Variabilidad espacial y diaria del contenido de humedad en el suelo en tres sistemas agroforestales

Spatial and diurnal variability of soil humidity in three agroforestry systems

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RESUMEN

En seis puntos de tres transectos (102 m) paralelos (9 m) en tres sistemas de uso del terreno (Quesungual menor de dos años, SAQ<2, Tradicional de Tala y Quema, TQ y Bosque Secundario, BS) se tomaron muestras de suelo a cuatro profundidades (0-5 cm, 5-10 cm, 10-20 cm y 20 a 40 cm) y tres horas (08, 11 y 15) durante 9 días. Se modeló el análisis estructural de la variación de los parámetros humedad volumétrica, densidad aparente, carbono orgánico, arena y arcilla. El coeficiente de variación de los parámetros evaluados presentó rangos para densidad aparente (0.76 y 15.1%), carbono orgánico (30.4 y 54.3%), humedad volumétrica (9.5 y 23.5%), arena (12.8 y 22.5%) y arcilla (14.0 y 29.2%). En los análisis geoestadísticos el componente al azar de la dependencia espacial predominó sobre el efecto pepita (nugget). Con las funciones de los semivariogramas estructurados para cada variable se generaron mapas de contorno interpolados a escala fina los cuales mostraron heterogeneidad en las propiedades evaluadas. La autocorrelación de Morán (I) indicó que rangos de muestreo menores a 9 m podrían ser adecuados para detectar la estructura espacial de la variable humedad volumétrica.

Palabras clave: Variabilidad espacial; humedad de suelo; densidad aparente; carbono orgánico.

ABSTRACT

The objective of this study was to determine the level of soil spatial variability in areas under the following land use systems: Quesungual slash and mulch agroforestry system under two years old (QAS<2), the traditional Slash-and-burn system (SB) and Secondary forest (SF). Soil samples were taken in three parallel transects of 102 m in length, separated by 9 meters. The profile was sampled at the depths of 0 to 5 cm, 5 to 10 cm, 10 to 20 cm, and 20 to 40 cm, at three times during the day (09, 11 am and 05) for 9 days. Coefficient of variation for soil properties varied for bulk density (0.76 and 15.1%), organic carbon (30.4 and 54.3%), volumetric humidity (9.5 and 23.5%), sand (12.8 and 22.5%) and clay (14.0 and 29.2%). The geo-statistical analysis showed that the random component of the spatial dependence was predominant over the nugget effect. The functions of semivariograms, structured for each variable were used to generate maps of interpolated contours at a fine scale. The Moran (I) autocorrelation indicated that sampling ranges of less than 9 m would be adequate to detect spatial structure of the volumetric moisture variable.

Keywords: Spatial variability; soil humidity; bulk density; organic carbon.

INTRODUCTION

The spatial variability of soil properties is attributed mainly to the interaction of geological and pedological factors, however, it is also affected by the erosion and depository processes generated by land use systems (Iqbal *et al*., 2005).

The soils in Honduras are considered the oldest in Central America. They are vulnerable to erosion, of low fertility (with deficiencies in P, S and B), with severe leaching, and in some areas, very acidic. However, the good porosity on very steep hillsides allows cultivation. These soils occur over extensive areas of old lava flows that form a relatively impermeable layer, termed Talpetate in Nahua, and hardpan in English (Williams, 1994). The depth of this layer varies from very close to the surface to up to 2 m depth, and can limit root growth, and the capacity for vegetation to survive drought periods (Barrance *et al*., 2003).

The Quesungual agroforestry system (QAS<2), which is practiced in the southeast of Honduras as an alternative to the slash and burn agricultural system, is based on the maintenance of soil cover using crop residues and the pruning of trees and bushes (Welchez *et al.,* 2006). The objective of this study was to compare using geostatistical analyses the spatial and diurnal variability of the volumetric humidity of the soil in the Quesungual agroforestry system (QAS<2), the traditional system of slash and burn (SB), and secondary forest (SF), to determine the spatial variability of the soil properties: bulk density, organic carbon, sand and clay content in the different systems.

