



Geostatistical methods applied to soil fertility zoning

Métodos geo estadísticos aplicados a la zonificación de la fertilidad del suelo

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ARTICLE DATA

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Cite: Albornoz-Bucheli, C.; Benavides-Cardona, C.; Muñoz-Guerrero, D. (2022). Geostatistical methods applied to soil fertility zoning. *Revista de Ciencias Agrícolas*. 39(1): 85-98.

doi: <https://doi.org/10.22267/rcia.223901.171>

Received: April 27 2021.

Accepted: October 05 2021.



ABSTRACT

In conventional agricultural production systems, soil management is generally carried out without considering the spatial variability of its properties. This situation generates not only soil degradation but also an increase in production costs associated with the management of this factor. The objective of this research was to evaluate, through geostatistical methods, the spatial variability of soil fertility in Botana Experimental Farm of Universidad de Nariño. Spatial variability maps were estimated using the ArcGIS 10 program, the Kriging interpolation method, and the optimal ranges of soil fertility for the Andean region as projection parameters for making decisions related to land use. The fertility zoning of the farm was established, classifying soil as having high, medium, and low fertility. Most of the experimental farm had low fertility soils (20.7ha), and only 3ha had good conditions. Statistical analysis indicated a high variability in soil chemical properties. Properties such as pH and bulk density showed low variability.

Keywords: spatial variability; soil physics; interpolation; soil analysis; precision agriculture.

RESUMEN

En sistemas de producción agrícola convencional, generalmente el manejo de suelos se realiza sin considerar la variabilidad espacial de sus propiedades. Esta situación genera no solo degradación del mismo, sino también incremento en los costos de producción asociados al manejo de este factor. El objetivo de la presente investigación fue evaluar a través de métodos geo estadísticos la variabilidad espacial de la fertilidad de suelos en un área de uso agropecuario (Granja experimental Botana, Universidad de Nariño). Se realizó la estimación de mapas de variabilidad espacial, empleando el programa ArcGIS 10 y el método de interpolación Kriging, teniendo en cuenta los rangos óptimos de fertilidad de los suelos para la región andina como parámetros de proyec-

ción en la toma de decisiones relacionadas al uso del suelo en el área estudiada. Se estableció la zonificación de la fertilidad de los suelos seleccionados de la granja, clasificándolos en: suelos de fertilidad alta, media y baja. La mayor parte de la finca experimental presentó suelos de baja fertilidad (20,7ha) y solo 3ha, buenas condiciones al respecto. El análisis estadístico indicó una alta variabilidad en las propiedades químicas del suelo. Las propiedades como el pH y la densidad aparente mostraron una baja variabilidad.

Palabras clave: variabilidad espacial; física del suelo; interpolación; análisis de suelo; agricultura de precisión.

INTRODUCTION

In conventional agriculture, a large percentage of crop yield variability is due to the differentials that may exist in the soil properties (Bramley, 2009). This variability can be analyzed from different perspectives, scales based on both the intervention objectives and the level of decision required. It also depends on natural disturbances and human actions, especially in agricultural practices (Fraterrigo & Rusak, 2008).

Mapping, the use of cartographic tools, is a valuable approach to adapt work processes to landscape changes. Mapping is referred to as a tool because it is an important means to strengthen decision making, in this case, to improve agricultural production through nutrient use efficiency (NUE) (Murillo, 2006).

The recognition of the role of fertilizers in increasing agricultural production, and consequently, in the production of food, fiber, and even energy, contrasts severely with the negative nature of the information that is currently being released on fertilizers use (Murillo, 2006).

For agricultural sciences, information at different scales is often used to support decision making with respect to diagnosis, monitoring, and predictions related to the management of productive systems (Pachepsky & Hill, 2017). At the research level, the spatial variability of physical and

chemical properties of soils at the field scale has been more widely considered than the patterns of such distribution (Reza *et al.*, 2017). In this sense, the modeling of these properties will allow, among others, to estimate the distance in which different soil samples are independent as well as to improve the sampling process either for planning activities in a traditional way or under a precision agriculture scheme (Peralta & Costa, 2013; Peralta *et al.*, 2015).

In terms of production and academic contributions, various activities are carried out in most production units. Regarding Botana Experimental Farm of Universidad de Nariño - Colombia, is a site where different activities take place, including growth, development, and productivity assessment of certain crops from the Andean region. In each of these, physical and chemical studies of the soils are generally conducted to determine their fertility level, which benefits the crop or system under study.

However, in most of the agricultural production units in the region, the results of soil analysis are not very useful over time. One of the reasons that account for this is the fact that the analyses are not properly stored or processed in databases, which hinders production planning in the long run. If properly used, these databases or mapping, which depict the spatial distribution of the physical and chemical properties of soils, would make it possible to estimate the

productive potential of the farm. This would result in appropriate agricultural, forestry, and livestock planning, without the need to repeat the already executed processes.

