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Evaluation of soil quality in recovery process in the Brazilian Amazon (RO) based on fuzzy logic

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Abstract: The restoration of the mined soil in the Brazilian Amazon is a complex work that must consider the uniqueness of the tropical ecosystem, so it is necessary to establish efficient indicators relating the essential factors that influence the quality of the soil. In this way the present article has the purpose of evaluating the main chemical, physical and biological parameters of a mined area in a recovery process located in the Jamari-RO National Forest and generate a soil quality index through the Fuzzy Logic. The use of fuzzy logic to evaluate soil was efficient, allowing the integration of high complexity variables and a dynamic environment in a single soil quality fuzzy index (SQFI), allowing the comparison of the quality of the different stages of recovery. The integrated analysis of the chemical, physical and biological indicators in the degraded areas presented significant correlations between the results, being able to be considered a good tool to evaluate the quality of the soil degraded by the mining. The physical indicator presented high potential and stood out showing great importance as an indicator of, however, the use of complete system allows tracking eachsubsystem and identifying which components need improvement and management actions for environmental recovery and conservation.

Keyword: Soil quality; soil indicators; environmental recovery; conservation; fuzzy logic.

I. INTRODUCTION

According to the Ministry of Mines and Energy mining activities account for almost 4% of Brazil's output, corresponding to US $ 40 billion in 2017, with a surplus of US $ 23.4 billion corresponding to 20% of all products exported by Brazil (MME, 2017). While mining activities have fostered economic growth and development in the last century, they are also responsible for causing large-scale environmental degradation (ICMM, 2017).

During mineral exploration occurs the removal of soil and vegetation, raising the risks of erosion due to structural alteration, such changes seriously compromise the ecosystem functions of the soil and for this reason it becomes mandatory in most countries to carry out the restoration of the degraded ecosystem (Stanturf et al., 2014, Luna et al 2016). Despite all the economic benefits associated with this sector, the exploitation of mineral reserves in important ecosystems, such as the Amazon Forest, requires careful management to minimize environmental impacts and associated problems, restoring the soil structure as close to the original as possible (Ribeiro, 2016; Fengler et al, 2017).

Assessing and monitoring areas impacted by mining presents a major challenge since tropical soils are dynamic and complex, making recovery assessment difficult to measure using standard methodologies that do not take into account the specificities of the ecosystem. Therefore, it is fundamental to find efficient indicators that consider the physical, chemical and biological characteristics of the area, responsible for the fundamental functions of soil quality (Doran & Parkin, 1996; Ribeiro, 2016).

The use of environmental indicators to assess soil quality presents high potential, due to the sensitivity to environmental changes and the possibility of understanding its functioning. They are able to translate the complexity of environmental conditions, so it has been increasingly effective in making decisions, assisting in the evaluation, identification of priority actions and anticipation of future trends (Roveda et al., 2012). However, in the literature there is a shortage of methodologies integrating chemical, physical and biological indicators, in an efficient way to evaluate soil quality, that presents results consistent with the analyzed scenario.

In this context, the use of fuzzy logic or fuzzy set theory introduced by has been applied in several areas of the exact sciences, human and environmental, since it presents great potential for research, since they integrate several indicators (Kaufmann et al., 2009; França et al., 2015). This methodology can provide an alternative to address the uncertainties associated with the particular environmental area, between classes not clearly defined, and fuzzy modeling systems, based on the knowledge of specialists to help this issue (Silva, 2014, Mukhopadhyay et. a. 2014), allowing the creation of environmental quality index.

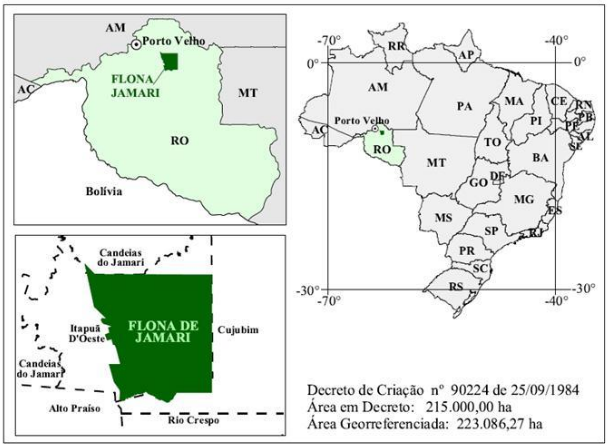
Considering the nature of the processes of environmental recovery of mined areas and considering the complexity associated to the dynamics of these processes, the objective of this study was to integrate chemical, physical and biological soil attributes using the fuzzy inference system, in order to generate a quality index of the mined soil.

