Spatial variability of soil chemical properties and its effect on crop yields: a case study in maize (*Zea mays* L.) on the Bogota Plateau

Variabilidad espacial de las propiedades químicas del suelo y su efecto sobre el rendimiento del cultivo: estudio de caso en maíz (*Zea mays L.*) para choclo en la Sabana de Bogotá

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ABSTRACT

To evaluate the effect of soil chemical properties on the crop yield of corn, in the context of site-specific fertilization, we characterized the spatio-temporal variability of these properties and crop yield in a lot at the Centro Agropecuario Marengo of the Universidad Nacional de Colombia (Mosquera, Colombia). Using a systematic sampling grid of 32 points (25 x 25 m), soil samples were taken before crop sowing and 60 days after sowing (das) to determine soil pH, N (%); Ca, K, Mg, Na, Al, H (cmol+ kg^{-1}), P, Cu, Fe, Mn, Zn and B (mg kg^{-1}). At 162 das, harvest and yield components were evaluated by site. The data was processed using multivariate procedures, descriptive analysis and geostatistical analysis. Emergent properties were obtained from the original chemical variables using principal component analysis (PCA); these new variables were evaluated using geostatistical analysis to show spatial distribution and its correlation with performance. The PCA allowed the finding of three patterns of spatial variability in the soil corresponding to the variables related to soil fertility CO, Ca, Mg, K, CIC and B, the availability of nutrients by soil redox potential, and the variability associated with salinity explained by the Na content and soil electrical conductivity. The first group of variables largely explains the spatial variability of crop yield of corn.

Key words: fertilization, geostatistical analysis, productivity, soil.

RESUMEN

Para evaluar el efecto de las propiedades químicas del suelo sobre el rendimiento del cultivo del maíz para choclo, en el contexto de la fertilización específica por sitio, se caracterizó la variabilidad espacio temporal de esas propiedades y del rendimiento del cultivo, en un lote del Centro Agropecuario Marengo de la Universidad Nacional de Colombia (Mosquera, Colombia). Usando una red sistemática de muestreo de 32 puntos (25 x 25 m), referenciados dentro del lote, antes de siembra del cultivo y 60 días después de siembra (dds), se tomaron muestras de suelos para determinar pH; N (%); Ca, K, Mg, Na, Al, H (cmol+ kg^{-1}); P, Cu, Fe, Mn, Zn y B (mg kg^{-1}). A los 162 dds se evaluó la cosecha y los componentes de rendimiento por punto. El procesamiento de los datos se realizó mediante procedimientos multivariados, análisis descriptivos y análisis geoestadísticos. Se obtuvieron propiedades emergentes a partir de las variables químicas originales mediante análisis de componentes principales (ACP); a esas nuevas variables se les realizó análisis geoestadístico para conocer su distribución espacial y su correlación con el rendimiento. El ACP permitió encontrar tres patrones de variabilidad espacial en el suelo y que corresponden a: las variables relacionadas con la fertilidad del suelo CO, Ca, Mg, K, CIC y B; la disponibilidad de nutrientes por potencial redox del suelo; y, la variabilidad relacionada con la salinidad explicada por el contenido de Na y conductividad eléctrica del suelo. El primer grupo de variables explicó en gran medida la variabilidad espacial del rendimiento del cultivo del maíz.

Palabras clave: fertilización, análisis geoestadístico, productividad, suelo.

Introduction

The variability that occurs in crop development and yield is caused by specific ecological conditions of each site, by genetic factors specific to the planting material and crop management conditions that depend on the management and/or cultural aspects of the producers (Srinivasan, 2006; Leiva, 1998; Cerri *et al*., 2004; Jin and Jiang, 2002; Leiva, 2006).

The spatial variability of soil occurs due to pedogenetic factors and their use and management (Rodenburg *et al*., 2003; Viera and Gonzalez, 2003), and is expressed in physical and chemical properties (Cerri *et al*., 2004; Jin and Jiang, 2002; Corwin *et al*., 2003; Bailey *et al*., 2001), mineralogy (Sovik and Aagaard, 2003), moisture content and field capacity (Reichardt *et al*., 2001), in the organic matter content and mineralization of carbon (Amador *et al*., 2000).