According to Álvarez *et al.* (2015), today, several research centers are using geographic information systems (GIS) to elaborate soil maps, which are of vital importance for planning and correct soil management. In turn, appropriate management increases the competitive capacity of soils and the possibilities to better channel agricultural and agroforestry programs and projects. Using GIS, soil fertility zonation studies facilitate adequate planning in terms of agricultural use of soil and its optimal management (Álvarez *et al.*, 2015). Similarly, these tools allow making timely recommendations that would permit the optimization of resources and the definition of productive systems that become a very important input for farm management and thus take measures that promote the implementation of Precision Agriculture in these research centers.

Site-specific fertilization involves the assessment of the spatial relationships between soil properties and crop yield. In this sense, the spatial distribution of physical, chemical, and biological parameters of soil has been observed to affect crop yield (Machado *et al.*, 2000). However, the spatial dependence of soil biological parameters has been little explored (Moreno, 2011). One of the most important uses of GIS is spatial analysis, especially the use of interpolations of different types of variables. In agriculture, the use of this tool makes it possible to analyze the variability of different characteristics in the landscape such as soil, diseases, and pests, among others (Clay *et al.*, 2007). This undoubtedly helps to quantify the impact of this variation on production and the possible

management guidelines required to optimize farm yields (Bertsch *et al.*, 2002).

Considering the above, this research aimed to assess the implementation of soil fertility zoning at Botana Experimental Farm of Universidad de Nariño as a tool to contribute to productive processes, research, and academic practices of the agriculture programs of the University and productive systems of the region.

MATERIALS AND METHODS

Location. The present study was carried out at Botana Experimental Farm of Universidad de Nariño – Department of Nariño, at 2820 m asl, 12.4°C and an average annual rainfall of 694mm. It is located in a low mountain dry forest life zone (bs-MB) at 1°09'30.8"N; 77°16'31.8"W.

Fieldwork and laboratory methodology. Through the use of a Geographic Information System, a sampling grid of 0.5 hectares was established, for a total of 106 soil samples in the productive areas of Botana Experimental Farm. That is, the samplings were drawn from an overall area of 55 hectares (productive area). This aspect guaranteed the significance of the study area about the established interpolation method and the areas dedicated to production within the system.

Once the sampling grid was defined, the sampling points were identified and 15 soil subsamples were taken in each grid using an Edelman auger. These subsamples were mixed into a single sample, placed in plastic bags and labeled. The samples were sent to the laboratory of Universidad de Nariño to determine their physical-chemical characteristics (Table 1 and Table 2).

Table 1. Chemical parameters analyzed in the samples.

Essays	Method	Technique	U. of measure
pH, potentiometer Soil: Water Ratio (1: 1)	NTC 5264	Potentiometric	
	Walkley- Black (Colorimetric) - NTC 5403	Spectrophotometric uv-vis	%
Organic mater	Bray II y Kurtz NTC 5350	Spectrophotometric uv-vis	mg/Kg
Available phosphorus	CH3COONH4 1NpH7 NTC 5268	Volumetric	
Cation Exchange Capacity (CEC)			
Exchange calcium	CH3COONH4 1NpH7 NTC 5349	Atomic absorption spectrophotometry	cmol+ / Kg
Magnesium Exchange			
Exchange Potassium	Extracción KCl 1N NTC 5263	Volumetric	
Shift Aluminum			
Available iron			
Manganese available	DTPA - NTC 5526	Atomic absorption spectrophotometry	mg/Kg
Copper available			
Zinc available	Hot water NTC 5404	Spectrophotometry uv-vis	
Boron available	Based on organic matter	Calculation	%
Total Nitrogen	Walkley- Black (Colorimetric) NTC5403	Spectrophotometry uv-vis	%
Organic carbon	(Ca (H2P04) 2.H20) 0,008M NTC 5402	Spectrophotometry uv-vis	mg/Kg

Table 2. Physical parameters analyzed in the samples.

Essays	Method	Technique	U. of measure
Texture	Touch		Textural grade
Bulk density	Graduated cylinder	Gravimetric	g/cc

Statistical and geostatistical analysis.

