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3 EDITORIAL

FITOMEJORAMIENTO, RECURSOS GENÉTICOS Y BIOLOGÍA MOLECULAR / PLANT BREEDING, GENETIC RESOURCES & MOLECULAR BIOLOGY

7 Preliminary assessment of AFLP fingerprinting of *Rubus glaucus* Benth. elite genotypes
Evaluación preliminar de la huella genómica de genotipos élite de *Rubus glaucus* Benth. con marcadores AFLP
Diana Duarte, María Isabel Chacón, Víctor Núñez, and Luz Stella Barrero

17 Evaluation of an Andean common bean reference collection under drought stress
Evaluación de una colección de referencia de fríjol andino bajo condiciones de sequía
Juan Carlos Pérez-Vega Matthew W. Blair, Fredy Monserrate, and Gustavo Ligarreto

27 Gene silencing and applications for functional gene validation: The case of Geminiviruses
Silenciamiento génico y aplicaciones para la validación funcional de genes: el caso de los Geminivirus
Simón Pedro Cortés and Camilo Ernesto López

FISIOLOGÍA DE CULTIVOS / CROP PHYSIOLOGY

35 Effects of leaf removal and cluster thinning on yield and quality of grapes (*Vitis vinifera* L., Riesling × Silvaner) in Corrales, Boyaca (Colombia)
Efecto del deshoje y del raleo de racimos sobre el rendimiento y la calidad de las bayas de vid (*Vitis vinifera* L., Riesling × Silvaner) en Corrales, Boyacá (Colombia)
Pedro José Almanza-Merchán, Gerhard Fischer, Pablo Antonio Serrano-Cely, Helber Enrique Balaguera-López, and Jesús Antonio Galvis

43 Evaluation of seed yield and oil contents in four materials of *Ricinus communis* L.
Evaluación del rendimiento de semilla y contenido de aceite en cuatro materiales de *Ricinus communis* L.
Roberto Antonio Cabrales Rodríguez, José Luis Marrugo Negrete, and Guido Armando Plaza Trujillo

49 Nickel: The last of the essential micronutrients
Níquel: el último de los micronutrientes esenciales
Miguel Ángel López and Stanislav Magnitskiy

PROTECCION DE CULTIVOS / CROP PROTECTION

57 Histopathological and morphological alterations caused by *Plasmodiophora brassicae* in *brassica oleracea* L.
Alteraciones histopatológicas y morfológicas causadas por *Plasmodiophora brassicae* en *Brassica oleracea* L.
Donald Riascos, Emiro Ortiz, Daimy Quintero, Lina Montoya, and Lilliana Hoyos-Carvajal

FISIOLOGÍA Y TECNOLOGÍA POSCOSECHA / PHYSIOLOGY & POST-HARVEST TECHNOLOGY

63 Activity of pectic enzymes involved in the ripening process of lulo (*Solanum quitoense* Lam.)
Actividad de enzimas pécticas involucradas en la maduración del lulo (*Solanum quitoense* Lam.)
Jeimmy Marcela Rodríguez Nieto and Luz Patricia Restrepo Sánchez

73 Assessment of the processing profile of six "creole potato" genotypes (*Solanum tuberosum* Phureja Group)
Evaluación de la aptitud de procesamiento en seis genotipos de papa criolla (*Solanum tuberosum* Grupo Phureja)
Jesús Elías Rivera, Anibal Orlando Herrera, and Luis Ernesto Rodríguez

83 Spatial variability of hydrodynamic parameters in the native savanna of the Colombian Eastern plains
Variabilidad espacial de parámetros hidrodinámicos en sabanas nativas de los Llanos Orientales colombianos
Helber M. Orjuela-Matta, Yolanda Rubiano-Sanabria, and Jesús H. Camacho-Tamayo

91 Effect of nitrogen over corn-grass association in the renovation of pastures at piedmont of the Eastern Plains of Colombia
Efecto del nitrógeno sobre la asociación maíz–pastos en la renovación de praderas del piedemonte de los Llanos Orientales colombianos
Álvaro Rincón Castillo and Gustavo Adolfo Ligarreto Moreno

99 Evaluation of corn production parameters and their spatial relationship with chemical attributes of the soil
Evaluación de parámetros productivos de maíz y su relación espacial con atributos químicos del suelo
Alba Leonor da S. Martins, Emanoel G. de Moura, and Jesús H. Camacho

107 Evaluation of models for estimating the reference evapotranspiration in Colombian Coffee Zone
Evaluación de modelos para calcular la evapotranspiración de referencia en la zona cafetera de Colombia
Víctor Hugo Ramírez, Alexandra Mejía, Elsa Viviana Marín, and Rafael Arango