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Spatial and temporal variability occurs on different scales. The level of a climate variable can be relatively homogeneous within a cultivation site and depending on the topography of the region, vary widely with distance. In contrast, the levels of physical and chemical variables of soil may switch to sub-meter scales (Srinivasan, 2006; Leiva, 2006; Cerri *et al*., 2004; Jin and Jiang, 2002). The variability of the biological, physical and chemical properties of soil is a major reason for the variability of crop production (Jin and Jiang 2002; Rodriguez *et al*., 2008).

Recognizing the importance of quantifying, understanding and managing the variability that occurs in agricultural systems in Colombia, different approaches have been used to implement site-specific management, from work at the regional level to determine homogeneous agro-ecological zones where two spatially distant sites can belong to the same homogeneous management zone, and share similar characteristics to smaller scale projects where sites characterized by spatial continuity are necessary for the analysis of spatial correlation between sampling site (Isaacs *et al*., 2004; Rubiano, 2005; Leiva, 2006; Peña *et al*, 2009).

Due to the high number of interactions in ecological processes, a considerable part of the mechanisms that contribute to the variability of a variable, such as performance or quality of the harvest site, remain uncertain, this is because in complex systems, such as agricultural, there are attributes that cannot be explained by individual variables, due to diverse relationships and the fact that they do not act in isolation. These attributes are called emergent properties, so a challenge to the analysis of information management is site-specific data to be analyzed in a comprehensive manner, with appropriate methodologies and techniques to reduce system complexity and improve their understanding by using multivariate analysis.

The present study aimed to determine the effect of spatial variability of soil chemical properties on the yield of maize on the Sabana de Bogotá, for possible implementation of site-specific fertilization. For this purpose we evaluated the spatial variability of crop production of corn and chemical properties of the soil, and then analyzed the correlation between these two types of variability.

Materials and methods

The research was conducted on a commercial lot of 2 ha at the Centro Agropecuario Marengo (CAM) of the Universidad Nacional de Colombia, Bogotá, located in the municipality of Mosquera, Cundinamarca (Colombia), coordinates 4° 42’ N; 74° 12’ W, 20 km from Bogotá DC. The altitude is 2,547 m a.s.l.; the average yearly temperature is 12.9°C, average precipitation of 820 mm year^{-1}, average relative humidity of 78% and sunshine of 4.8 h d^{-1}. The soil was classified, according to USDA taxonomy as Fluventic Humic Dystrudepts.

In the experimental plot, a systematic network of samples using a regular grid (grid) 25 x 25 m was laid out, with sampling points referenced by cartesian coordinates (X and Y). A total of 32 points were taken, avoiding the edge effects of the lot. At each referenced point, soil samples were taken in two periods for chemical analysis of organic carbon (OC) by Walkley-Black method, exchangeable bases: calcium (Ca), potassium (K), magnesium (Mg) and sodium (Na) by extraction with 1N ammonium acetate pH 7; CIC analyzed by the displacement of NH4 exchanged with 1M NaCl, pH, phosphorus (P) by the Bray II method, copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn) by extraction with DTPA and boron (B) by extraction with phosphate monobasic (azomethine-H). The first take was done before planting the maize, without any tillage, the second at 60 das. The only crop fertilization was performed at 20 das, using 15-15-15 for the equivalent of 25 kg ha^{-1} N, 25 kg ha^{-1} of P_2O_5 and 25 kg ha^{-1} of K_2O.

Corn variety ICA V-508 was planted: starchy, yellow and adapted to cold weather (Moreno, 1984), the planting distance used was 0.80 cm between rows and 0.25 cm between plants, for a density of 50,000 plants/ha. We performed the commercial management used by corn producers in the area, applied uniformly throughout the crop. At 162 das, the corn was harvested. To evaluate the performance, an area of 9 m^2 was denoted around each point and all plants within this area were harvested and quantified for performance. Each ear was weighed, including the mats and grains cob, according to market standards. The measurements were taken as kg m^{-2}.

Assuming that the variables of soil and yield of maize have spatial structure, geostatistical analysis was performed for each of these variables. Experimental semivariograms were calculated for all variables and were adjusted to theoretical semivariance models using GS+™ software version 9. Interpolation was performed using the ordinary Kriging method and the spatial trend was visualized with contour maps (Giraldo, 2002).

Multivariate analysis was performed by groups of variables, to reduce the dimensionality of the data and to facilitate the interpretation of the information contained in the data using the covariance matrix of principal component analysis (PCA) in SPSS™ version 15 (Diaz-Monroy, 2002; Hidalgo, 2003). Bivariate analysis was also performed with Pearson's linear correlation between soil variables and performance between the factorial coordinates of the major components and performance.