The data were descriptively analyzed and a principal component analysis was performed using the SPAD software. The geostatistical analysis was carried out with ArcGIS 10 software (ArcGIS, 2010). The semivariogram was obtained for each characteristic and through an iterative process where the active lag and the step were modified; the theoretical model of best fit was established, taking into account as parameters of decision the coefficient of determination (R^2) and the sum of squares of the residuals (RSS). Subsequently, a cross-validation analysis was carried out, of importance in the estimation

of values in unsampled sites, through the point Kriging interpolation method, because the samples come from points and not from combinations or mixtures (Balzarini, 2014). This interpolation was the basis for the construction of thematic maps that allow visualizing the spatial variability of each of the physical and chemical properties analyzed. In the mentioned software, spatial distribution maps were also made for each variable, subsequently reclassifications of the results were performed to generate other fertility distribution maps for each variable in the three ranges, according to the values for the Andean region (Table 3).

Table 3. Interpretation of results (ICA, fertilization in various crops, fifth approximation).

Bases	cmol+/Kg			Phosphorus and minor elements	mg/Kg			pH	
	Low	Medium	High		Low	Medium	High	Value	Category
Ca	< 3	03-jun	> 6	P	< 20	20 - 40	> 40	< 5.5	Extremely acidic
Mg	< 1.5	1.5 - 2.5	> 2.5	Fe	< 25	25 - 50	> 50	5.5 - 5.9	Moderately acidic
K	< 0.2	0.2 - 0.4	> 0.40	Mn	< 5	05	> 10	6.0 - 6.5	Suitable
Organic matter according to climate (%)				Cu	< 2	02	> 3	6.6 - 7.3	Neutral
Cold	< 5	5 -10	> 10	Zn	< 1.5	1.5 - 3	> 3	7.4 - 8.0	Alkaline
Half	< 3	3-5	> 5	B	< 0.2	0.2 - 0.4	> 0.4	> de 8	Very alkaline
Warm	< 2	2-3	> 3	S	< 10	-20	> 20		

RESULTS AND DISCUSSION

General statistics. When analyzing the soil fertility traits of the total area samples, a high

percentage of variation was found, which suggested that there was a high intrazonal variability (Table 4).

Table 4. General statistics of the soil fertility variables at Botana Experimental Farm.

Variable	Half	Median	D.E.	Var (n)	CV	Mín	Máx	Asymmetry	Kurtosis
pH	5.67	5.63	0.44	0.2	7.84	4.54	7.04	0.64	0.82
MO	5.23	4.59	2.16	4.6	41.24	1.88	14.7	1.42	2.83
P	62.04	21.85	98.41	9593.7	158.62	4.34	611.0	3.64	15.79
CIC	20.71	20.4	6.44	41.08	31.09	10.7	37.9	0.58	-0.24
Ca	7.51	6.83	2.6	6.67	34.55	0.05	15.3	0.89	1.43
Mg	3.3	3.07	1.22	1.47	36.93	1.38	8.7	1.54	3.53
K	0.9	0.68	0.85	0.71	94.13	0.0	5.37	2.25	7.33
Fe	273.92	264.0	68.31	4622.21	24.94	142.0	395.0	-0.06	-1.07
Mn	28.62	25.2	16.74	277.64	58.5	3.6	90.6	0.86	1.09
Cu	3.11	2.86	1.93	3.71	62.22	0.17	14.5	2.95	12.76
Zn	5.82	3.16	8.55	72.39	146.94	0.17	55.0	3.86	16.19
B	0.19	0.14	0.1	0.01	50.09	0.06	0.63	2.35	6.23
N	0.46	0.18	2.7	7.23	585.59	0.07	28.0	10.28	100.83
C	3.03	2.66	1.25	1.55	41.22	1.09	8.51	1.42	2.8
S	6.55	5.83	4.75	22.36	72.57	2.55	46.4	5.96	45.25
DAP	0.89	0.89	0.09	0.01	10.22	0.6	1.06	-0.61	0.43

Taking into account some classifications for this type of results in similar studies, such as the one carried out by Vásquez (2009), we can classify the variability of the data as follows:

Relatively low or homogeneous variations are only presented for pH and bulk density (DBH), as shown in Table 5, whose similar results were obtained in a study of the variability of soil fertility of the experimental farm of the University of Magdalena (Vásquez, 2009). There is also agreement with the results found by Henríquez (2013), Londoño & Moreno (2014) and Ibarra *et al.* (2009).

The traits that presented extremely heterogeneous variability were P, K, Cu, Zn, N and S. These results also coincide with what was found by Londoño & Moreno (2014). Likewise, Gutiérrez *et al.* (2010), Moreno (2011) and Alesso *et al.* (2017) found in a soil fertility distribution study that available phosphorus and potassium showed high coefficients of variation. Moreno (2011) argues that although pH is a factor that influences the availability of phosphorus in the soil, he did not find a relationship between the high variability shown by this element and the low coefficients of variation observed in pH.