MATERIALS AND METHODS

The study was carried out at 2448 m^2 in the Community of Camapara, municipality of Candelaria, Department of Lempira, Honduras (14º04’60” N, 88º34’00” W, 17 - 25^{o}C, annual precipitation 1400 mm), in the sub-watershed of the river Lempa, sub-humid tropics. In the zone, 80% of the agriculture is subsistence, and is concentrated on farms smaller than 5 ha. The soils are classified as Entisols (Lithic Ustorthents), are acidic, stony and with a low P content, and low content of organic material.
A QAS system of 2 years establishment (QAS<2: 512 masl, 64.7%) was selected for its environmental and social advantages; the traditional slash and burn (SB: 532 masl, 12.8%) because it is the most common system in use in the region in spite of its negative effects; and the secondary forest (SF: 540 masl, 23.5%) as a control system.
Three transects were laid along the line of the slope (N-S), each separated by 9 meters. In each transect six sampling points were marked every 18 meters. The samples were taken at the beginning of the rainy period, over nine days (26th May to 3rd June 2006) at four depths a (0 - 5, 5 - 10, 10 - 20 and 20 - 40 cm). Around each fixed point, eight additional points were established with a separation of 3 m in the x coordinate and 6 m in the y coordinate, forming a rectangle of 6 x 12 m. Each day, sampling began at transect 1 at 09 hours, at transect 2 at 11, and at transect 3 at 15.00 hours. The first day, the fixed points were sampled (Figure 1).
Humidity was determined using the gravimetric method, texture by hydrometer (Gee and Bouder, 1986), and organic carbon by dry digestion (Rabenhorst, 1988). In undisturbed

samples (taken in metallic rings 5 cm high x 5 cm diameter) the bulk density was determined.

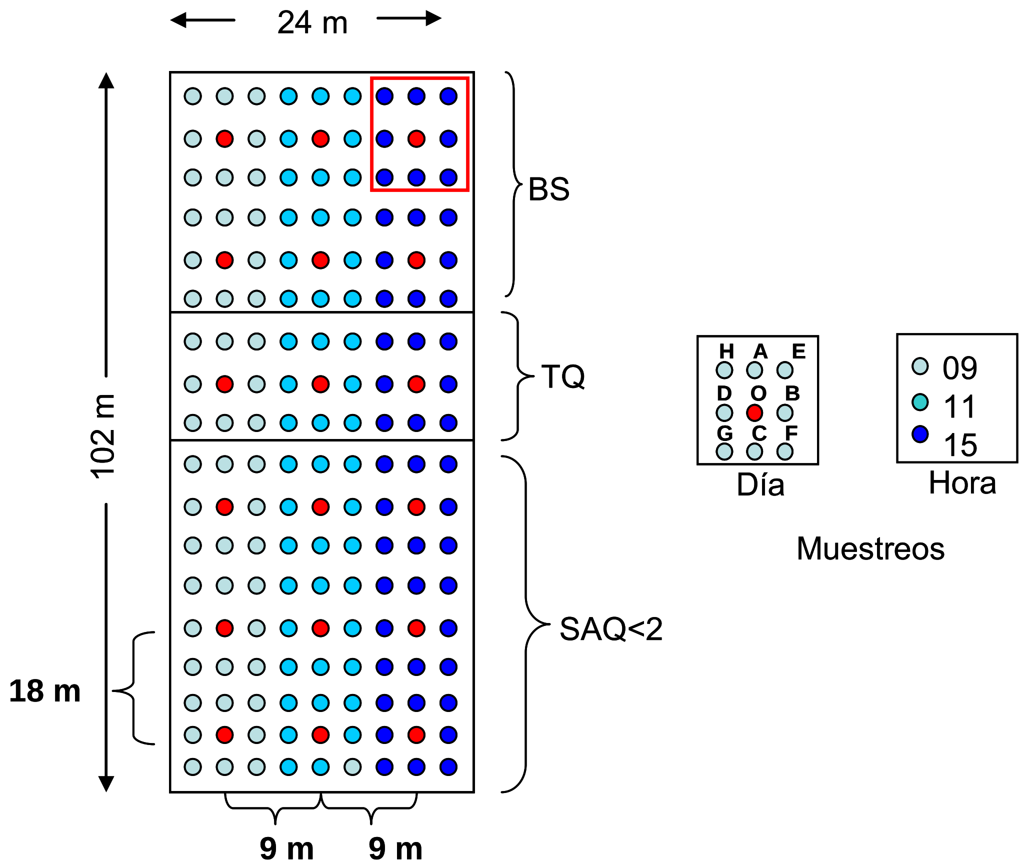

Figure 1. Sampling distribution in time and space along the transect in the land use systems of Flash and Burn (SB), Quesungual Agroforestry System (QAS<2), and secondary forest (SF), Camapara, Candelaria, Lempira, Honduras 2006

With descriptive statistical methods, the maximum, minimum, mean, median, standard deviation and asymmetry were determined (Shapiro and Wilk, 1965). Using an ANOVA (SAS Institute, 1996) each variable was compared along the transect, with the test of significant minimum difference (P<0.05). The variables with a high coefficient of variation were transformed using the squared root or natural logarithm.

