic concept during the wet season and therefore their degree of belonging to the Calcisols increases.

During the 2012 wet season, profile 4 (Is = 0.27) had a higher degree of belonging to Calcisols (Ic = 0.18) compared to other profiles (Fig 3). Likewise, profile 3 has a higher degree of belonging to Calcisols during the wet season of 2013 (Is = 0.29; Ic = 0.18) (Fig 3). This result is explained by the fact that profiles 3 and 4 are the least salty compared to the others. In any case, the degree of belonging of the Solonchaks to the Calcisols rises as the Solonchaks move away from their central taxonomic concept, this is remarkable during the wet season, whatever the season and the year considered.

However, this experiment was carried out on very salty Solonchaks. Therefore, a small or large change in EC does not affect significantly taxonomy. Similarly, these soils are considerable $CaCO_3$ content (18.5% < $CaCO_3$ < 20.2%),

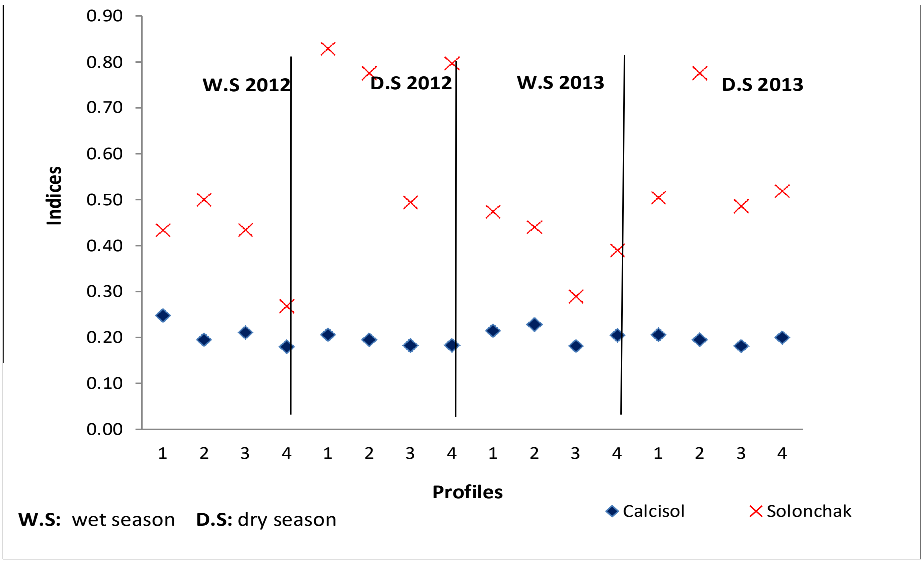


**Fig 3:** Classification of profiles by fuzzy logic.

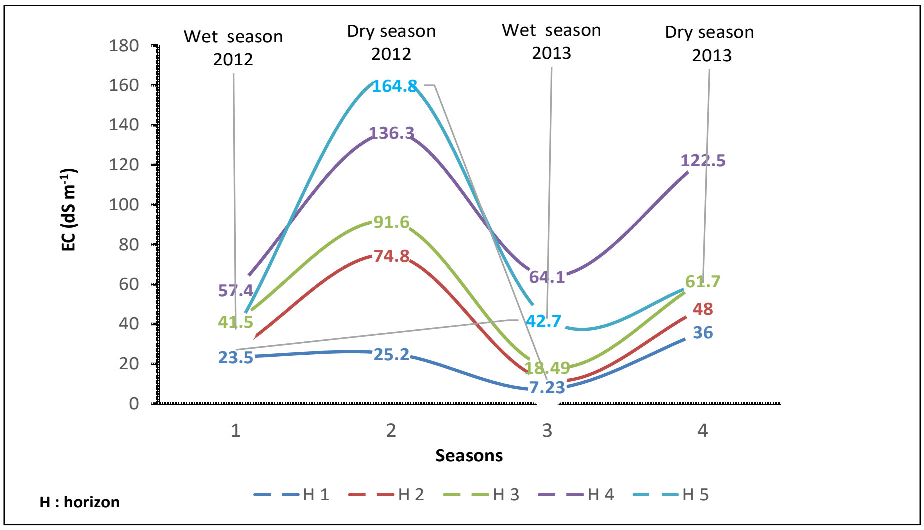


**Fig 4:** Horizon's salinity seasonal variation of profile 1.

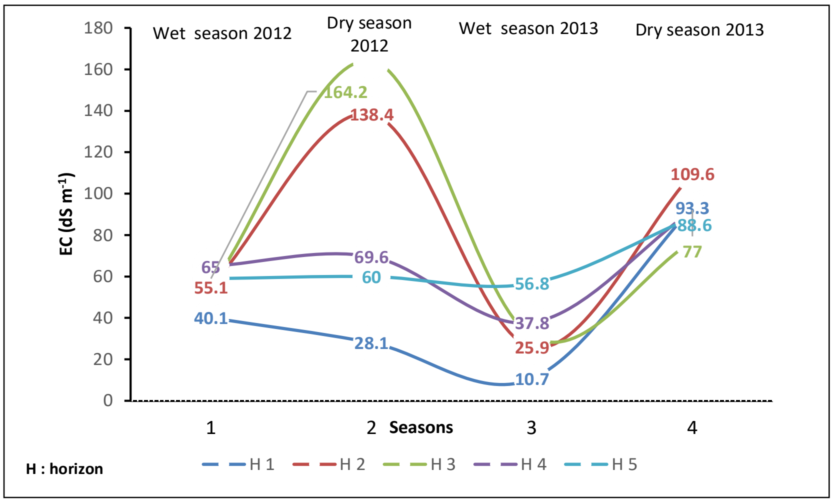


**Fig 5:** Horizon's salinity seasonal variation of profile 2.

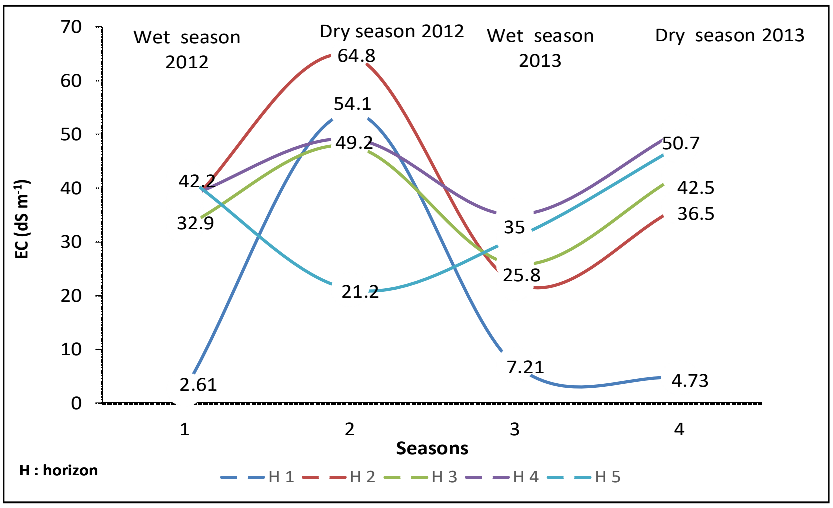


**Fig 6:** Horizon's salinity seasonal variation of profile 3.

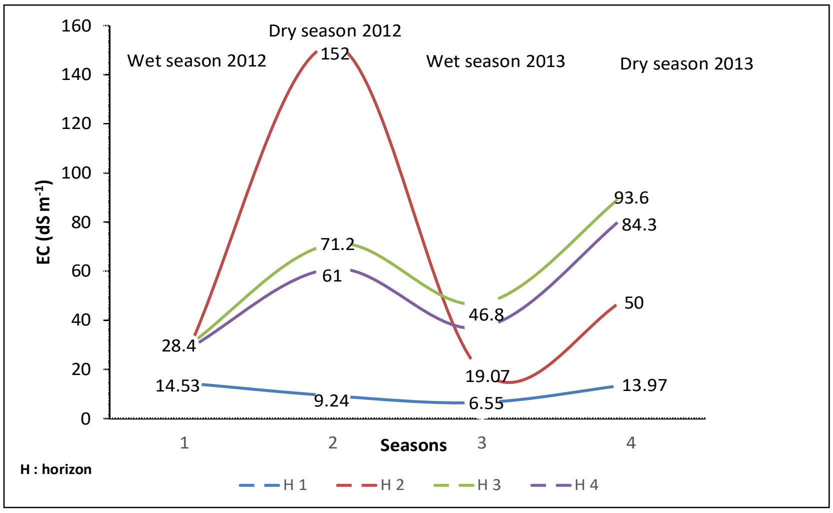


**Fig 7:** Horizon's salinity seasonal variation of profile 4.

and the temporal variation of this parameter has not been taken into account, because of its few variation during the season. Amrhein and Suarez (1987) and Marion *et al.* (1990) have shown that soil $CaCO_3$ is generally super saturated with respect to pure calcite, which explains its low variation in soil. Concerning the taxonomy, these soils approach or move away from the Solonchaks only as a function of EC. So, whatever the season considered, the indices are always in the order Is > Ic.