ECONOMÍA Y DESARROLLO RURAL / ECONOMY & RURAL DEVELOPMENT

115 Potentiality of symbolic capital in the rural space as generator of territorial development
Potencialidad del capital simbólico en el espacio rural como generador de desarrollo territorial
Alma Lorena del Cid

125 Agribusiness model approach to territorial food development
Modelo agroempresarial con enfoque territorial para el desarrollo alimentario
Héctor Horacio Murcia

133 Agrofuels policy in Colombia: expectations and rural development
La política de agrocombustibles en Colombia y sus expectativas en el desarrollo rural
Sandra Liliana Mejía Alfonso

141 Speeches and practices of the rural development: A reading from Caldas department, Colombia
Discursos y prácticas de desarrollo rural: una lectura desde el departamento de Caldas, Colombia
Nelly del Carmen Suárez-Restrepo and Carlos Eduardo Ospina-Parra

147 Paradigm-region and vocation-region in Nariño department, Colombia
Paradigma-región y vocación-región en Nariño, Colombia
Ilich Ruiz-Reynel

ANEXOS / APPENDIX

153 Requisitos para publicar en la revista *Agronomía Colombiana*
Requirements for publishing in *Agronomía Colombiana journal*

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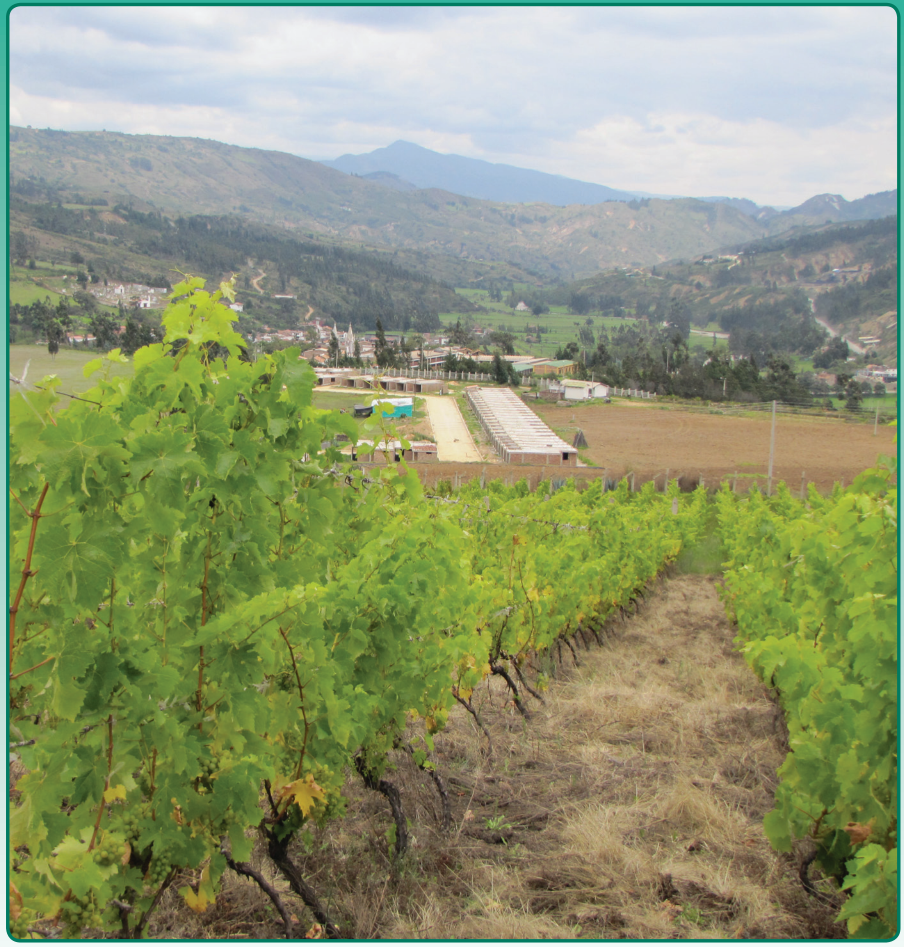