The degree of spatial variability was determined using geostatistical methods, using an autocorrelation (Semivariogram, or kriging) method (Trangmar *et al*., 1985; Bailey y Gatrell, 1998). Before applying the geostatistical tests, the normality, trend and anisotropy of each variable were determined. The geographic tendency was estimated with the software GS-Plus (1995). When the variable presented a geographical tendency, a first order model (linear) was developed for the dependent variable z, and the geographic coordinates (independent variables).

As the exact form of the semivariogram is not known, the model selected is an approximation of the function (Journel y Huijbregts, 1978). However, to select the best model the trial and error Jackknife procedure was followed, which uses data from close points to obtain the best correspondence between the estimated and the actual value (Bailey y Gatrell, 1998).

The function of the semivariogram (Goovaerts, 1977) was estimated using the formula:

$$\gamma(h) = \frac{1}{2N(h)} \left\{ \sum_{i=1}^{N(h)} \left[z(Xi + h) - z(Xi) \right]^2 \right\}$$

in which:

γ = semivariance for the class interval (h)
N(h) = number of pairs separated by the distance between two sampled positions

z (Xi) = variable measure in the spatial position (i)
z (Xi + h) = variable measure in the spatial position (i+h)

The three basic parameters of the semivariogram describe the spatial structure as: γ (h) = Co + C; in which Co represents the nugget effect, or the local variation that occurs at a scale less than the sampling intervals, and Co + C is the threshold or total variance. The distance in which the levels of the semivariogram fall in the threshold is called the range.

Contour maps of each variable for each horizon were produced using the method of *kriging* (David 1977; Clark 1979).

For the spatial autocorrelation the statistic I (Moran 1950) was used, the range of which oscillates from + 1.0 (strongly positive), passing through zero (random behavior), to -1.0 (strongly negative) (Viera *et al.*, 1981).

Moran's I statistic is estimated using the formula:

$$I = \left[\frac{n}{\sum_{i=1}^{n} \sum_{j=1}^{n} Wij} \right] \left[\frac{\sum_{i=1}^{n} \sum_{j=1}^{n} Wij \left(Xi - \overline{X} \right) \left(Xj - \overline{X} \right)}{\sum_{i=1}^{n} \left(Xi - \overline{X} \right)^2} \right]$$

In which:
n = number of points
X = variable of interest
$\overline{X}$ = mean
Wij = spatial weight that describes the proximity or distance between the i-th and the j-th points.

The correlelograms for volumetric humidity, bulk density, organic carbon, sand and clay were calculated from the points of a grid of 8.3m.

The class of spatial dependency was considered strong when the spatial relationship (% *nugget* = *nugget* of the semivariance / total semivariance ×100) was <25%, moderate between 25 and 75% and weak >75% (Cambardella *et al*.,1994).

RESULTS AND DISCUSSION

For the evaluation of the diurnal variability in soil humidity, the data with the greatest differences were used (09 y 15 hours). Differences were observed in volumetric humidity content between land use systems, soil depth, and time of sampling. In SB only from 0 to 5 cm were the values at 09 significantly greater (23.0% vs 15.2%), as a consequence of greater evaporation due to lack of cover. As expected, in QAS<2 no significant differences were observed due to the cover maintaining humidity levels. From 5 to 10 cm, the difference signified a decrease of 8.1%. At 20 to 40 cm no significant differences were observed (Table 1).
In SF, the values at 0 to 5 cm were significantly greater at 09 hours, a difference corresponding to a reduction of 24.6%; from 5 to 10 cm, the values were significantly less at 09, a difference equivalent to an increase of 14.2%; from 10 to 20 cm the values were significantly less (22.0%) at 09 hours, a difference that signified an increase of 21.4%; from 20 to 40 cm no notable differences were seen in the humidity content (Table 1).
In the three systems, the diurnal reduction in the humidity content occurred on the surface (0 to 5 cm), corroborating the beneficial effects of the QAS<2, in which the cover, or mulch, contributes to the lesser variation in humidity. In the SB, the high surface evaporation was associated with the drastic loss of humidity. The loss of humidity in the SF, the equivalent of half of that which occurred in the SB, was attributed to the greater activity of the vegetation. While in QAS<2 the moisture content increased at 5 – 10 cm, the same as in the SF at 5 – 20 cm, in the SB it decreased across the whole profile.
The bulk density at the different depths varied between 1.02 and 1.41 g cm^{-3} in the three land use systems. The surface values were significantly less ($P<0.05$) than those at 5 to 40 cm (Table 2). The values were positively correlated with the volumetric humidity content at 0 to 5 cm of depth.