II. MATERIALS AND METHODS

2.1. Study location

The experimental area is located in the Jamari National Forest, managed by the Brazilian Institute for the Environment and Renewable Mineral Resources (IBAMA), located 90 km from the city of Porto Velho - RO, by Br-36. It presents an area of approximately 225,000 ha, of which 90% is covered by Tropical Forest, where species of high commercial value are found for wood exploitation and mineral reserves (LONGO et al., 2011).

Figure 1: Experimental area location of the Jamari National Forest



Fount: IBAMA National forest management plans

The soils are predominantly of the class dytropic Red-Yellow Latosoil texture (Kandiuand) and dytropic Red-Yellow Latosoil (Paleudult) covered by open rainforestwith small patches of tropical rainforest, characterized by a high richness of spaced arboreal individuals and a diverse wildlife, including several species threatened with extinction (MMA/IBAMA, 2010; Fengler et al., 2017). Acid pH ranging from 3.4 to 5.0.The climate of the region is hot and humid, with average temperatures of 24 ° C, relative humidity varies around 80 to 85% (Soil Survey Staff, 1999). The experiment was carried out in a mining area in recovery process, and data were collected between 2011 and 2014 by research group of Land Recovery.

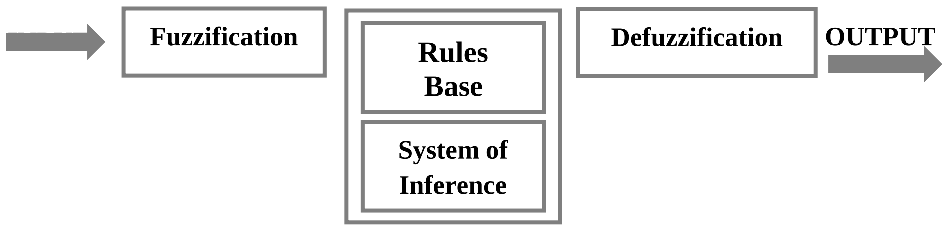
2.2. Fuzzy logic based modeling system

The fuzzy systems are inference processes rules fuzzy based that can be applied as controllers that actions output recommended from an assessed state or condition(SHAW & SIMÕES, 2001). Involving four main steps: The fuzzification; The construction of the rule base; The inference; and defuzzification. In these systems, the modeling of variables in fuzzy sets with their respective domains, proposition of linguistic terms and characteristic functions compound the fuzzification stage.

According to França et al., (2015), in these systems, the input sets correspond to the criteria of interest to evaluate the phenomenon studied, and the outputs are equivalent to the diagnosis according to these criteria. For building the rule base, the relationship between such sets is modeled, through logical connectives that equate pertinence values calculated through characteristic functions to establish the fuzzy relationship in the mathematical modeling, following the procedure as in the Mandani Method (BARROS & BASSANEZI, 2006; FRANÇA et al., 2015). Finally, in the defuzzification process the values generated in the inference are transformed to real numbers (crisp), through methods such as the Center of Gravity (centroid), adopted in this work.

Following these procedures, the modeling was developed by the construction of a System Based on Rules Fuzzy. For this, the values of the parameters analyzed in each system were used in the inference system as shown in figure 1:

Figure 1: Fuzzy Inference system



Thus, three fuzzy systems were developed for modeling the Soil Quality Index.The system in fuzzy logic was developed based on the experience of professionals from the Land Recovery group of the Institute of Science and Technology of Sorocaba. To model the data in the SIF in order to evaluate soil quality, several parameters were considered relevant by the experts, it was necessary to divide the parameters in three systems, being the chemical,biological and system of the mined soil, according to figure 2.