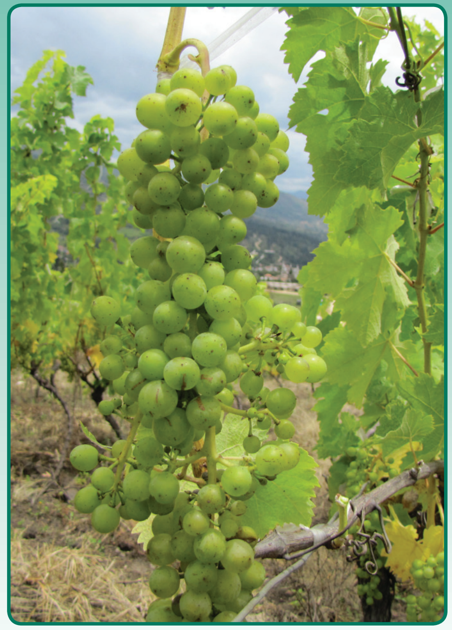

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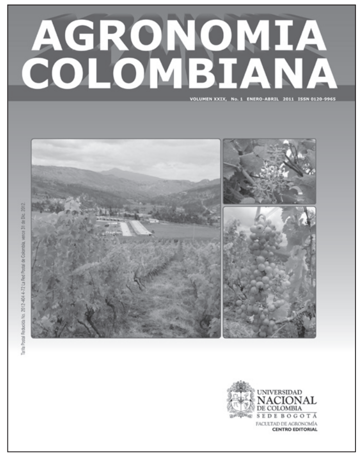

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Evaluation of corn production parameters and their spatial relationship with chemical attributes of the soil

Evaluación de parámetros productivos de maíz y su relación espacial con atributos químicos del suelo

Alba Leonor da S. Martins[1], Emanoel G. de Moura[2], and Jesús H. Camacho-Tamayo[3]

ABSTRACT

The characterization of the soil spatial variability allows a better understanding of the relationships between the soil attributes and the environment. The objective of the study was to evaluate the spatial variability of corn production parameters and their relationship with soil chemical attributes. The study was carried out in the municipality of Miranda do Norte (MA, Brazil) in a Typic Plinthaquults. A mesh of 113 points was designed, taking samples at regular distances of 10 m, determining pH, organic material, P, K, Ca, Mg, and exchangeable acidity. The corn production parameters were ear weight, weight of 100 grains, and yield. The results were analyzed by means of descriptive statistics and geostatistical techniques. The pH and the weight of 100 grains were the only attributes with low variability. The sum of the bases did not show spatial dependence. The corn yield and the ear weight showed similar high correlation and spatial dependence. The production parameters showed a significant influence of the soil chemical attributes, principally those that define the acidity and the cations presence. The contour maps allowed the identification of the soil spatial attributes and their relationship to corn yield.

Key words: precision agriculture, spatial structure, *Zea mays* L., semivariogram, kriging.

RESUMEN

La caracterización de la variabilidad espacial del suelo permite una mejor comprensión de las relaciones entre las características del suelo y el ambiente. El objetivo del trabajo fue evaluar la variabilidad espacial de parámetros productivos del maíz y su relación con atributos químicos del suelo. El estudio se realizó en el municipio de Miranda do Norte (MA-Brasil) en un Typic Plinthaquults. Se diseñó una malla de 113 puntos, tomando muestras cada 10 m y determinando pH, materia orgánica, P, K, Ca, Mg y Ac.I. Los parámetros productivos del maíz fueron peso de la espiga, peso de 100 granos y productividad. Los resultados fueron analizados mediante estadística descriptiva y técnicas de geoestadística. El pH y el peso de 100 granos fueron los únicos atributos con baja variabilidad. La suma de bases no presentó dependencia espacial. La producción de maíz y el peso de la espiga presentaron alta correlación y dependencia espacial similares. Los parámetros productivos presentaron influencia significativa de los atributos químicos del suelo, principalmente aquellos que definen la acidez y la presencia de cationes. Los mapas de contorno permitieron verificar la distribución espacial de los atributos del suelo y su relación con la productividad de maíz.

Palabras clave: agricultura de precisión, estructura espacial, *Zea mays* L., semivariograma, kriging.

Introduction

Farmers have observed variations in the soil across the centuries that are attributes of the management of their crops; nevertheless, their areas under cultivation are managed as if they were uniform. During the last few decades, with the realization that these areas are not uniform, these variations in the soil are taken into consideration, changing the management for each one of them and adopting modern technologies to increase the crops productivity and optimize the use of fertilizers and other external inputs. These changes have led to a search for new alternative technologies and new concepts for the management of the productive process, due to large amounts of information, which vary in space and time.

The soil variability occurs due to factors that act at different spatial and temporal scales, produced by natural, complex pedagogical processes (relief and moisture regimes) or induced by human actions (Molin *et al*., 2008), as happens in the crops production, which modify the variability of thea soil (Burgos *et al*., 2006), especially in tasks such as tilling and fertilization, principally on the surface (Camacho-Tamayo *et al*., 2008).