Results and discussion

Spatial variability of crop yield and soil chemical properties

The corn yield had a coefficient of variation (CV) of 50% and ranged between 1.82 and 0.11 kg m^{-2}, with an average of 0.84 kg m^{-2} (Tab. 1). The high CV of performance, consistent with the same variety with a uniform crop management under similar weather conditions in the field of culture, suggests that this variability can be explained by other factors, including the various soil variables analyzed.

Tab. 1 shows that some variables showed considerable variability with coefficients of variation above 30%. This was the case during the two sampling periods for EC, K, Na, Al, H, before planting, for P and B, and 60 das for Cu, Mn and Zn. In particular, it highlights the high variability of exchangeable Al and H, in contrast to the low variability presented by the pH. In the case of Al, however, it is important to note that the values found are not limiting for the crop (Tab. 1).

TABLE 1. Descriptive analysis of maize yield and nutrient content in the soil at crop establishment and 60 das on the Bogota Plateau.

Variable	Unit	Period	Min	Max	Mean	SD	Bias	Kurtosis	CV
Rdto	kg m^{-2}		0.11	1.82	0.84	0.42	0.25	-0.59	50
CE	dS m^{-1}	1	0.47	1.87	0.75	0.28	2.37	7.27	38
CE	Ds m^{-1}	2	0.44	3.03	1.25	0.5	1.62	4.23	41
pH		1	4.81	5.36	5.00	0.12	0.89	1.08	2
pH	%	2	4.77	5.62	5.17	0.19	-0.15	0.14	4
CO	%	1	1.76	4.3	3.06	0.52	0.17	0.61	17
CO	%	2	2.25	4.58	3.27	0.6	0.26	-0.64	18
N	%	1	0.15	0.37	0.26	0.05	0.17	0.61	17
N	cmol+ kg^{-1}	2	0.19	0.39	0.28	0.05	0.22	-0.68	19
Ca	cmol+ kg^{-1}	1	8.28	13.75	10.93	1.31	0.34	0.18	12
Ca	cmol+ kg^{-1}	2	8.00	13.43	10.69	1.34	0.17	-0.52	13
Mg	cmol+ kg^{-1}	1	2.46	4.01	2.99	0.36	1.31	1.93	12
Mg	cmol+ kg^{-1}	2	2.13	4.38	3.00	0.39	0.93	4.46	13
Na	cmol+ kg^{-1}	1	0.77	2.60	1.17	0.37	2.02	6.01	32
Na	cmol+ kg^{-1}	2	0.46	3.65	1.06	0.53	3.93	19.59	49
K	cmol+ kg^{-1}	1	0.39	1.95	0.88	0.43	1.21	0.51	49
K	cmol+ kg^{-1}	2	0.40	2.58	0.98	0.52	1.83	3.19	52
Al	cmol+ kg^{-1}	1	0.03	0.50	0.15	0.10	1.86	4.62	67
Al	cmol+ kg^{-1}	2	0	0.64	0.14	0.11	2.82	12.63	80
H	cmol+ kg^{-1}	1	0.03	0.25	0.13	0.05	0.25	-0.41	40
H	cmol+ kg^{-1}	2	0	0.28	0.12	0.06	0.18	0.48	52
CIC	cmol+ kg^{-1}	1	21.26	29.75	24.85	2.27	0.56	-0.38	9
CIC	mg kg^{-1}	2	21	30.60	24.50	2.31	0.86	0.27	9
P	mg kg^{-1}	1	36.80	140.10	65.29	20.66	1.77	4.53	32
P	mg kg^{-1}	2	77.60	144.30	129.16	18.59	-1.51	1.11	14
Mn	mg kg^{-1}	1	3.25	15.75	11.88	3.26	-1.31	1.23	27
Mn	mg kg^{-1}	2	1.24	11.66	5.31	2.84	0.82	-0.08	53
Zn	mg kg^{-1}	1	10.48	39.5	27.4	5.66	-0.45	1.70	21
Zn	mg kg^{-1}	2	3.74	36.18	14.12	6.78	1.10	2.17	48
Fe	mg kg^{-1}	1	440.00	605.00	523.19	47.95	-0.04	-0.90	9
Fe	mg kg^{-1}	2	402.00	490.00	436.69	21.44	0.78	0.27	5
Cu	mg kg^{-1}	1	0.90	3.28	2.66	0.61	-1.51	1.46	23
Cu	mg kg^{-1}	2	0.34	2.26	0.93	0.45	1.51	2.38	49
B	mg kg^{-1}	1	0.17	0.72	0.34	0.13	1.36	1.90	37
B	mg kg^{-1}	2	0.37	0.92	0.56	0.12	1.14	1.17	22

Period 1: before sowing; period 2: 60 das.

