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MATHEMATICAL METHODS IN SOIL CLASSIFICATION

Spatial Heterogeneity of the Soil Cover in the Yucatán Karst: Comparison of Mayan, WRB, and Numerical Classifications[1]

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Abstract—In karstic areas, geopedologic information integrating soil and relief features, especially concerning short-distance variability, is usually scarce. The aim of this paper was to compare soil classes in the Yucatán karst using the Mayan soil nomenclature, the *World Reference Base for Soil Resources* (WRB), numerical soil classification (NSC), and geostatistics. The landscape is a flat-to-slightly-undulating karstic plain. Soil properties were determined at 54 sampling points on a regular grid covering an area of 1350 m^2. Six indigenous soil classes were identified on the basis of the terrain position, topsoil color, stoniness, rockiness, rock type, and soil depth. Five WRB soil units were recognized belonging mainly to Leptosols. Furthermore, six NSC groups were determined mainly on the basis of organic matter and stoniness. Soil organic material and texture explained 57% of the variation of the soil cover. An isotropic model of organic carbon shows a range of 39 m.

INTRODUCTION

Leptosols are the most common soils in the world (12%). This is also the case in Mexico (24%) and in the state of Yucatán (80%) [10, 14]. The high spatial heterogeneity of Leptosol areas complicates soil inventory, agricultural development, agronomic experimentation, and transfer of agricultural technology, among other things [8, 17].

Leptosols are the dominant soils in karstic areas, characterized by very fragmented soil-relief patterns. In such areas, geopedologic information integrating soil and relief features, especially concerning short-distance variability, is usually scarce, making it difficult to formulate appropriate planning strategies for agricultural use and environmental preservation [5–7, 15, 17].

The state of Yucatán, in southeast Mexico, has an extensive territory of undulating topography, forming a karstic plain developed on a deep sequence of Cenozoic limestone layers. Calcareous bedrock and the subhumid climate have contributed to the formation of soils showing differences in depth [17, 6], stone content [17, 6], Fe and Al as residual material [5, 15], and other chemical and physical soil properties [5, 6]. The soil mantle, composed mainly of weakly developed protosoils [5, 6, 15], is highly variable along microcatenas recurrent at short distances.

[1] This article was submitted by the authors in English.

To describe the spatial soil heterogeneity in this region, several approaches can be used including the indigenous Mayan soil nomenclature (**MSN**), the *World Reference Base for Soil Resources* (**WRB**), numerical soil classification (**NSC**), and geostatistical interpolation, among others.

In Yucatán, MSN is the most commonly used terminology among farmers, researchers, and extension agents. It is adapted to the intricate soil distribution pattern in this region and reflects the precision agriculture developed by Mayan farmers through long-term empirical experimentation on their small farming plots. The indigenous classification system uses differentiating soil properties and meso-/microlandscape features, which are easy to identify visually.

Soil groups were also created using NSC to detect relationships between soil groups based on property values and spatial location. Finally, multivariate and geostatistical methods were used to analyze the structure of the soil cover, as they help understand spatial heterogeneity and thus allow improvements of agricultural and forest productivity as well as environmental preservation in areas with high soil variability [4–6].

The objective of this study was to compare soil groupings and spatial patterns obtained by applying MSN, the WRB, NSC, and geostatistical analysis and to identify relevant soil properties for preparing low-cost soil maps in areas of small traditional-farming plots.