The characterization of the spatial variability of the soil allows a better understanding of the complex relationships

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between the soil attributes and the environment (Goovaerts, 1998), helping decision-making for the adequate soil use and crops production (Bouma *et al*., 1999). Interest in information relevant to the soil spatial attributes has increased, resulting in the development of models and management systems (Godwin and Miller, 2003). However, site specific management of the soil by can be unviable if the cost of the required analyses is high (Bongiovanni and Lowenberg-Deboer, 2000). Determining the variability of the soil attributes by means of appropriate sampling and processing of the results using tools such as geostatistics can establish optimum distances and the dependence between two or more variables can lead to a reduction of the sampling costs. Geostatistics is a tool that is adequate for understanding the variation of the soil attributes, and can be used at different scales on the basis of precise initial data, depending on the desired resolution of the study (Webster, 2008).

Šamonil *et al.* (2010) affirm that there exists a heterogeneity of the attributes in different types of soils, and that the spatial dependence is influenced by the relief, which leads to establishing areas of management differentiated on the basis of each attribute analyzed, and also indicates the necessity of carrying out studies of the different classes of soil.

This study had the aim of evaluating the spatial variability of some corn production parameters and their relationship with the chemical attributes, in a Typic Plinthaquults, by means of statistical and geostatistical techniques.

Materials and methods

Area of study

The study was carried out in the municipality of Miranda do Norte (MA, Brazil), in 1 ha cultivated with corn (*Zea mays* L.) under an agroforestry system, a zone where family agriculture predominates, located at 3° 36' 47" south latitude, 44° 34' 30" west longitude and 53 m.a.s.l. The soil is a Typic Plinthaquults, with medium texture and flat relief. According to Köppen classification, the region is Aw'- tropical humid climate, with an average temperature of 27°C and precipitation between 1600 and 2000 mm annually, concentrated in the months of December and June, a dry climate predominating in other months.

Sampling and laboratory analysis

For the sampling, a mesh of 113 points was designed, regularly distanced each 10 m. At each point, soil samples were taken at a depth of 0 - 0.20 mm, which were air dried until they reached an equilibrium point and later were passed through a sieve of 2 mm, for the performance of the analysis, obtaining pH ($CaCl_2$ 0.01M), available P content (resin), organic matter (OM), K, Ca, Mg and exchangeable acidity Ac.E, according to the methodology proposed by Raij *et al.* (2001). On the basis of these results the cation exchange capacity (CEC) was calculated, the sum of the bases (SB) and base saturation (V%) of the soil. Corn productivity was evaluated by collecting ears in an area of 8 m^2 at intervals of 10 x 10 m, in order to estimate the average ear weight (Ew), crop yield (Cy) and weight of 100 grains (Gw).

Processing and data analysis

Initially an exploratory study of data was carried out, calculating average, median, minimum and maximum, coefficient of variation (CV), skewness and kurtosis. Additionally the Kolmogorov-Smirnov test was carried out in order to evaluate the normality. All of the statistical analyses were processed using the software SPSS™ 17.0. For the analysis of the CV, the Warrick and Nielsen classification (1980) was considered, with low variability for values lower than 12%, medium between 12 and 60%, and high for values greater than 60%.

For the fit of the experimental data to the theoretical semivariogram models, the regionalized variable theory was considered, which uses different methods of analysis of spatial variation, one of them being the semivariogram (Webster and Oliver, 2007). On the basis of the fit to these models, the nugget (C_0), sill (Co+C) and range (A) were determined, besides the Degree of Spatial Dependence (DSD) as the ratio between the nugget and the sill (C/Co+C), being considered strong for DSD above 0.75, moderate for DSD between 0.25 and 0.75 and weak for DSD below 0.25 (Cambardella *et al*., 1994). The semivariograms were calculated using the program GS+. For the selection of the theoretical semivariogram models, the least sum of squared residuals (SSR), the coefficient of determination (R^2) of the equation of fit and similar values obtained between the real and the estimated value were considered, which are obtained in the crossed validation, appropriate indicators for such purpose (Faraco *et al*., 2008; Johann *et al*., 2010).

On the basis of the semivariogram models of the attributes that expressed spatial dependence, interpolation by ordinary kriging was carried out, which is considered the best unbiased linear estimator and that of least variance (Diggle and Ribeiro, 2000), for making a prediction at non-sampled sites, the results being shown by means of contour maps. This procedure was performed using the program Surfer v.9 (Golden Software Inc., 2008).

Results and discussion

Statistical analysis

According to the Kolmogorov-Smirnov test, not all the attributes approach normal distribution (Tab. 1), in that the P, pH, cation exchange capacity (CEC) and base saturation (V) showed great differences between the mean and the median and high values of skewness in relation to the other attributes analyzed. A similar situation was observed for the production values of the ear weight (Ew) and crop yield (Cy). According to Cressie (1993), more than normality it is convenient to verify that the distribution does not show long tails, in order not to compromise the results, especially when kriging is carried out, where the estimations are based on mean values (Warrick and Nielsen, 1980). Another important fact is the occurrence of the proportional effect between the mean and the data variance, along a surface, which permits estimating defined sills in the theoretical semivariogram models.