The content of organic carbon at the different depths varied between 0.62 and 1.72 % in the three use systems and significantly ($P<0.05$) between horizons. The greatest contents (SB: 1.69, QAS<2: 1.63 and SF: 1.72 %) were seen at 0 to 5 cm. In general, the organic carbon content correlated positively with the clay content and negatively with that of sand. No significant differences were found for sand and clay content between the land use systems, nor between depths; negative correlations were detected between sand and clay.

The semivariogram of the volumetric humidity showed a moderate spatial dependency at all depths. The dependency was strong at 0 to 5 cm, and moderate at 10 to 40 cm. The organic carbon content only presented a moderate dependency at 5 to 10 cm. The spatial dependency at the four depths was moderate for the sand and clay content (Table 3).

The range of the models of the semivariograms indicated the presence of spatial structure beyond 18 m. The range for all the horizons was greater for volumetric humidity and sand and clay content (210.9 m), followed by bulk density (27.3 - 176.4 m), and organic carbon

(78.6 m). The analysis of spatial structure indicated variability for volumetric humidity, bulk density, organic carbon, and sand and clay content.

Results presented by Iqbal *et al*., (2005) showed adjustment to the spherical model for soil humidity content, at field capacity, with moderate spatial dependence except in the sub-surface (strong dependence); adjustment to the exponential model and moderate dependence for bulk density, and for sand and clay content in Endoaquepts soils, cultivated with cotton (*Gossypium spp.*), in Perhshire, USA.

Table 1. Descriptive statistics for volumetric moisture contnt (%) in the systems of slash and burn (SB), Quesungual Agroforestry System (QAS<2) and secondary forest (SF) at 0-5, 5-10, 10-20, and 20-40 cm of depth, Candelaria, Honduras 2006.

System	Depth (cm)	Hour	Min	Max	Mean[&]	Median	Asymmetry [&&]	SD
SB	0-5	09	19.5	26.5	23.0a	22.9	-0.13	2.53
		11	11.3	27.8	21.6a	22.5	-1.27	4.94
		15	12.3	17.0	15.2b	15.6	-0.53	1.68
	5-10	09	20.0	26.7	22.8a	21.9	0.33	2.46
		11	20.1	26.2	22.2a	21.6	0.81	2.06
		15	19.4	24.0	21.5a	21.4	0.27	1.84
	10-20	09	20.0	26.5	23.6a	23.8	-0.28	2.26
		11	19.2	24.5	22.0a	22.2	-0.23	1.71
		15	16.2	25.2	21.7a	22.4	-0.80	3.48
	20-40	09	18.3	24.1	21.3b	21.6	-0.40	1.62
		11	20.2	27.3	23.3a	23.0	0.41	2.42
		15	15.6	23.3	20.3b	21.4	-0.98	2.83
QAS<2	0-5	09	14.8	34.9	22.3a	22.5	0.42	5.14
		11	9.0	31.5	20.2a	20.5	0.01	4.95
		15	14.3	28.9	20.4a	19.4	0.73	3.83
	5-10	09	14.1	28.9	19.4b	19.1	0.91	3.41
		11	13.6	32.4	21.7a	21.4	0.87	3.25
		15	15.5	30.3	21.9a	22.8	0.12	3.71
	10-20	09	17.2	31.9	23.9a	23.9	0.03	3.72
		11	16.2	31.1	23.1b	24.6	-0.14	3.81
		15	16.0	28.1	22.1b	21.9	0.14	2.59
	20-40	09	16.1	33.1	23.7a	22.2	0.41	4.94
		11	11.5	53.6	24.1a	23.6	2.52	6.72
		15	17.2	33.5	23.5a	24.0	0.39	3.42
SF	0-5	09	20.5	31.5	25.8a	24.4	0.53	4.07
		11	21.1	32.5	26.0a	25.3	0.96	3.42
		15	17.9	28.8	20.7b	30.6	2.31	3.22
	5-10	09	15.7	27.1	21.8b	22.0	-0.17	3.84
		11	17.0	25.1	20.6b	21.4	0.01	2.41
		15	19.5	28.1	24.9a	26.5	-0.95	3.05
	10-20	09	16.7	26.8	22.0a	21.8	0.17	3.97
		11	18.2	37.3	23.5a	22.5	2.00	5.68
		15	20.0	30.6	26.7a	27.9	-0.78	3.30
	20-40	09	14.1	34.1	22.6a	22.9	0.74	6.11
		11	18.4	26.9	21.2a	20.9	0.95	3.13
		15	15.3	25.7	22.6a	24.3	-1.45	3.73