The high value of the coefficient of variation for P (158%) agrees with several works reported in the literature. In this sense, Molina *et al.* (2005) cite similar results. While the following: Ovalles (1991); Paz *et al.* (1996); Melchiori & Echeverría (2000), Ponce *et al.* (1999); Sadeghian *et al.* (2001); Jaramillo (2002) and Silva *et al.* (2003), say it may be due to residuality due to fertilization with P; and that other factors influencing phosphorus retention by the soil, such as: a) Organic matter. In general, it has been found that the effect that the organic phase of the soil P-S diminishes the fixation of phosphorus. b) Presence of hydrated iron and aluminum oxides. In acid soils, these abound and form insoluble compounds with phosphorus. e) Amount and type of clay.

Geostatistical analysis of soil fertility. An exploratory data analysis was performed using the Infostat software, applying a basic statistic to identify the mean, variance, standard deviation, kurtosis and skewness of the data. The SPAD software was applied for multivariate analysis to determine the explanatory traits of the main soil components. In the ArcGIS 10 program, the geostatistical analysis was performed (ArcGIS, 2010). For each trait, the semivariogram was obtained, and through an iterative process in which the active lag and the step were modified.

Table 5. Classification of the variability of the soil fertility parameters at Botana Experimental Farm.

Category of variables	Variability coefficient (CV)	Traits
Relatively homogeneous	< 20	DAP, pH
Moderately heterogeneous	20-40	CIC, Ca, Mg, Fe.
Normally heterogeneous	40-60	MO, Mn, B, C.
Extremely heterogeneous	>60	P, K, Cu, Zn, N, S.

Source: Vásquez (2009).

A theoretical model of best fit was established, taking into account as decision parameters the coefficient of determination (R²) and the sum of squares of the residuals (RSS), for which the first must be the closest to 100% and the second the smallest within the situations raised. The parameters of the best-fit theoretical semivariograms obtained for each of the properties studied are recorded in Table 6.

The models of the selected semivariograms correspond to those with the greatest spatial adjustment that explain the distribution of the evaluated variables. Table 6 shows that the semivariograms with the spherical model are the best fits for CIC, Fe, Zn, B, N and C. For

MO, P, Ca, K and S, it was the Gaussian, and for Mg and texture, the Exponential model corresponded.

The range indicates the distance from which the samples are spatially independent of each other, and represents the size of grain or stain that the variable represents; in this sense, the traits with the greatest scope of spatial dependence were pH, P, Zn and B. On the other hand, the traits with the minor spatial dependence were Ca, Mg, N, C and texture. It is also observed in Table 6 that in all cases, the effective range exceeded the minimum sampling distance used in this study, which was 50m, suggesting an adequate sampling distance (Van *et al.*, 2000).

Table 6. Parameters of the semivariograms for the fertility variables using the Kriging model.

Variable	Model	Nugget effect Co	Sill Co+C	%C ₀ / (C ₀ +C)	Effective Range (m)	Root-Mean-Square	Root-Mean-Square Standardized	Average Standard Error	Dependence
pH	Spherical	0.02	0.21	9.5	325	0.26	0.97	0.27	Strong
MO	Gaussian	0.03	0.04	75	91.3	1.36	0.89	1.48	Moderate
P	Gaussian	0.3	0.67	44.8	305.3	40.7	1.39	51.9	Moderate
CIC	Spherical	0.02	0.013	153.8	263.2	3.85	1.01	4.05	Weak
Ca	Gaussian	0.01	0.25	4	74.2	2.47	1.77	3.95	Strong
Mg	Exponential	0.018	0.05	36	82	0.93	0.9	0.96	Moderate
K	Gaussian	0.15	0.76	19.7	97.6	0.55	1	1.14	Strong
Fe	Spherical	0.007	0.06	11.7	373	39.6	0.92	44.9	Strong
Cu	Gaussian	0.09	0.16	56.3	342	1.47	1.17	1.21	Moderate
Zn	Spherical	0.65	0.47	138.3	355	2.9	0.95	4.44	Weak
B	Spherical	0.03	0.06	50	376	0.05	1.17	0.04	Moderate
N	Spherical	0.01	0.03	33.3	78.5	0.04	1.02	0.04	Moderate
C	Spherical	0.01	0.04	25	78	0.74	0.96	0.78	Strong
S	Gaussian	0.07	0.05	140	208	2.1	0.97	2.17	Weak
Textura	Exponential	0.09	0.05	180	71.5	1.27	0.87	1.48	Moderate

Nugget: variance of spatial discontinuity due to measurement error or micro variability. Sill: maximum threshold of the semi-variance. Range Ao: range of spatial dependence where the sill is reached.