However, MFIS exhibited high precision concerning the membership value is due to the fact that the threshold values of diagnostic criteria defined by conventional classifications would not be suitable for soil that is considered as a continuum system (Duchaufour, 1998). Consequently, significant information is lost, especially for both taxonomic fragmentation and soil mapping. However, fuzzy classification is continuous and numerical (McBratney and Odeh, 1997) that use the linguistic variables and Gaussian membership functions. This precision is very useful in soil management practices and land evaluation systems (Sharififar *et al.* 2016). Fuzzy classification allows us to identify the distance and closeness of the Solonchaks to their central taxonomic concept, during seasonal variations.

## CONCLUSION

MFIS has shown that these Solonchaks have a relatively higher degree of membership in Calcisols, especially during the rainy season. As the Solonchaks move away from the central taxonomic concept, their degree of belonging to the Calcisols becomes more important. Unlike the dry season, when the Solonchaks get closer to their central taxonomic concept, we observe a decrease in their degree of belonging to Calcisols.

We conclude that the four profiles have a similar behavior concerning the variation of Is. Indeed, the EC is a preponderant factor in the variation of Is obtained by MFIS for all profiles. Thus, the variation of Isis closely related to the salinity seasonal variation.

The results obtained by this research have shown that the classification of soils by MFIS allows a fairly precise level of perception, insofar as fuzzy logic allows us to identify the variation of soils in relation to their central taxonomic concepts taxonomic variations. This is not possible for conventional classifications.

Since the approach adopted could be applied to any type of soil in the world, fuzzy logic could be an effective tool for improving conventional classifications of soils. Fuzzy logic is therefore an undeniable tool in precision farming.

## REFERENCES


Ahumada, A., Altunkaynak, A.and Ashraf, A. (2015). Fuzzy logicbased attenuation relationships of strong motion earthquake records, Expert Systeme with Applications. 42 (3): 1287-1297.

Amrhein, C. and Suarez, D.L. (1987). Calcite supersaturation in soils as a result of organic mattermineralization. Soil Science Society of America Journal. 51: 932-937.

Carré, F. and Jacobson, M. (2009). Numerical classification of soil profile data using distance metrics, Geoderma. 148: 336-345.

Chunsheng, Liu., Chunping R. and Nengjian, W. (2019). Load Identification Method Based on Interval Analysis and Tikhonov Regularization and Its Application. J. Electr. Comput. Eng. 1985025:1-1985025:8.

Dimicco, R. and Kilts, G. (2003). Fuzzy logic in Geology1. Academi Press.

Djili, K. (2000). Contribution to the knowledge of the soils of northern Algeria: Creation of a computerized database and the use of a geographic information system for the spatialization and vectorization of pedological data. Thèse Doctorat. INA, Alger, pp. 384.

Duchaufour, P. (1998). Thoughts on soil classifications. Etude et Gestion des Sols. 5: 201-205.

FAO, (2002). Capacity Building for Drainage in North Africa. Doc. FAO., Rome, pp. 21.