TABLE 2. Models fitted to experimental semivariograms for yield variables of maize, the nutrient content at the time of crop establishment and 60 das in a lot on the Bogota Plateau.

Variable	Period	Model	Nugget	Sill	Range*	R^2**
Yield		Gaussiano	5.820	31.630	164	0.99
H	1	EPP	0.003	0.003	105	0.38
H	2	Spherical	0	0.011	37	0.01
Al	1	Spherical	0	0.009	41	0.75
Al	2	Exponential	0.001	0.004	89	0.60
B	1	Gaussiano	0.01131	0.03932	329	0.96
B	2	Exponential	0.002	0.021	166	0.98
Ca	1	Gaussiano	0.826	2.692	206	0.98
Ca	2	Gaussiano	0.672	3.354	217	0.96
N	1	Spherical	0.041	0.447	216	0.95
N	2	Gaussiano	0.062	0.400	90	0.99
CE	1	Spherical	0.001	0.078	42	0.50
CE	2	Exponential	0.019	0.263	63	0.76
CIC	1	Gaussiano	2.610	9.229	244	0.82
CIC	2	Spherical	0.330	5.653	117	0.99
Cu	1	Gaussiano	0.100	0.507	101	0.99
Cu	2	Exponential	0.016	0.206	52	0.38
P	1	Exponential	1	352.3	69.9	0.99
P	2	Spherical	76.000	453.500	160	0.99
Fe	1	EPP	2117.74	2117.741	-	0.80
Fe	2	Exponential	67.000	534.600	120	0.98
Mg	1	Spherical	0.031	0.130	96	0.99
Mg	2	Exponential	0.014	0.173	140	0.99
Mn	1	Spherical	4.790	11.990	108	0.99
Mn	2	Exponential	0.660	8.255	29	0.09
pH	1	Spherical	0.005	0.016	87	0.96
pH	2	Exponential	0.007	0.043	109	0.90
K	1	Exponential	0.014	0.198	100	0.62
K	2	Gaussiano	0.126	0.313	125	0.98
Na	1	Exponential	0.008	0.142	69	0.65
Na	2	Spherical	0.000	0.306	64	0.66
Zn	1	Gaussiano	12.200	55.400	211	0.97
Zn	2	Exponential	0,1	43,96	48,9	0,79

Period 1: before planting; Period 2: 60 days after sowing. EPP: pure nugget effect. * Effective range of the model. ** R^2 of the semivariogram.

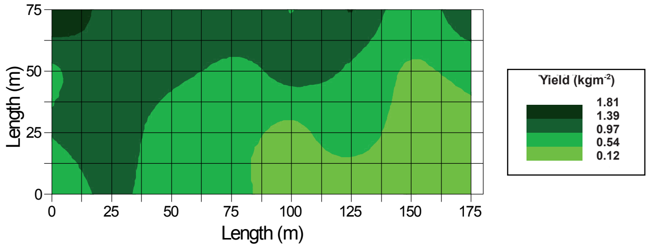

FIGURE 1. Spatial distribution (coordinates in m) of the variable fresh weight of the yield of the corn (kg m^{-2}) in a lot on the Bogota Plateau.

Theoretical models of semivariance set are shown in Tab. 2 and the spatial distribution of yield (kg m^{-2}) are presented in Fig. 1.

For the contents of Fe and H before planting it was not possible to set a theoretical model, showing a pure nugget effect-EPP (ratio between the sill and the nugget of 100%), indicating lack of spatial correlation. The variables Al, Mn, and Cu H (60 das) R^2 values were lower in the models, so that maps of each variable estimated with these models may not adequately represent its spatial distribution in the field.

The adjustment of other variables to dimensional models indicates that the average values of the variables do not show clear trends in any direction, so that they meet the assumption of isotropy and use of these models to make estimates at unsampled sites provides adequate spatial representation of what happens in the field with each of these variables (Viera and González, 2003).

To determine the degree to which spatial variability in yield can be explained by the chemical properties of the soil, we performed bivariate correlation analysis using Pearson's method (Tab. 3).