The spatial dependence was analyzed through the relative Nugget effect [%C0 / (C0 + C)], cited by Trujillo (2011). That revealed a strong dependence for pH, Ca, K, Fe and C (<25%), while MO, P, Mg, Cu, B, N and texture have a moderate dependence (25-75%) and weak spatial dependence (> 75%) for CIC, Zn and S.

Spatial distribution maps. According to Balzarini (2014), Kriging interpolations allow the generation of spatial distribution maps for each of the physical and chemical traits studied. As an example, the spatial distribution maps for soil organic matter (SOM) and Mg are indicated below in Figure 1.

Considering the samplings carried out and the interpolation of the evaluated variables, Figures 2 and Figure 3 show the values reclassified according to the fertility ranges for the Andean zone mentioned in Table 3 of this document. First, Figure 2 indicates the spatial distribution for Boron B, Calcium Ca, Carbon C, Cation Exchange Capacity CIC, Copper Cu, Potassium K and Magnesium Mg, while Figure 3 shows the corresponding

values for Manganese Mn, Organic Matter SOM, Nitrogen N, Phosphorus P, Zinc Zn, pH and Texture. In this way, maps with high, medium and low ranges were generated for the said traits. From the data observed in the maps, it is inferred that variables such as Mg, Mn, Ca and K occupy most of the surface of Botana Experimental Farm in a high range, both distributed in the upper, middle and lower part of the farm. The Cu and P presented a certain range, especially towards the middle and lower zones. The variables B, C, N and MO, did not present high ranges, only medium and low.

According to the texture data obtained (Figure 3), the vast majority of the soils of Botana Experimental Farm (12ha) have a sandy clay loam to clay loam texture, and only 5ha are of a sandy loam to loamy texture. The thematic map for pH (Figure 3) shows areas ranging from red (neutral) to green (very strongly acidic). In general, most of the farm has moderately acidic soils (16has).

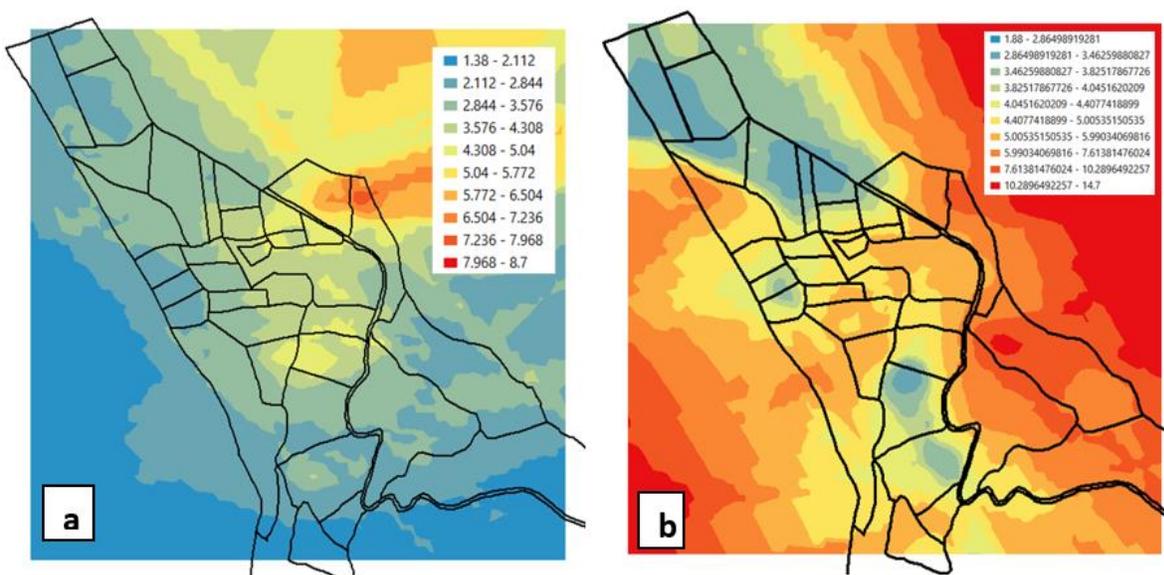


Figure 1. Interpolation of the spatial distribution according to the Kriging method for SOM (a) and Mg (b).