For the other attributes and Gw, the values found for the mean and the median are similar, indicating symmetric distributions, which are verified by the values close to zero for skewness and kurtosis, approaching normal distribution, which is confirmed by the normality test.

Crop yield and Ew showed medium variability. In the case of these parameters, it is convenient to consider that their behavior depends not only on the edaphic conditions and that their variability can be affected by environmental conditions (i.e. wind and relative humidity) which influence the process of pollination (Ortega and Santibañez, 2007).

According to the coefficient of variation (CV), the pH and Gw showed low variability. This characteristic of low variability of the pH is reported by several authors in different soil classes (Camacho-Tamayo *et al.*, 2008; Cruz *et al.*, 2011). The other attributes showed medium variability, highlighting the fact that the P and the K were the attributes with the greatest variability (CV of 45.90% and 38.80% respectively), explained by the incorporation of these elements in agricultural production (Camacho-Tamayo *et al.*, 2008).

Geostatistical analysis

The sum of the bases was the only attribute that did not show a fit to the theoretical semivariogram models, indicating that their behavior in the soil is random, showing a seed effect (Tab. 2). The attributes fit different models, with a predominance of spherical and exponential models.

Because of the values obtained for the coefficient of determination (R^2) and the crossed validation coefficient (CVC), it can be seen that the fit to the models was adequate, with values close to one in the majority of the attributes analyzed, as is also reported by Silva *et al.* (2003), in that Ca and Mg exhibited the lowest values of R^2, possibly influenced by the anthropic management, occasioned by the surface distribution of amendments, a practice that is carried out in this zone with frequency in corn cultivation, which modifies the natural distribution of the attributes (Camacho-Tamayo *et al.*, 2008).

The greatest ranges were observed for pH, Ac.E, CEC and V, attributes that are strongly correlated. Of the production

TABLE 1. Descriptive statistics of organic matter (OM), pH, P, K, Ca, Mg, exchangeable acidity (Ac.E), sum of bases (SB), cation exchange capacity (CEC), base saturation (V), weight of 100 grains (Gw), ear weight (Ew) and crop yield (Cy).

Attribute	Mean	Median	CV, %	Minimum	Maximum	Skewness	Kurtosis	K-S
OM, g kg^{-1}	38,188	38,00	18,76	25,00	58,00	0,56	0,00	ns
pH	47,541	46,00	8,60	42,00	59,00	0,85	-0.06	*
P, mg dm^{-3}	16,505	14,00	45,90	5,200	39,00	0,8	0.01	*
K , $mmol_c$ dm^{-3}	19,32	20,00	38,80	0,2	38,00	-0,20	0.07	ns
Ca, $mmol_c$ dm^{-3}	20,503	20,45	30,40	8,00	33,60	0,11	-0.69	ns
Mg, $mmol_c$ dm^{-3}	21,924	21,70	17,65	12,20	32,00	0,23	0.19	ns
Ac.E, $mmol_c$ dm^{-3}	33,98	34,00	31,29	13,00	58,00	0,21	-0.39	ns
SB, $mmol_c$ dm^{-3}	44,83	44,50	18,50	26,40	66,00	0,06	-0.65	ns
CEC, $mmol_c$ dm^{-3}	79,67	77,6	15,14	58,1	111,8	0,66	-0.16	*
V, %	57,186	56,00	17,98	36,60	81,30	0,38	-0.59	*
Gw, g	25,79	25,80	5,96	21,90	29,40	-0,08	-0.27	ns
Ew, g	87,23	78,3	37,13	40,00	154,4	0,63	-0.65	*
Cy, Kg ha^{-1}	3,01	2,70	39,5	1,10	5,40	0,56	-0.63	*

CV: coefficient of variation; K-S: Kolmogorov-Smirnov test ($p \leq 0.05$), *: significant.

parameters, Ew and Cy showed similar ranges, and a strong correlation can be seen between them, indicating that the greater the ear weight the greater the productivity.

No attribute or production parameter showed weak DSD. The variables that fit to spherical models showed moderate DSD. The attributes pH, Ca and Ac.E, as well as Cy, showed strong DSD. A moderate DSD of pH, P, K and Mg is also reported for Oxisols (Camacho-Tamayo *et al*., 2008), indicating that it is a common characteristic in soils undergoing crop production.