TABLE 3. Pearson correlation coefficients between the variables of soil and crop yield of corn in Lot 7 at (CAM).

Variables	Correlation coefficients of yield	
	Before sowing	60 das
CO	0.69**	0.77**
Ca	0.52**	0.55**
Zn	0.40*	0.34
Mg	0.35	0.58**
K	0.28	0.56**
P	0.14	0.63**
Cu	-0.11	0.21
Mn	-0.08	-0.15
B	-0.03	0.52**
Fe	-0.03	0.30
Na	0.16	0.26
Al	-0.22	-0.24
H	-0.02	0.41*
CIC	0.45*	0.67**
pH	-0.39 *	-0.54**
CE	0.24	0.51**

das, days after sowing.
* Significant ($P \leq 0.05$), ** Highly significant ($P \leq 0.001$).

Due to many significant correlations found between soil variables and yield, as well as the diversity of patterns found when variables are spatially displayed with contour maps, it is difficult to make a management decision by allowing site-specific implementing in the field, taking into account all variables, so we used principal component analysis (PCA) to reduce the dimensionality, facilitating the interpretation of the information and grouping of the variables that explain the crop behavior (Diaz-Monroy, 2002). This independent analysis was performed for the two data sets.

In analyzing the content of elements in the soil, four components explained 77% of the variability of the soil before planting and 79% of the variability at 60 das (Tab. 4).

Using the information from the main components, geostatistical analysis was performed. Tab. 5 presents the semivariance models adjusted for these components. EPP was found for component IV before planting, showing absence of spatial correlation of the emergent property that accounts for this component. The other components were adjusted to semivariance dimensional models, but model adjustment of component IV at 60 das was low ($R^2 = 0.18$), so it may not properly represent spatial behavior in the field.

For the first three components, in the analysis of the variables of soil before planting and 60 das, the models show spatial dependence structure, in components I and II spatial autocorrelation occurs at a greater distance compared to component III that presented lower ranges of semivariance function. This indicates that soil properties explained by each of the components have different spatial behavior

TABLE 4. Variance explained by each principal component characteristic of the soil before planting and 60 das.

Component	Variances					
	Before sowing			60 das		
	Total	Variance (%)	Cumulative variance (%)	Total	Variance (%)	Cumulative variance (%)
1	5.513	34.455	34.455	6.317	39.480	39.480
2	3.309	20.683	55.137	3.378	21.113	60.593
3	1.963	12.271	67.408	1.797	11.229	71.821
4	1.590	9.937	77.345	1.187	7.418	79.239

das, days after sowing.

TABLE 5. Theoretical models fitted to experimental semivariograms of the principal components obtained for each set.

Period	Comp	Model	Nugget	Sill	Range*	R^{2**}
1	I	Gaussiano	0.37900	2.43900	194.7	0.96
1	II	Spherical	0.19800	1.11400	97.9	0.99
1	III	Gaussiano	0.04400	1.00100	41.4	0.71
1	IV	EPP	0.86456	0.86456	104.9	0.01
2	I	Spherical	0.00600	1.22300	135.9	0.99
2	II	Exponential	0.45900	1.26500	157.2	0.98
2	III	Spherical	0.04600	0.99900	54.8	0.99
2	IV	Exponential	0.00300	0.94200	46.2	0.18

Period 1: before planting; Period 2: 60 days after sowing. EPP: pure nugget effect. * Effective range of the model (m). ** R^2 of the semivariogram.

TABLE 6. Bivariate correlation between crop yield and main components obtained for each set of variables.

	Before sowing				60 das			
	I	II	III	IV	I	II	III	IV
Correlation coefficient	0.463	0.066	0.06	0.261	0.723	-0.315	-0.067	-0.008
Significance	0.008	0.719	0.746	0.15	0	0.079	0.715	0.964

das, days after sowing.

within the lot, which confirms the importance of grouping variables through the ACP.

To establish the relationship between the principal component and crop yield, a correlation analysis was performed (Tab. 6). The results show significant correlations between yield and the main component I of the properties of the soil before planting and 60 das. Other components showed no correlation with yield. In addition, the main components I obtained before and at 60 das correlated with each other in a highly significant manner (0.746 $P \leq 0.01$).