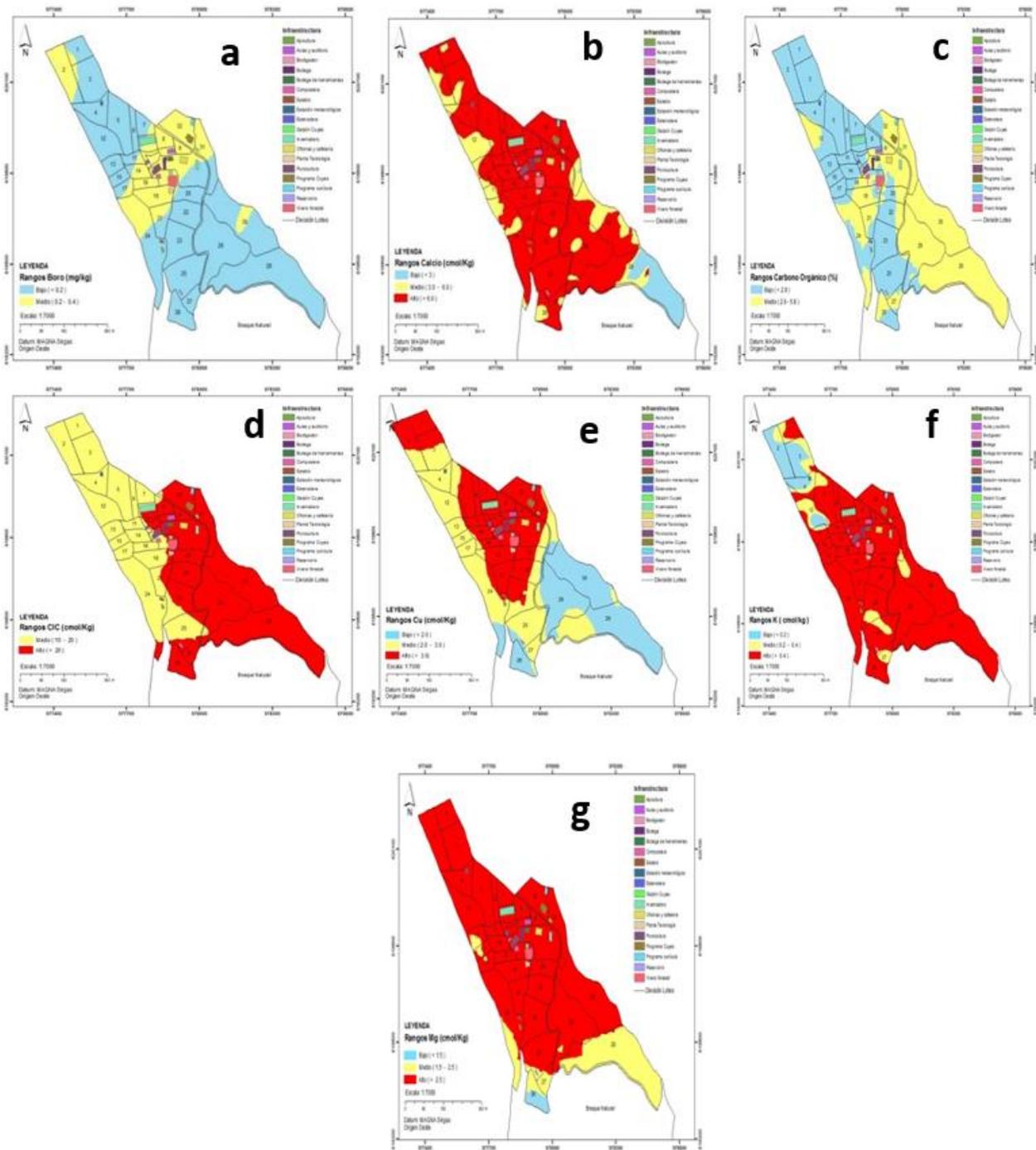


Figure 2. Classification of spatial distribution of B (a), Ca (b), C (c), CIC (d), Cu (e), K (f) and Mg. The colors red, blue and yellow represent high, medium and low contents, respectively.