[&] Values followed by the same letter are not statistically different (DMS; P<0.05).
[&&] Shapiro-Wilk test, used to test the level of significance of normality (P<0.05);
SD – Standard Deviation.

Table 2. Descriptive statistics for Bulk Density (BD), Organic carbon (OC), Sand and clay, in the systems of slash and burn (SB), Quesungual Agroforestry system (QAS<2), Secondary forest (SF), at 0-5, 5-10, 10-20, and 20-40 cm of depth. Candelaria, Honduras, 2006.

[&] Values followed by the same letter are not statistically different (DMS; P<0.05).

System	Var	Depth (cm)	Min	Max	Mean[&]	Median	Asymmetry[&&]	SD
SB	BD g cm^{-3}	0-5	0.81	1.16	1.02b	1.09	-0.63	0.15
		5-10	1.18	1.25	1.22a	1.24	-0.82	0.03
		10-20	1.25	1.27	1.26a	1.27	-0.74	0.01
		20-40	1.16	1.38	1.25a	1.20	0.59	0.09
QAS<2		0-5	0.70	1.41	1.06d	1.09	-0.82	0.15
		5-10	0.93	1.57	1.21c	1.27	-0.36	0.15
		10-20	1.13	1.71	1.35b	1.32	0.21	0.13
		20-40	0.93	1.72	1.41a	1.43	0.11	0.18
SF		0-5	1.11	1.28	1.18c	1.18	0.31	0.07
		5-10	1.20	1.53	1.33b	1.27	0.61	0.14
		10-20	1.25	1.71	1.44a	1.34	0.57	0.20
		20-40	1.37	1.46	1.41a	1.41	0.21	0.03
SB	OC %	0-5	1.00	2.88	1.69a	1.66	0.48	0.51
		5-10	0.64	1.85	1.15b	1.06	0.47	0.38
		10-20	0.37	1.51	0.87c	0.85	0.32	0.31
		20-40	0.20	1.53	0.70c	0.66	0.75	0.37
QAS<2		0-5	0.26	3.10	1.63a	1.44	0.35	0.69
		5-10	0.13	2.51	1.11b	1.04	0.68	0.48
		10-20	0.17	2.45	0.85c	0.79	1.07	0.43
		20-40	0.13	1.74	0.66d	0.58	0.90	0.37
SF		0-5	0.70	3.28	1.72a	1.74	0.32	0.64
		5-10	0.52	1.81	1.16b	1.06	0.18	0.42
		10-20	0.38	1.58	0.89c	0.95	0.07	0.33
		20-40	0.18	1.32	0.62d	0.61	0.37	0.30
SB	Sand %	0-5	35.6	58.1	42.58a	42.40	1.35	5.46
		5-10	29.1	54.7	42.09a	40.90	0.16	6.27
		10-20	28.6	58.0	43.27a	42.70	0.05	7.15
		20-40	25.8	55.0	42.29a	45.00	-0.76	7.07
QAS<2		0-5	32.0	70.8	43.23a	42.25	1.62	5.86
		5-10	32.4	69.0	42.81a	42.55	1.02	6.36
		10-20	32.3	69.0	44.31a	42.90	0.83	8.08
		20-40	29.6	65.3	45.16a	44.35	0.40	7.60
SF		0-5	33.5	54.5	42.92a	43.00	0.20	4.66
		5-10	33.2	63.7	43.22a	43.10	0.87	7.34
		10-20	32.5	66.6	43.78a	42.15	1.07	7.96
		20-40	30.8	75.2	44.78a	42.30	1.13	10.1
SB	Clay %	0-5	18.7	32.7	26.53a	27.50	-0.64	3.74
		5-10	16.0	35.4	27.38a	28.90	-0.92	4.84
		10-20	14.7	37.6	26.70a	26.60	-0.23	5.66
		20-40	14.2	39.2	25.55a	25.00	0.40	6.30
QAS<2		0-5	11.6	33.0	26.53a	26.80	-1.75	3.79
		5-10	9.1	34.1	27.19a	27.75	-1.38	4.29
		10-20	10.3	35.4	25.93a	26.80	-0.57	5.60
		20-40	11.6	37.0	24.16a	23.95	-0.03	6.08
SF		0-5	17.5	31.9	26.28a	26.30	-0.55	3.22
		5-10	17.6	32.3	26.94a	28.60	-0.70	4.09
		10-20	14.2	34.8	26.98a	28.55	-0.70	5.77
		20-40	11.2	37.6	25.62a	28.00	-0.34	7.49