Emergent variables in the soil

The emergent property of component I may be called 'soil fertility' because it is caused by the contents of Ca, Mg, K, N, P and CIC before planting and 60 das for the same variables and B (Tab. 7). By comparing the variables that explain these components, the values themselves and their signals and spatial distribution, we find that these positively affect yield and are responsible to a greater degree for spatial variability in the range of that found. This important result is consistent with that found in research in conditions similar to the present study (Ospina, 1999; Fenalce, 2002; Rodriguez *et al*., 2008). Figs. 2 and 3 shows the spatial distribution of the components I in the two periods, within the lot areas with higher values in the color scale being the most fertile soil.

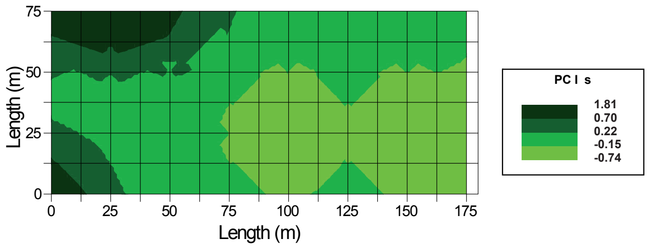

FIGURE 2. Spatial distribution (coordinates in m) of component I associated with the fertility of the soil before corn crop establishment in a lot on the Bogota Plateau.

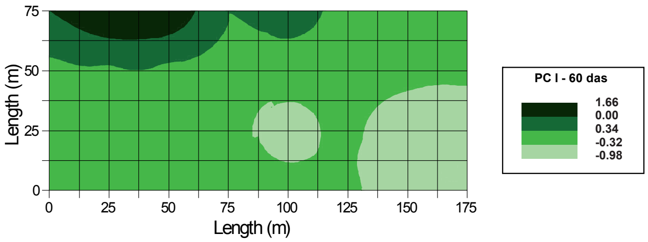

FIGURE 3. Spatial distribution (coordinates in m) of component I associated with the fertility of the soil at 60 days corn crop on the Bogota Plateau.

Other studies in maize also agree with the findings in this investigation where nitrogen is the element that most often limits the growth and crop yield. This is because plants require relatively high amounts of N (between 1.5 and 3.5%

TABLE 7. Vectors of the main components per element before planting and 60 das.

	Before sowing				60 das			
	I	II	III	IV	I	II	III	IV
Al	-.703		.219	.480	-.534	-.496	-.012	.070
B	.368	-.308	-.115	.463	.842	.092	.153	.106
Ca	.955				.876	.063	-.125	-.290
CE	.495	.244	.806		.451	-.525	.344	.188
CIC	.777	-.297	-.231	.275	.823	-.426	-.198	-.173
Cu	-.367	.834	-.204		.486	.687	.078	.221
Fe		-.781	-.202	-.149	.389	-.008	-.823	.208
H			-.104	.542	.246	-.489	-.153	.658
K	.830		-.121	-.112	.879	-.039	.003	.310
Mg	.868	.237	.163		.823	-.064	.407	-.223
Mn	-.257	.820	-.187		.112	.854	.161	.299
N	.821	-.282		.209	.811	-.328	-.338	-.070
Na	.250		.944		.388	-.240	.756	.100
P	.708	.514	-.275		.682	.199	-.106	-.465
pH	.105	-.320	-.150	-.825	-.198	.850	-.070	-.021
Zn	.477	.759	-.174		.674	.538	-.021	.174

das, days after sowing.

of plant dry weight) and because they usually do not have enough soil N available to maintain adequate levels of production. This deficiency can reduce grain yield and quality (Rincón and Ligarreto, 2008; Below, 2002), in addition, the metabolism of N has an impact on the growth and development of corn in two general functions: (1) establishing and maintaining photosynthetic capacity, (2) development and growth of reproductive sinks (Below, 2002). On the other hand, the deficiency of N in maize has been described by its effect on the determination of number of grains per plant, because its availability encourages differences in the rate of growth of the ear (critical time) and the number of grains per plant is related to the rate of growth in the critical period (D'Andrea *et al.*, 2008).

Calcium absorption in corn grown in tropical conditions occurs gradually in the vegetative stage at the beginning of floral differentiation. Like other nutrients, Ca does not accumulate during the full bloom stage, but its absorption reaches a marked increase from grain filling. This accumulation may be due to high demand during the process of cell division in the steps outlined, so that its availability influences the crop yield potential (Rengel, 2003).