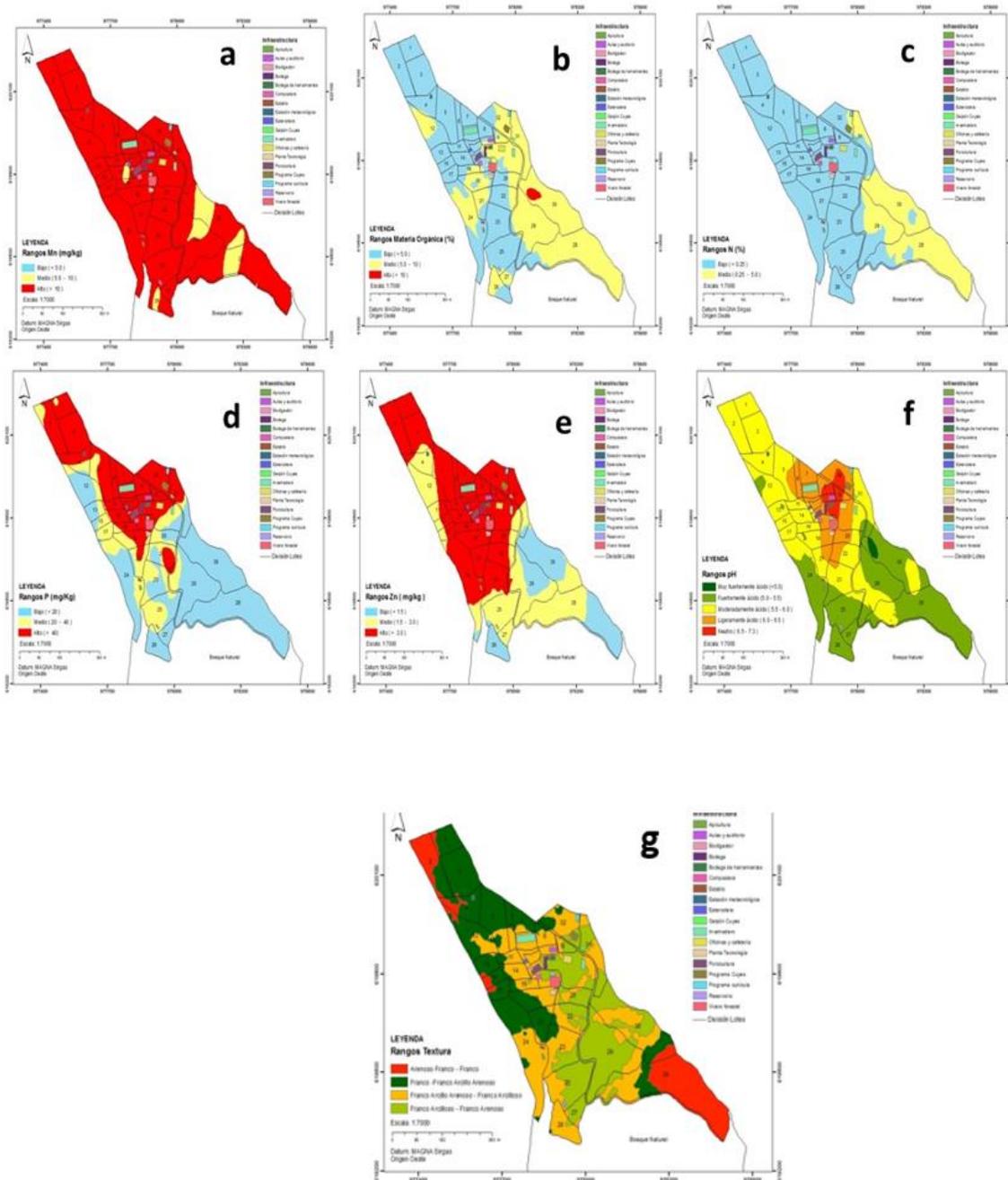


Figure 3. Classification and spatial distribution of Mn (a), SOM (b), N (c), P (d), and Zn (e). Where the red, blue, and yellow colors represent high, medium and low content of the evaluated variables, respectively; For pH (f), where red for pH represents values greater than 6.5 and green less than 5.0; For Texture (g), red represents sandy loam to loam soils, dark green loam to clay loam, orange clay loam, and light green sandy clay loam.

Classification analysis. To define relatively homogeneous zones based on the principal components, the first three components were

selected, explaining 80% of the variability of the data. This analysis allowed obtaining three clusters (Figure 4).