Lineal correlation and kriging

The correlation analysis revealed that of the greatest coefficients found among the attributes (Tab. 3), those that explain the linear relationship of the soil acidity (pH and Ac.I) to the contents of Ca and Mg stand out, and as a consequence the sum of bases, cation exchange capacity (CEC) and base saturation (V). This behavior is confirmed in the contour maps, where areas of high values of pH (Fig. 1D) showed the greatest values of V (Fig. 1E) and the least values of Ac.E. The OM also showed a significant correlation with V, which is reasonably verified in the contour maps (Figs. 1E and 1F).

According to Canellas *et al*. (2000), the OM directly influences the behavior of V and CEC. Another important fact is the strong influence of the Ac.E on CEC, attributes that showed high positive correlation and that can be seen in the maps (Figs. 2E and 2F) and in the semivariograms obtained for these attributes, which fit the same model (Tab. 2), with similar range. This behavior is also reported by Salviano *et al*. (1998) and is explained by the greater presence of this cation in the soil, with respect to the others used in the calculation of the CEC (Tab. 1).

For the production parameters, it can be seen that only Gw showed a significant correlation with the content of K, indicating that K directly influences Gw. This significant correlation is reflected in the contour maps, where areas with greater grain weight correspond to areas of greater K content (Figs. 1A and 2B), being divergent at the bottom right of the maps.

Corn productivity is strongly affected by Ew, as is proven in the significant correlation and the resemblance of the contour maps between these parameters (Figs. 1B and 1C). The influence of the OM on the formation of the ears and corn yield is also verified, parameters that showed a positive correlation. The attributes related to the soil acidity also influenced Cy and the ears formation.

The low relationship between production and the P and K contents is also reported by other authors (Santos *et al*., 2001), but does not correspond to the majority of the studies of fertility, which show a direct relationship between these attributes and grain production. A possible explanation for these results is the high rate of fertilization with nutrients applied homogeneously by the farmers of the zone, which can hide the effects of the inherent fertility of the soil. Another explanation could be that the level of fertility of the soil at the time of the study was not a limiting factor for yield, and that possibly there are other determining attributes of the soil for crop production, such as the physical attributes or the presence of microorganisms (Ortega and Santibáñez, 2007).

TABLE 2. Parameters of the variogram models obtained of organic matter (OM), pH, P, K, Ca, Mg, exchangeable acidity (Ac.E), sum of bases (SB), cation exchange capacity (CEC), base saturation (V), weight of 100 grains (Gw), ear weight (Ew) and crop yield (Cy).

Atributte	Model	Co	Co+C	Range, m	C/Co+C	R^2	CVC
OM	Exponential	17,03	38,35	76,80	0,56	0,90	0,90
pH	Exponential	0,06	0,29	103,20	0,78	0,97	0,95
P	Spherical	23,14	46,29	92,20	0,50	0,91	0,94
K	Spherical	0,16	0,38	39,00	0,59	0,83	1,01
Ca	Exponential	3,20	29,77	21,60	0,89	0,69	0,97
Mg	Exponential	5,16	12,59	60,30	0,59	0,78	0,92
Ac.E	Gaussian	21,00	100,34	99,94	0,79	0,99	1,01
SB	NE	51,05	51,05	-	-	-	-
CEC	Gaussian	51,40	114,30	107,04	0,55	0,81	0,83
V	Gaussian	46,80	130,10	98,73	0,64	0,99	1,00
Gw	Spherical	0,80	1,86	45,80	0,57	0,94	0,93
Ew	Spherical	0,05	0,12	106,20	0,62	0,93	1,09
Cy	Exponential	0,66	1,46	107,70	0,85	0,84	1,00

NE: nugget effect; R^2: coefficient of determination; CVC: cross validation coefficient.