In maize, potassium deficiency causes accumulation of sugars in the stem, it appears that the low content of K in the cell limit the translocation of sugars to the ear, which interrupts the growth cycle and hinders the normal development of the grain; during the grain development period the presence of K is important, to promote the transport of the products of photosynthesis from the leaves to the ears (Rengel, 2003).

Boron deficiency affects many plant physiological processes such as the transport of sugars, synthesis and structure of cell wall lignification, carbohydrate metabolism, RNA metabolism, AIA, phenols and ascorbate, respiration and plasma membrane integrity.

Bazinga *et al.* (2002) explain that the abortion of the ears occurs when assimilate supply is below the threshold required for normal development and this happens when the levels of soil fertility is low, making CIC an indicator of soil fertility because it is associated with an adequate base saturation. On the other hand, the variability does not explain chemical properties and performance is contained in other components may explain other emergent properties that characterize the dynamics that occurs in the floor of the test group.

Component II in the soil before sowing (bs) is explained by the values of Mn, Cu and Fe, while component II in the soil after sowing is explained by Mn and pH (Tab. 7). By comparing the coordinates of the principal components factor before planting and 60 days after, it was found that they are significantly correlated (0.456 $P \leq 0.001$). When analyzing the variables that explained component II of the chemical properties of soil, we can deduce that the emergent property of the second component is the redox potential, this assertion is supported by the fact that this potential is correlated with the solubility of mineral nutrients such as Mn, Cu and Fe which explains their values within these components (Marschner, 2002), this agrees with the fact that during the present study ponding and drying presented the lot in relatively short periods of time and according to a study of soils on the Bogota Plateau, conducted by IGAC, approximately 44% of soils suitable for agriculture have constant water logging caused by restricted natural drainage (Universidad Nacional de Colombia, 1970).

Figs. 4 and 5 show the spatial distribution of the component II, the highest values of the scales presented can be associated with the highest or lowest redox potential under reducing conditions. The redox potential is a quantitative measure of a particular system to reduce susceptible substances, is positive and high in strongly oxidizing systems and negative and low in strongly reducing systems.

The variability in the observed patterns between the two seasons for this emergent property can be explained by the

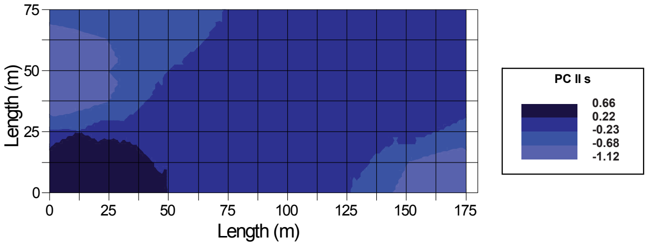

FIGURE 4. Spatial distribution (coordinates in m) of component II associated with the redox potential of the soil before corn crop establishment on the Bogota Plateau.

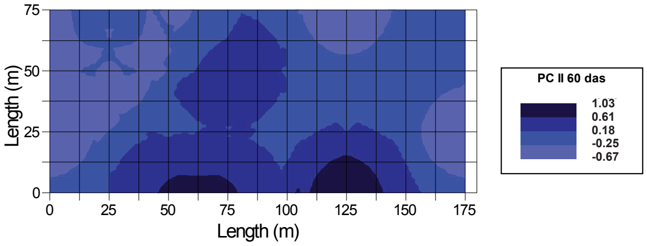

FIGURE 5. Spatial distribution (coordinates in m) of component II associated with the redox potential of the soil after corn crop establishment on the Bogota Plateau.

higher accumulated rainfall that occurred before the first soil sampling (32.62 mm for the 7 d preceding the sampling) and with respect to the second (11.55 mm for this cumulative), this coupled with poor natural drainage of the soil, led to limiting conditions before crop establishment compared with those presented at 60 das.

From the spatial point of view, in places where reducing conditions are more severe, the extractability of Fe is greater, this is because the oxides of manganese and iron are subject to dissolution and precipitation processes that are associated with changes in redox conditions (Tack *et al.*, 2006) and after the organic matter, in soil with Mn oxides are the following electron acceptors, as well in acid soils, such as in the study with high contents of Mn and low nitrate , there may be significant levels of Mn^{2+} (Marschner, 2002, Santiago *et al.*, 2008). With lower redox potential and iron-rich soils Fe^{3+} to Fe^{2+} has been reduced, preventing the precipitation of ferric phosphate and releasing P to the environment (Santiago *et al.*, 2008).