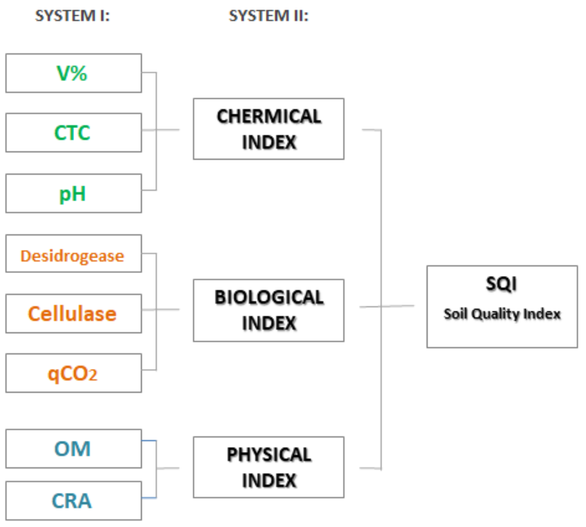
3.3. Definition of linguistic variables and linguistic terms.

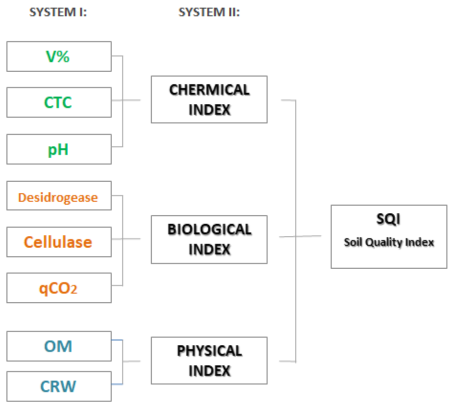
After the systems were divided the linguistic terms were defined to express the input and output variables. 1) Chemical System: Soil fertility percentage ("V%"), cation transpositioncapacity ("CTC") andhydrogen potential "pH" were considered as input variables to analyze soil fertility. The linguistic terms used as output variables were "DEGRADED", "DEFICIENT", “NATURAL" and “AGRONOMIC”; 2) Biological System: soil biological activity biológica was analyzedbased on data of Desidrogease (“DES”), cellulase (“CEL”) and metaboliccoefficient (“qCO2”) as input variables, while the linguistic terms used as output variables were "DEGRADED", "ALTERED", “DISTURBED", “DEVELOPED” and “NATURAL”; and finallly 3) Physical Sytem: used the data OrganicMatter (“OM”) and capacity real water in soil (“CRW”) as input variables and the language terms used as output variables were“LOW”, “MEDIUM” e “HIGH”.

According to França (2014), in the process of fuzzy inference, the linguistic variables determine the relations between the input and output variables, these being mathematically established by the rules associated with the processes. Then the rule base for each of the systems was defined with considering the input variables and output variables cited above, totaling 63 fuzzy relational rules. The rules were defined in consensus between the experts and authors according to the individual perception of each one, based on their personal knowledge and experience.

In the fuzzy inference the data of the present study were evaluated mathematically, applying one of the most used methods in systems based on the knowledge of expertsthe Mandani method, according to Roveda et al. (2012).

Figure 2. Diagram of the SIF division





3.4. Definition of membership function values in sets.

The first system determines the quality of the soil in relation to the fertility that was evaluated through the chemical analysis of the soil. In the V% relevance function, the values were fuzzified so that the linguistic modifier "LOW" was assigned the value of the first quartile 7,7, To "MEDIUM" the value of second quartile 18,2 and "HIGH" to the value of third quartile 27,9, being that the values of 7,7 e 27,9, maximum and minimum, considering the values of the reference system in relation to a natural environment.

The values have variable pertinences in the sets Low and Medium and High, respectively. The input variables V%, CTC and pH have a set of similar relevance functions. The same model of functions used for build the chemical system fuzzy with output variable described were followed to assemble all other sets in the biological and physical soil system based on the values in table 1.

Table 1. Indicators evaluated and values based on quartiles.