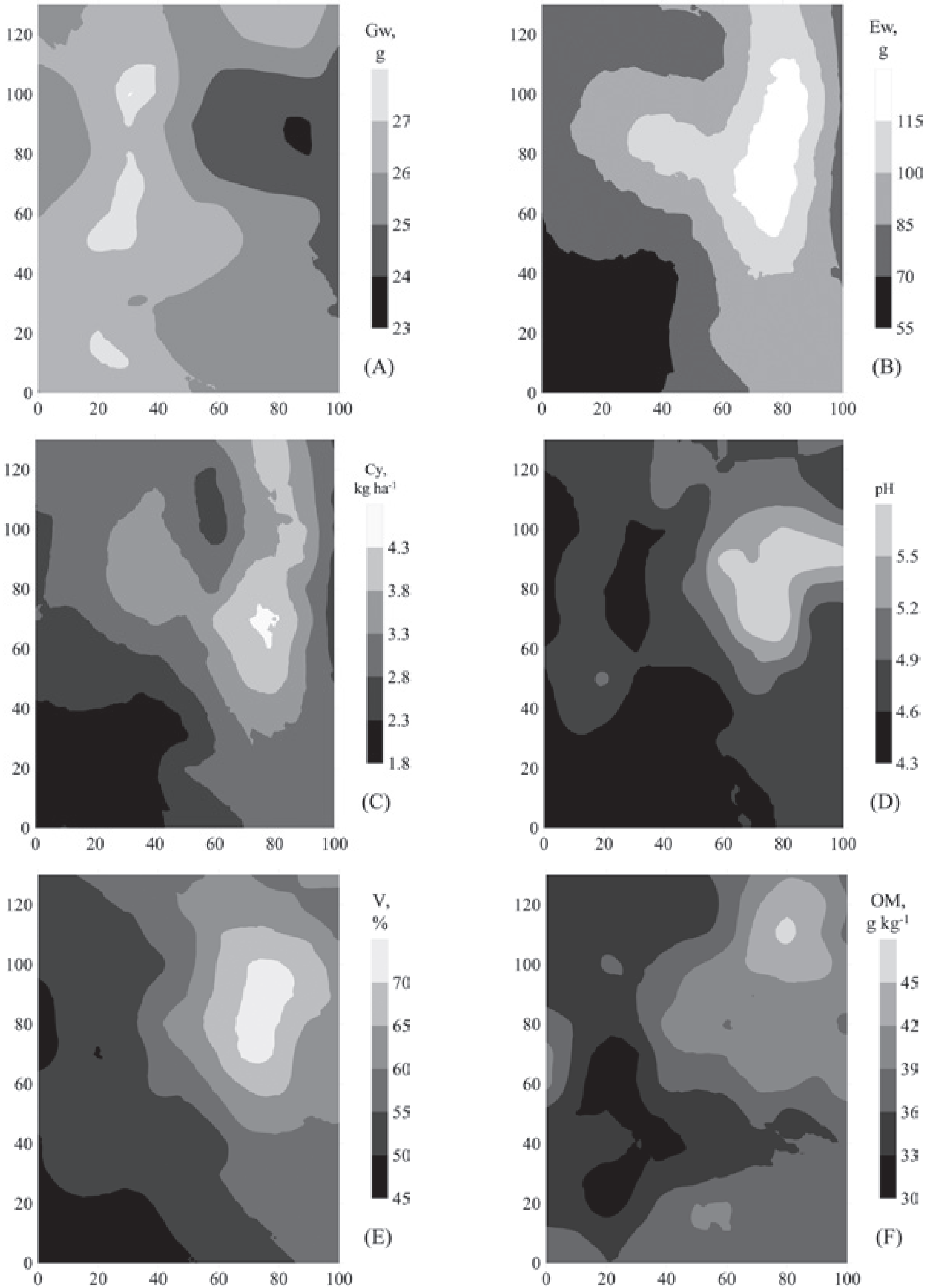

FIGURE 1. Contour maps obtained by kriging of weight of 100 grains (**Gw**) (A), ear weight (**Ew**) (B), crop yield (**Cy**) (C), **pH** (D), base saturation (**V**) (E) and organic matter (**OM**)(F).