[&&] Shapiro-Wilk test, used to test the level of significance of normality (P<0.05);
SD – Standard Deviation.

Table 3. Semivariogram parameters for volumetric humidity (VH), Bulk Density (BD), Organic carbon (OC), sand and clay at 0-5,5-10, 10-20, and 20-40 cm of depth. Candelaria, Honduras, 2006.

Var	Depth (cm)	Mod.	Nugget	Sill	Nugget %	Spatial Class	Range	R
VH	0-5	Exp[&]	0.03780	0.07570	50	M	210.9	0.061
%	5-10	Exp.	0.01976	0.03962	50	M	210.9	0.367
	10-20	Lin[&&]	0.01854	0.03718	50	M	210.9	0.269
	20-40	Exp.	0.02965	0.05940	55	M	210.9	0.287
BD	0-5	Exp.	0.00312	0.01336	23	S	176.4	0.667
g cm^{-3}	5-10	Sp[&&&]	0.00036	0.00479	8	S	27.3	0.923
	10-20	Exp.	0.00237	0.00869	27	M	169.0	0.529
	20-40	Exp.	0.00394	0.00789	50	M	147.5	0.148
OC	0-5	Lin.	0.05915	0.06365	93	W	78.6	0.165
%	5-10	Exp.	0.03800	0.07610	50	M	78.6	0.111
	10-20	Lin.	0.04311	0.04311	100	W	78.6	0.000
	20-40	Lin.	0.04115	0.04473	92	W	78.6	0.102
Sand	0-5	Exp.	0.01163	0.02726	43	M	210.9	0.542
%	5-10	Exp.	0.01735	0.03480	29	M	210.9	0.602
	10-20	Exp.	0.02557	0.05124	50	M	210.9	0.765
	20-40	Exp.	0.02794	0.05598	50	M	210.9	0.710
Clay	0-5	Exp.	0.02061	0.04132	50	M	210.9	0.196
%	5-10	Exp.	0.02708	0.05746	47	M	210.9	0.397
	10-20	Exp.	0.04670	0.09990	47	M	210.9	0.619
	20-40	Exp.	0.06030	0.12070	30	M	210.9	0.322

Mod. = Model; [&] Exp. = Exponential; [&&] Lin. = Lineal; [&&&]Sp = Spherical
% Nugget = (Nugget of the semivariance)/(total semivariance)×100;
% Nugget: <25% (S) = Strong Spatial dependence; between 25 and 75% (M) = Moderate spatial dependence; and > 75% (W) weak spatial dependence.

The contour maps showed higher volumetric moisture content in the north east part in the systems SF, SB, and in the upper part of the QAS<2 (Figure 2); lower content at 0 -5 cm in the east of SB; greater content in the high part of the transect, except at 5 – 10 cm in the south west of the QAS<2. Moisture content was continuous at 10 – 40 cm in QAS<2, although with greater area of low content at 10 – 20 cm.

The highest organic carbon content (Figure 3) presented at 0 – 10 cm in the middle part of QAS<2, followed by SF; lesser contents were observed in the high and low part of the QAS<2, a tendency that was maintained to a depth of 40 cm, although with lesser values.

At all depths, the highest sand content presented in the lower part of the QAS<2, with increasing extensions on increasing depth. In general, higher organic carbon content corresponded to lower content of sand.

The lowest clay content at the four depths presented in the lower part of QAS<2. In general, the behavior was in opposition to that of sand content.

The autocorrelation at distance zero corresponded to one, and decreased with increasing distance to 78.7 m, reaching non-significant levels. Moran's I index was 0.36 for volumetric moisture content at 0 to 5 cm; the indices of bulk density at 0 – 5, 5 – 10, 10 – 20, and 20 – 40 cm were 0.50, 0.59, 0.56, and 0.53 respectively. The remaining variables presented correlation values between less than 0.327 and -0173. At the distance 8.33 m, variation was detected in volumetric humidity at 0 – 5 cm, and in bulk density at all depths.