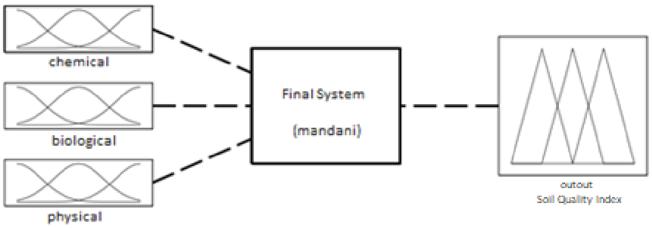
Indicators of degraded soil								
	V%	**CTC**	**pH**	**Desidrogease.**	**Cellulase**	**qCO_2**	**OM**	**CRW**
Min.	3.00	15.00	3.400	0.0800	2.140	0.01100	3.00	0.55
1º Qu.:	10.75	26.00	3.875	0.4075	6.912	0.007369	10.00	33.95
Median:	19.00	36.00	4.100	0.8600	11.555	0.013950	14.00	43.30
Mean	20.50	38.66	4.136	0.9763	13.383	0.017926	14.29	44.67
3º Qu.:	27.25	48.00	4.300	1.3600	16.808	0.023025	18.00	53.58

Max.	66.00	105.00	5.800	4.2600	46.190	0.166500	35.00	83.19
Reference System: natural environmental								
Forest	5.4	89.2	3.7	1.1	16.3	1.6	24.6	61.9
Capoeira	3.1	99.1	3.7	1.3	14.5	1.6	26.7	67.8

3.5. Integration System

The result each system that evaluated the chemical, physical and biological condition of the mined soil was used as input in the final system, in order to generate the soil quality index, according to figure 3.

Figure 3. FINAL system to assess the quality of soil mined through Matlab®.



In the final system the input variables used were “DEGRADED”, “DEFICIENT”, AGRONOMIC” and “NATURAL”, while the output variables used were “DEGRADADA”, “VERY LOW”, LOW”, “MEDIUM”, “HIGH” and “VERY HIGH” inserted in theMatlab®.

Then the final rule base of the system related the chemical, biological and physical conditions resulting from the initial systems with considering the input variables and output variables, totalizing 81 Fuzzy relational rules (ANNEX 2). Finally the result of the defuzzification of the three systems is the generation of a single index of soil quality degraded by mining.

III. RESULTS AND DISCUSSION

The index that integrates the three evaluated systems tended to maintain the existing variability in the input variables, with a coefficient of variation of 32% (Table 2). The chemical, biological and physical soil systems showed variations in the coefficient of variation for the input variables, but in general they occurred in the high dispersion range (above 30%), according to the value obtained for the final quality index.

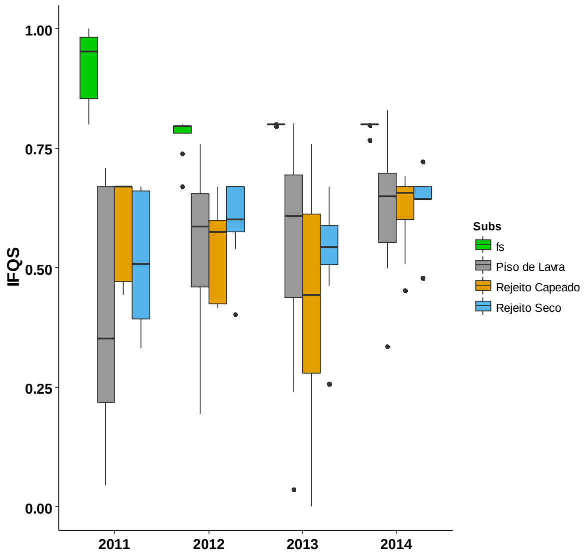
Table 2. Descriptive statistical analysis of the variables considered in the elaboration of the Fuzzy systems and in the quality indexes obtained for the 24 sites in recovery and natural areas in the analysis period from 2011 to 2014.

Statistic	CTC	V%	pH	IFChe	Cellulase	qCO2	IFBio	MO	CRW	IFPhy	IFFinally
No. of observations	120	120	120	120	120	120	120	120	120	120	120
Minimum	28.60	7.70	3.80	0.00	8.14	0.00	0.00	11.30	35.50	0.00	0.00
Maximum	60.00	27.90	4.33	1.00	17.30	0.02	1.00	20.00	59.00	1.00	1.00
1° Quartile	28.60	8.72	3.87	0.55	8.14	0.00	0.35	11.33	35.50	0.50	0.50
Medium	37.00	19.27	4.13	0.68	13.15	0.01	0.62	15.00	43.59	0.51	0.64
3° Quartile	53.76	27.90	4.33	0.68	17.17	0.02	0.62	19.50	56.38	0.99	0.73
Mean	41.22	18.38	4.09	0.56	12.70	0.01	0.50	15.44	45.83	0.66	0.60
Variance (n-1)	157.63	67.21	0.04	0.05	13.58	0.00	0.04	12.51	89.87	0.07	0.04
Standard deviation (n-1)	12.56	8.20	0.21	0.23	3.69	0.01	0.20	3.54	9.48	0.27	0.20
Coefficient of variation	0.30	0.44	0.05	0.40	0.29	0.58	0.41	0.23	0.21	0.42	0.32