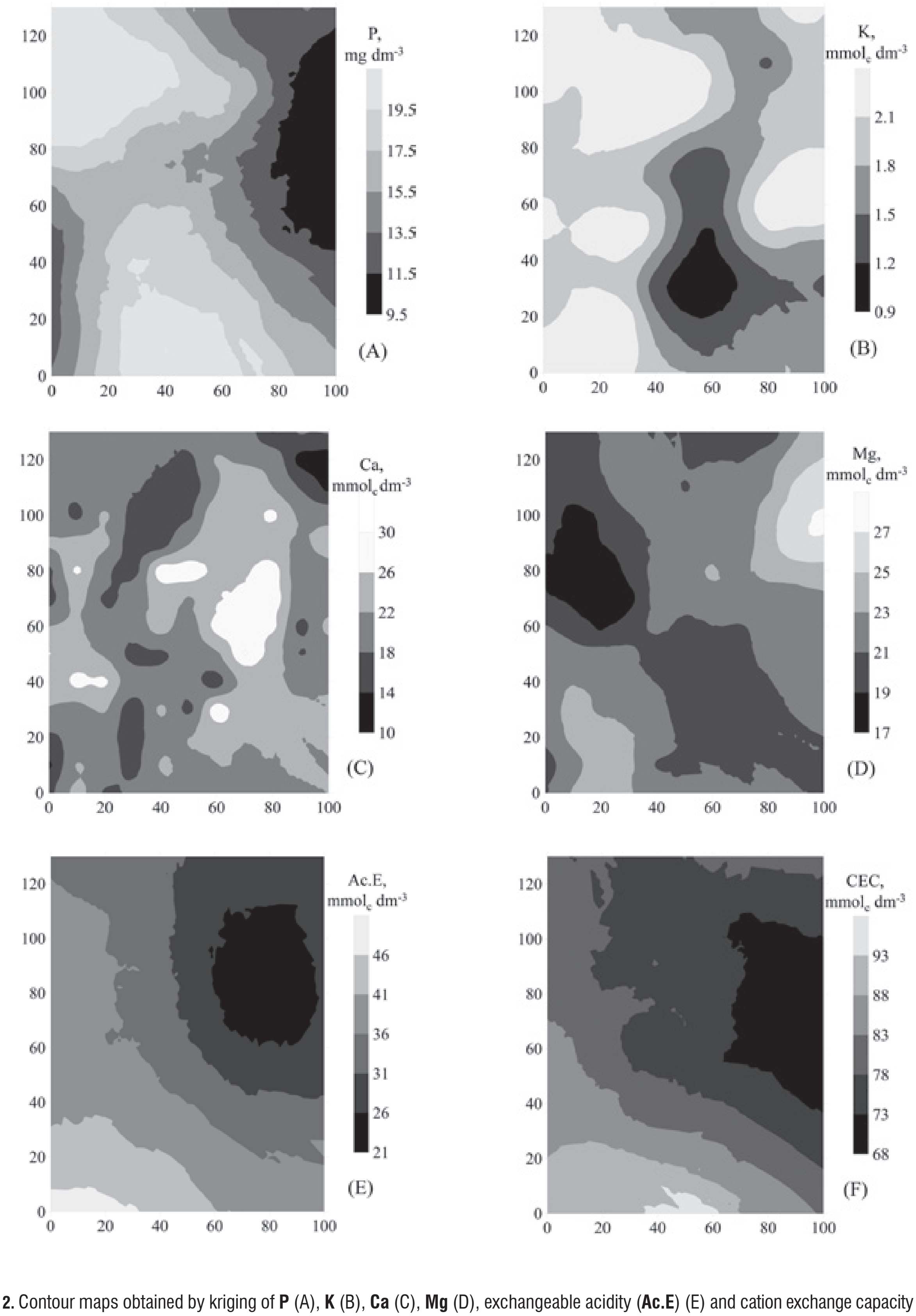

FIGURE 2. Contour maps obtained by kriging of **P** (A), **K** (B), **Ca** (C), **Mg** (D), exchangeable acidity (**Ac.E**) (E) and cation exchange capacity (**CEC**) (F).

TABLE 3. Linear correlation of organic matter (OM), pH, P, K, Ca, Mg, exchangeable acidity (Ac.E), sum of bases (SB), cation exchange capacity (CEC), base saturation (V), weight of 100 grains (Gw), ear weight (Ew) and crop yield (Cy).

Attribute	MO	pH	P	K	Ca	Mg	Ac.E	SB	CEC	V	Gw	Ew
pH	0,37**	1,00										
P	-0,12	-0,21*	1,00									
K	-0,02	-0,23*	0,20*	1,00								
Ca	0,32**	0,64**	-0,07	-0,29**	1,00							
Mg	0,37**	0,35**	-0,04	0,04	0,15	1,00						
Ac.E	-0,18	-0,77**	0,29**	0,26**	-0,34**	-0,11	1,00					
SB	0,45**	0,66**	-0,05	-0,08	0,83**	0,67**	-0,30**	1,00				
CEC	0,27**	-0,15	0,26**	0,19*	0,29**	0,41**	0,66**	0,47**	1,00			
V	0,34**	0,92**	-0,25**	-0,24*	0,64**	0,41**	-0,88**	0,70**	-0,26**	1,00		
Gw	-0,04	-0,12	0,05	0,19*	-0,12	-0,18	0,05	-0,17	-0,06	-0,14	1,00	
Ew	0,33**	0,44**	-0,12	-0,02	0,24**	-0,00	-0,40**	0,19*	-0,19*	0,39**	0,06	1,00
Cy	0,34**	0,43**	-0,10	-0,00	0,25**	-0,02	-0,39**	0,18	-0,18	0,38**	0,10	0,97**

* $p \leq 0.05$. ** $p \leq 0.01$.

Conclusions

The attributes showed low or medium variability, the cation exchange capacity (CEC) being the only attribute that did not show spatial dependence. The other attributes showed spatial dependence, fitting semivariogram models, with a strong or moderate degree of dependence.

The production parameters showed defined variability and spatial dependence. Corn productivity and ear weight are highly correlated attributes, with a similar behavior relative to variability and spatial dependence.

The use of different statistical tools helped to identify the spatial variability of the soil, as well as an understanding and establishment of the various relationships between the attributes that characterize the soil, techniques that can support decision making, for a better administration and control of agricultural production.

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