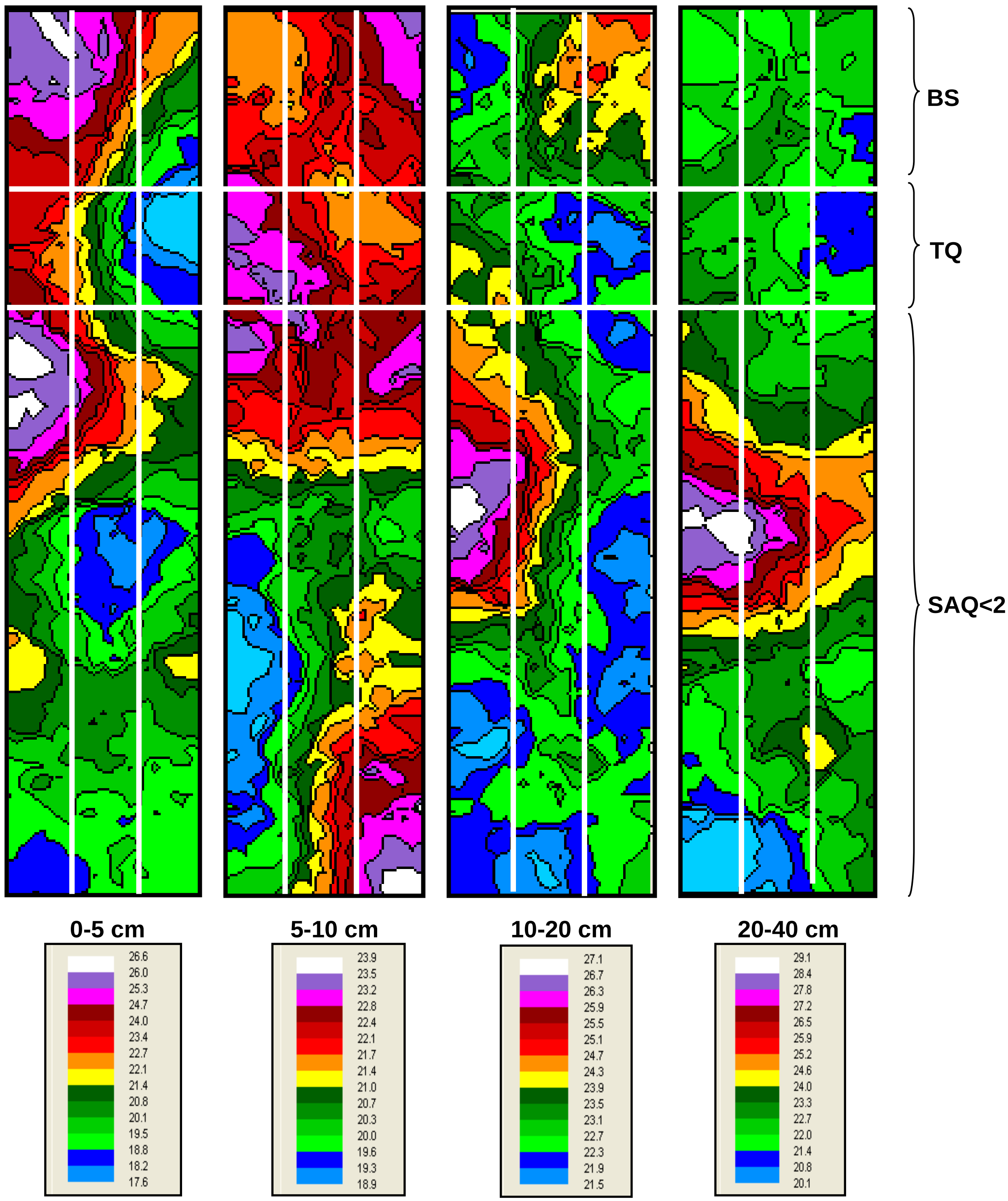

Figure 2. Contour map for volumetric moisture content (%) from 0 to 5, 5 to 10, 10 to 20, and 20 to 40 cm of depth. Candelaria, Honduras, 2006.