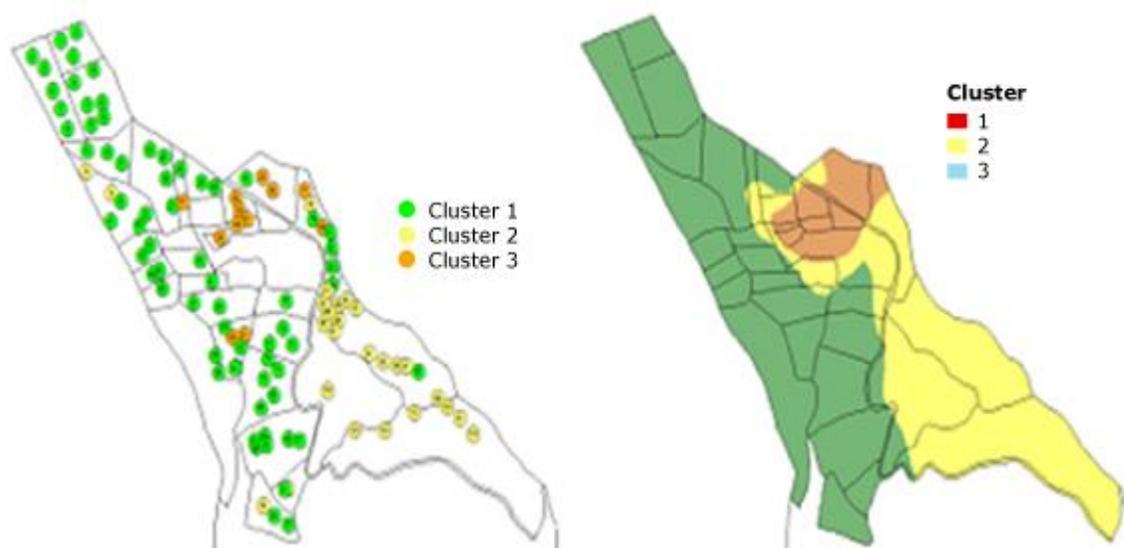


Figure 4. Location of the samples in each Cluster obtained and IDW interpolation of the Clusters.

Cluster 1. Making an interpolation of the sampled points that correspond to this group, an area of 20.7has was obtained, located towards the western side of Botana Experimental Farm, which corresponds to the lots: 1, 2, 3, 4, 5, 6, 7, 11, 12, 13, 14, 15, 16, 17, 18, 20, 21, 22, 32, 24, 35, 26 and 27. The traits of these batches are: high content of Mg, K, Zn, Mn and Ca; low C and SOM content; medium to low P and Cu content; medium CEC; moderately acidic pH, and sandy clay loam to loam texture.

Cluster 2. This group corresponds to an area of 13.9has, located towards the eastern part of the farm, which corresponds to lots: 28, 29, 30, and 31, part of 32, 7 and 11. The traits of this cluster are strongly acidic pH; medium SOM content; low content of P, B, Cu; high content of K, C, Ca, Mg, Mn; high CIC; texture Sandy Clay Loam to Sandy Loam.

Cluster 3. This group corresponds to an area of three hectares, located towards the southeastern part of Botana Experimental Farm. The traits of this zone are neutral pH; medium content of B; high content of Zn, K, P, Ca, Cu, Mg, Mn; high CEC; low C content; texture Sandy Clay Loam to Clay Loam.

According to the previous characteristics, we can assure them that the third cluster presents the best conditions; therefore, it corresponds to an area of high fertility. It should be noted that the administrative infrastructure of the farm is located in this area; however, there are many agricultural vocations with good fertility traits. The second Cluster presents quite favorable conditions for the development of cold-climate crops; therefore, it corresponds to a zone of medium fertility. The first Cluster presents quite limiting traits since it presents the lowest content in some elements, such as SOM, Cu, C and P, with a loamy-to-loamy sandy clay texture (Figure 5).

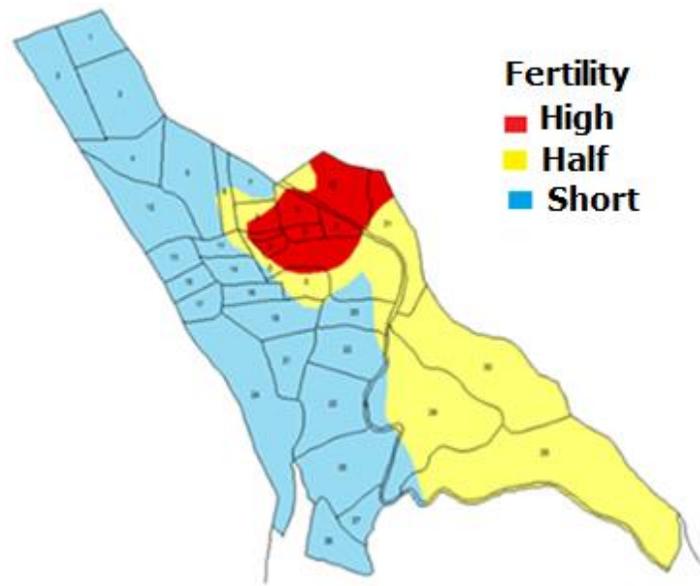


Figure 5. Zoning of soil fertility in Botana Experimental Farm (the numbers indicate the numbering of the lots managed by the Farm administration).

CONCLUSIONS

In general, the properties evaluated, except for pH and bulk density, showed significant variability and spatial distribution throughout the study area. Mg, Mn, Ca and K occupy most of the surface, while organic matter and phosphorus content are the most limiting properties. In this case, the distribution maps made it possible to identify spatial trends that, independently of signifying a specific fertility level, could be projected as references for differential nutrition actions in farm management.

Based on the restriction levels for the evaluated traits and possibly due to the soil mineralogy dominated by non-crystalline aluminosilicates, the low cation exchange capacity and soil management factors, three fertility zones could be identified on the farm: high, medium and low, the latter being the most predominant.

Conflict of interests: The authors declare that there is no conflict of interest.

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