Hadj Miloud, S. (2010). Morphology and properties of the references Solonchaksof Mina. Mémoire de Magister, ENSA, EL Harrach, Alger, 120.

Hadj Miloud, S. (2019). Contribution of fuzzy logic to the classification of the solonchaks of northern Algeria. Contribution of the mamdani inference system. Thèse de doctorat, ENSA, EL Harrach, Alger. 147.

Hadj Miloud, S., Djili, K. and Benidr M. (2018). Fuzzy Logic Expert System for Classifying Solonchaks of Algeria. Applied and Environmental Soil Science. pp. 11.

Haidara, I., Tahri M., Maananc, M. and Hakdaoui, M. (2019). Efficiency of Fuzzy Analytic Hierarchy Process to detect soil erosion vulnerability. Geoderma. 354: 113-853.

Halitim, A. (1988). Soils of Arid Regions of Algeria. Edition O.P.U., Alger, pp. 384.

IUSS Working Group WRB. (2015). World Reference Base for Soil Resources 2014, Update 2015. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps. World Soil Resources Reports No. 106, FAO, Rome.

Mahesh, C. Meena and Ramovatar, M. (2019). Modified ulaby model on backscattering as a function of salinity, frequency and soil moisture. Indian Journal of Agricultural Research. 53: 646-654.

Mamdani, E.H. (1974). Application of fuzzy algorithms for simple dynamic plants. Proceedings of the IEEE. 121(12): 1585-1588.

Mamdani, E.H. (1977). Application of fuzzy logic to approximate reasoning using linguistic synthesis. IEEE Transactions on Computers. 26: 1182-1191.

Marion, G.M, Schlesinger, W.H. and Fonteyn, P.J. (1990). Francis spatial variability of $CaCO_3$ solubilityin a chihuahuan desert soil. Arid Soil Research and Rehabilitation. 4: 181-191.

Mcbratney, A. and Odeh, I.A. (1997). Application of fuzzy sets in soil science: Fuzzy logic, fuzzy measurements and fuzzy decisions. Geoderma. 77: 85-113.

Morgan, R.S., Abd El-Hady, M. and Rahim, I.S. (2018). Soil salinity mapping utilizing sentinel-2 and neural networks. Indian Journal of Agricultural Research. DOI: 10.18805/IJARe.A-316.

Penman, H.L. (1948). Natural evaporation from open water, bare soil and grass. Proc. Roy. Soc. London, A193, 120-146.

Ross, J.T. (1995). Fuzzy Logic with Engineering Applications. New York: McGraw-Hill, inc, pp. 593.

Ruamporn, M., Dhruba, P. and Victor, G. (2020). Fuzzy logic for fine-scale soil mapping: A case study in Thailand. Catena. 190: 104-456.

Sabareshwari, V. and Ramya, A. (2018). Coastal saline Soils of India: A review. Agricultural Reviews. 39: 86-88.

Sharififar, A., Ghorbani, H. and Sarmadian, F. (2016). Soil suitability evaluation for crop selection using fuzzy sets methodology. Acta Agriculturae Slovenica. 107: 32-35.

Shi, X., Long, R., Dekett, R. and Philippe, J. (2009). Integrating different types of knowledge fordigital soil mapping. Soil Sci. Soc. Am. J. 73: 1682-1692.

Takagi, T. and Sugeno, M. (1985). Fuzzy identification of systems and its applications to modelling and control. IEEE Trans. Syst., Man, Cybern. 15(1): 116-132.

Wahyuni, E.S., Oyas, W. and Silmi F. (2016). A Comparative Study on Fuzzy Mamdani-Sugeno-Tsukamoto for the Childhood Tuberculosis Diagnosis. AIP Conference Proceedings 1755, 070003.

Yuanyuan, C., Limin, A. and Zundong, Z. (2009). Mamdani model based adaptive neural fuzzy inference system and its application. International Journal of Computational Intelligence. 5: 22-29.

Zimmermann, J. (2001). Fuzzy Set Theory and Its Applications. Kluwer Academic Publishers. 4th ed. London: 492.