The relationship found between Mn and pH is also explained by the reduction conditions of soils and under conditions of water logging in acid soils the soil pH increases (Snyder and Slaton, 2002; Domínguez-Vivancos, 1988). The redox potential is an intensity factor and is closely related to the soil aeration system, as well as pH, since both are conditioned on microbial activity and the type of reactions are carried out in the soil. Water influences these processes by modifying the distribution of air in the soil, and thus the diffusion of O$_2$ and CO$_2$ concentration (Santiago *et al.*, 2008; Marschner, 2002).

The fact that the redox potential is a cause of variability may help explain the general decline in performance in all culture sites. This compares with results reported by Rodriguez *et al.* (2008) under similar soil conditions, indicating that excess moisture during the growing cycle of corn reduced corn yield in some parts of the production lot.

The slowdown in growth is a typical symptom of species not adapted to water logging. In corn, limited aeration in the root in certain stages of development can cause a low concentration of N, K and P in the area of stem elongation and reduced elongation (Marschner, 2002).

Component III of the nutrient content before planting and 60 das were explained by the variability of CE and Na content and the soil salinity caused by the exchangeable sodium is in accordance with the emergent property of component III. This indicator showed somewhat different patterns in the two assessment periods but were correlated statistically (0.364 * p<0.05), these differences are probably due to higher rainfall before the first sampling , and this led to a higher water table compared to the one at 60 das. The highest values in the contour maps correspond to areas with higher salinity levels (Figs. 6 and 7).

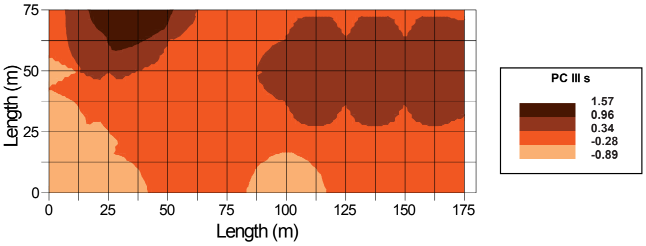

FIGURE 6. Spatial distribution (coordinates in m) of component III associated with the salinity of the soil before cron crop establishment on the Bogota Plateau.

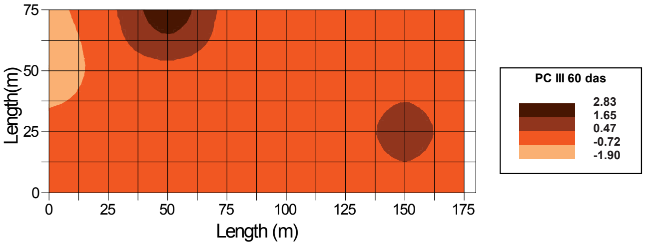

FIGURE 7. Spatial distribution (coordinates in m) of component III associated with soil salinity at 60 das corn crop on the Bogota Plateau.

The importance of identifying this pattern is that the salinity within a lot may limit water uptake by the plant by increasing the osmotic potential of the soil and cause nutritional imbalances causing reduced growth and development of plants (Carranza *et al.*, 2009; Corwin and Lesch, 2005). On the other hand, it is important to determine the pattern of variability in the soils of the Bogota Plateau because the rise of salts is a limiting factor in agricultural production, which is caused by poor natural drainage and high groundwater levels.

Conclusions

The crop yield presented spatial variability within the field, which was explained jointly by the spatial distribution of the soil content of nitrogen, calcium, potassium, magnesium and boron nutrients that are indicators of soil fertility and are important to development, growth and productivity of maize.

The use of principal component analysis (PCA) allowed grouping of the chemical variables and observance of three emergent properties of the soil: fertility, redox potential and salinity, making it possible to understand the complexity of the interactions between the elements in the ground.

Emergent properties related to the redox potential and soil salinity was not correlated with the spatial variability of the maize yield, but are credited with contribution to the reduction in general performance throughout the batch culture. Emergent properties of the soil: fertility, salinity, and redox potential presented spatial correlation structure shown in geostatistical analysis, but each property has a different spatial distribution pattern, therefore the management strategies for specific sites must be different, and that the cause of the variability of each pattern may be due to different circumstances.

The combined use of multivariate techniques and geostatistical analysis makes it possible to take information from many agricultural systems, reduce complexity, relatively easily visualization and make practical decisions to improve the technical criteria for maize fertilization through management by location.

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