Also, the Soil Quality Fuzzy Index (SQFI) differentiated the soils from the recovering sites in relation to the reference areas, under the condition of Amazonian soil (Figure 4). As the Box plots of the natural areas present with lower Whiskers with values higher than the areas in recovery there is an indicative of significant differences between these two types of treatment (Ferreira et al., 2016).

The areas under reclamation under the Substrate of Lavra still tended to present superior Whisker with values near the reference areas, unlike the areas located in tailings. This result is consistent with Yada et al. (2015) and Ribeiro et al. (2016), which obtained similar results, where, due to the better physical condition of the soil and lower degree of alteration by the mining process, the soil substrate presented better performance for the development of the microbiological conditions of plant development.

Figure 4. Box plots for the SQFI of the 24 recovery plots and the natural areas.



This substrate still showed a better evolutionary trend than the others, followed by dry and capeado rejects, in spite of the greater degree of alteration of the dry waste in relation to the capeado, that was covered with top soil, presenting a granulometric composition closer to the reference environments. This result was also obtained in Fengler et al. (2017), given the previous classification and preparation of the sites in recovery, with the definition of actions based on the preliminary assessment of environmental damage (Ribeiro et al., 2016), prior to planting, including the use of composting, associated with fertilization green, chemical fertilizers and liming.

These actions apparently compensated for the greater environmental damage of the dry tailings, the improvement of the organic matter and, consequently, the microbiological activity. Yada et al. (2015) also obtained similar results, with the sites in recovery under substrate dry tail obtaining similar microbial activity to the capped waste. These results indicate the representativeness of the QSIF in relation to the soil conditions in the sites in recovery and reference environment.

In the SQFI recovery sites, there were significant correlations (Table 5) with the basal area indicators (0.28) and mean height (0.24), as well as the Fuzzy Indexes of the Fertility (IFChe), Physical (IFPhy) and Biological (IFBio). The IFPhys presented the highest number of significant correlations with the other parameters, including all forest development indicators, due to the use of organic matter and CRW in its production, a parameter that also assumed significant correlations with several parameters. TheIFChepresented only a significant correlation only with the CTC (0.3) and the final fertility index. The absence of significant correlations with other soil properties can be explained by the nonlinear relationship of the obtained index.

The IFChe for soil fertility considered that values close to 1 serial attributed to areas close to the natural condition, while those close to 0.75 the agronomic condition and below 0.5 deficient or degraded soils. The natural condition is characterized by high CTC, low V% and pH, a rare condition for recovering mined sites, which generally present a low CTC, by the removal of the organic material, and present high pH and nutritional condition close to agronomics.