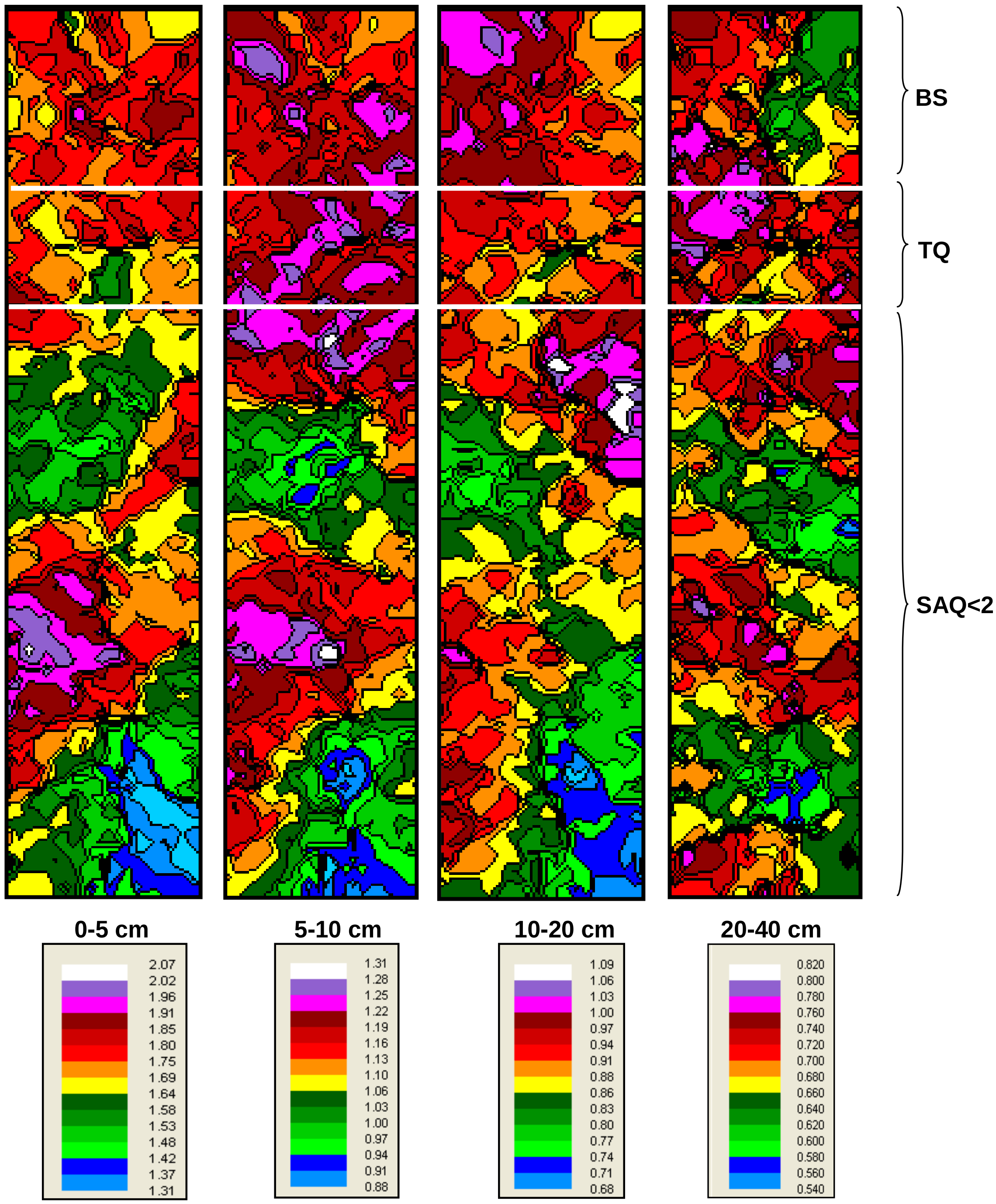

Figure 3. Contour map for organic carbon content (%) from 0 to 5, 5 to 10, 10 to 20, and 20 to 40 cm of depth. Candelaria, Honduras, 2006.

CONCLUSIONS

The tools of descriptive statistics were appropriate for showing variability in properties between land use systems, and between depths

The geostatistical analysis showed spatial variability between depths in volumetric moisture content, bulk density, and content of organic carbon, sand and clay.
The values of bulk density at the surface were significantly less than at the depth of 5 – 40 cm. The opposite trend was seen with organic carbon.
Moran's autocorrelation (I) showed sampling ranges less than 9 m could be adequate to detect spatial structure in volumetric humidity.

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