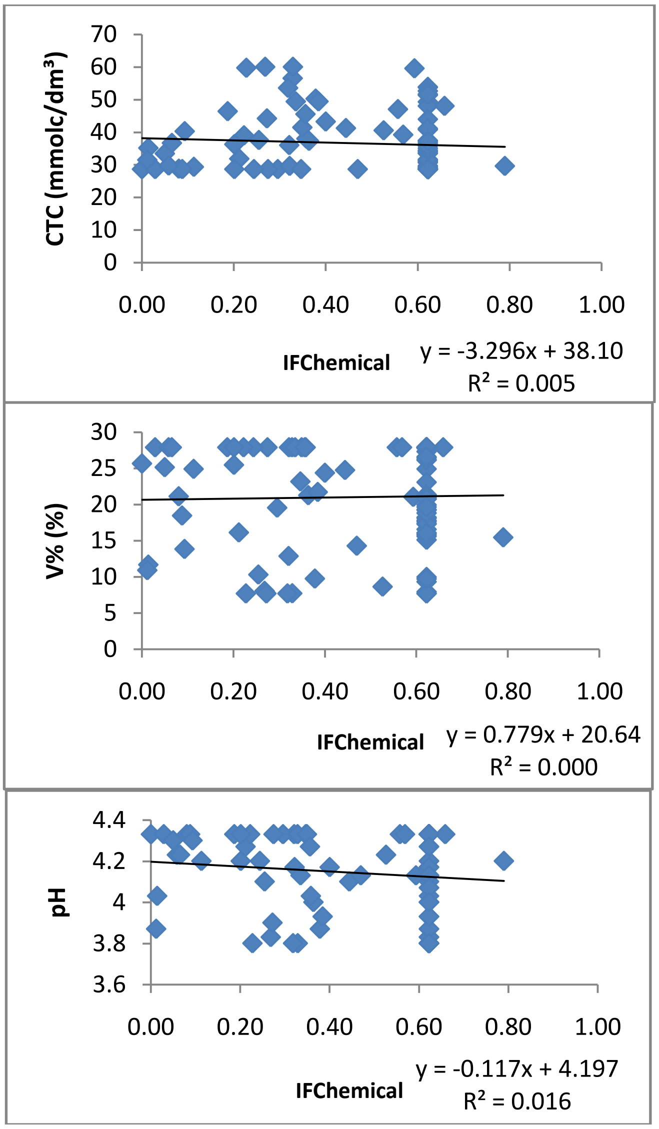
Table 5. Spearman correlation of the variables considered in the elaboration of the Fuzzy systems and in the quality indices obtained for the 24 sites in the recovery period from 2011 to 2014.

Variables	CTC	V%	pH	IFChe	C org	Cellulase	qCO2	IFBio	MO	CRW	IFPhy	IFFinally	R	AB	IT	Reg nat	H	Clay	Limo	Sand	Planting age
CTC	**1.00**	-0.18	**-0.38**	**0.30**	**0.29**	**0.28**	0.19	-0.17	**0.79**	**0.40**	**0.57**	0.03	**0.21**	0.14	**0.21**	**0.24**	0.10	0.19	0.16	-0.16	**0.47**
V%	-0.18	**1.00**	**0.55**	0.06	0.11	-0.19	-0.02	0.00	0.09	**-0.35**	-0.12	0.07	**-0.32**	-0.17	**-0.38**	**-0.37**	-0.11	**-0.21**	**-0.27**	0.19	-0.17
pH	**-0.38**	**0.55**	**1.00**	0.07	**0.27**	**-0.31**	**-0.42**	-0.11	**-0.27**	-0.08	-0.14	-0.10	**-0.49**	**-0.35**	**-0.22**	**-0.33**	**-0.34**	-0.06	-0.06	0.05	**-0.29**
IFChe	**0.30**	0.06	0.07	**1.00**	-0.11	0.05	0.08	0.03	-0.14	-0.08	-0.03	**0.70**	-0.03	0.09	0.11	0.08	0.14	0.04	-0.05	0.00	-0.04
Cellulase	**0.28**	-0.19	**-0.31**	0.05	-0.14	**1.00**	**0.39**	-0.18	**0.27**	**0.33**	**0.27**	0.09	0.18	0.16	**0.24**	**0.22**	**0.21**	0.16	0.16	-0.14	**0.34**
qCO2	0.19	-0.02	**-0.42**	0.08	**-0.37**	**0.39**	**1.00**	0.04	**0.25**	-0.02	0.08	0.20	0.17	0.03	0.03	0.02	0.15	-0.11	-0.10	0.11	0.15
IFBio	-0.17	0.00	-0.11	0.03	**-0.29**	-0.18	0.04	**1.00**	-0.17	**-0.27**	-0.19	**0.46**	0.06	0.08	-0.02	-0.06	0.07	-0.19	-0.15	0.17	0.00
MO	**0.79**	0.09	**-0.27**	-0.14	**0.25**	**0.27**	**0.25**	-0.17	**1.00**	**0.28**	**0.64**	0.14	**0.22**	0.11	0.15	0.15	**0.23**	0.13	0.12	-0.13	**0.31**
CRA	**0.40**	**-0.35**	-0.08	-0.08	**0.24**	**0.33**	-0.02	**-0.27**	**0.28**	**1.00**	**0.54**	0.03	0.09	0.13	**0.43**	**0.34**	0.07	**0.45**	**0.34**	**-0.40**	**0.22**
IFPhy	**0.57**	-0.12	-0.14	-0.03	**0.26**	**0.27**	0.08	-0.19	**0.64**	**0.54**	**1.00**	**0.22**	**0.21**	**0.23**	**0.30**	**0.32**	**0.25**	**0.34**	**0.38**	**-0.34**	**0.26**
IFFinal	0.03	0.07	-0.10	**0.70**	-0.04	0.09	0.20	**0.46**	0.14	0.03	**0.22**	**1.00**	0.06	**0.28**	0.19	0.17	**0.25**	0.03	0.02	-0.02	0.20
regnatural-all stratum (indv/ha)	**0.21**	**-0.32**	**-0.49**	-0.03	-0.07	0.18	0.17	0.06	**0.22**	0.09	**0.21**	0.06	**1.00**	**0.21**	**0.48**	**0.55**	**0.25**	0.14	0.12	-0.09	0.19
AB	0.14	-0.17	**-0.35**	0.09	-0.10	0.16	0.03	0.08	0.11	0.13	**0.23**	**0.28**	**0.21**	**1.00**	**0.22**	**0.30**	**0.53**	**0.24**	**0.24**	**-0.26**	**0.37**
IT	**0.21**	**-0.38**	**-0.22**	0.11	-0.03	**0.24**	0.03	-0.02	0.15	**0.43**	**0.30**	0.19	**0.48**	**0.22**	**1.00**	**0.82**	**0.22**	**0.27**	0.07	-0.15	0.16
Natural Regeneration	**0.24**	**-0.37**	**-0.33**	0.08	0.00	**0.22**	0.02	-0.06	0.15	**0.34**	**0.32**	0.17	**0.55**	**0.30**	**0.82**	**1.00**	**0.23**	**0.33**	0.14	**-0.22**	0.14
H	0.10	-0.11	**-0.34**	0.14	-0.07	**0.21**	0.15	0.07	**0.23**	0.07	**0.25**	**0.25**	**0.25**	**0.53**	**0.22**	**0.23**	**1.00**	-0.01	-0.04	0.04	0.11
Clay	0.19	**-0.21**	-0.06	0.04	0.14	0.16	-0.11	-0.19	0.13	**0.45**	**0.34**	0.03	0.14	**0.24**	**0.27**	**0.33**	-0.01	**1.00**	**0.75**	**-0.95**	0.00
Limo	0.16	**-0.27**	-0.06	-0.05	0.19	0.16	-0.10	-0.15	0.12	**0.34**	**0.38**	0.02	0.12	**0.24**	0.07	0.14	-0.04	**0.75**	**1.00**	**-0.87**	0.11
Sand	-0.16	0.19	0.05	0.00	-0.13	-0.14	0.11	0.17	-0.13	**-0.40**	**-0.34**	-0.02	-0.09	**-0.26**	-0.15	**-0.22**	0.04	**-0.95**	**-0.87**	**1.00**	0.06
Planting age	**0.47**	-0.17	**-0.29**	-0.04	0.08	**0.34**	0.15	0.00	**0.31**	**0.22**	**0.26**	0.20	0.19	**0.37**	0.16	0.14	0.11	0.00	0.11	0.06	**1.00**

The values in bold are different from 0 with a significance level alpha = 0.05

Therefore, the lack of significant correlations with other soil properties, such as pH and V%, which were used in their preparation, does not necessarily indicate a poor representativeness of the generated index, since there is a peculiarity that causes recovering sites that low pH, or low V% have a value close to 1 for IFChe (Figure 5), although they have a high CTC. In contrast to the IFBio, the high variability of the biological parameters in the recovery sites may be responsible for the lack of significant correlations with the other soil properties.

Figure 5. Behavior of the Fuzzy IndexChemical in relation to the variables used in its preparation in the 24 plots undergoing recovery in the period from 2011 to 2014.



IV. CONCLUSION

The proposed method allowed the elaboration of a system for the elaboration of management indicators for soils degraded by the mining. The Soil Quality Fuzzy Index presented consistency in representing the differences in the properties of the different substrates in which the recovering sites meet and in relation to the reference environments.

Considering a monitoring bias, the physical fuzzy index based on organic matter and water retention capacity presented great potential, since it was obtained with only two indicators and significant correlations were identified for diverse soil properties and forest development. However, for management purposes the use of the complete system allows to track, considering each subsystem (Chemical, biological or physical) which components of the environment need improvement and management actions.

V. Acknowledgements

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