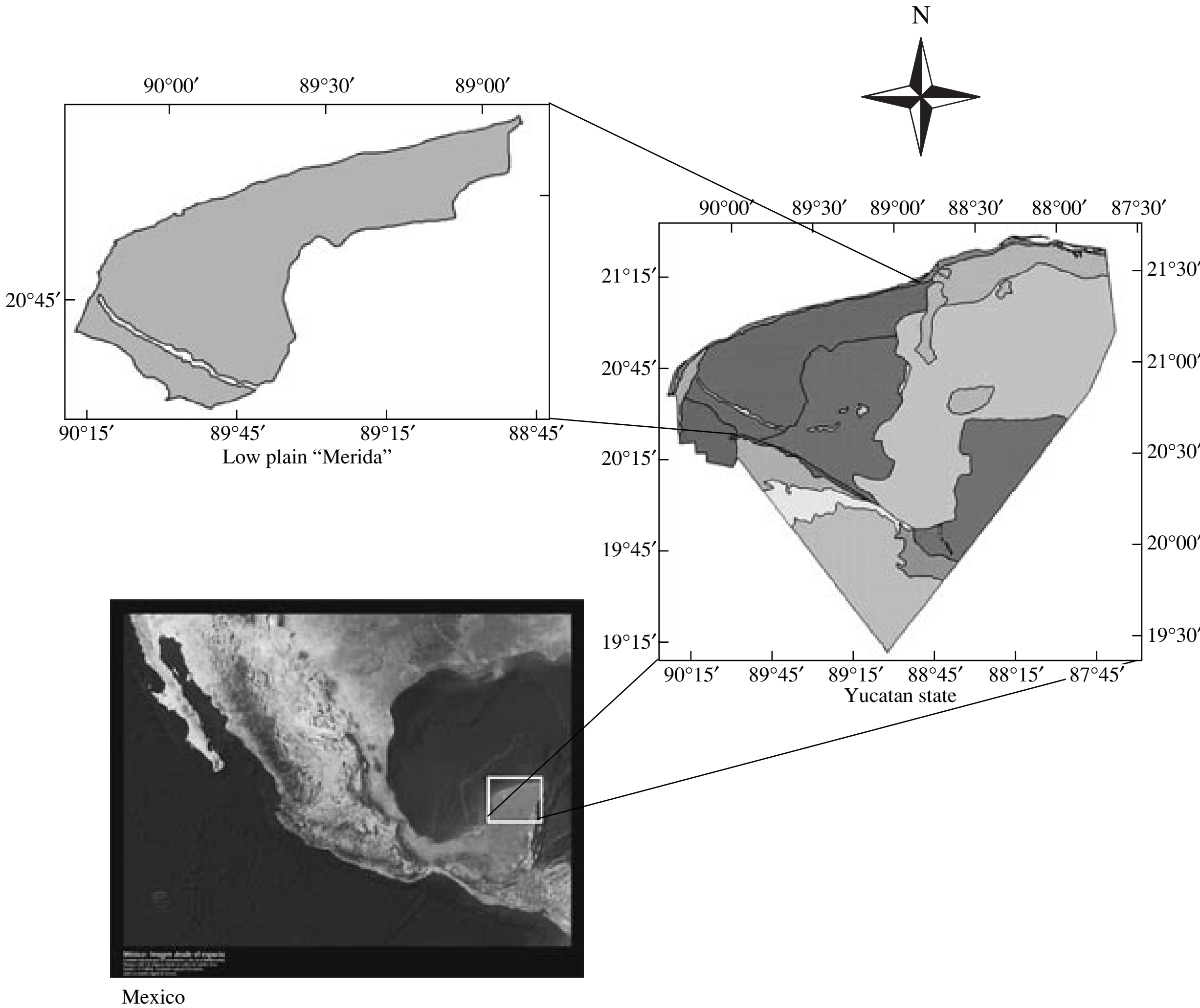

Fig. 1. Study area location.

MATERIALS AND METHODS

Study Site

The study area lies in a slightly undulating karstic plain that covers the north of the Yucatán peninsula. Dissolution depressions (i.e., sinkholes such as dolines and uvalas) alternate with rock-outcrop mounds, with 1–2 m of relative elevation. The regional climate is hot subhumid tropical with summer rains, and the vegetation is a low seasonal forest.

The study was conducted in a 1350 m^2 parcel belonging to the Autonomous University of Yucatán, located in the municipality of Mérida (20°51′57.36″ N; 89°37′23.04″ W) (Fig. 1). The parcel was divided into 54 quadrants of 25 m^2 (5×5 m) each, used for long-term agronomic experimentation [4].

Study Procedure

The soils were first mapped with the help of Mayan farmers and then classified using the WRB taxonomy. The two data sets were compared to detect relationships and levels of correspondence between soil classifications. A principal components analysis (PCA) was carried out to identify topsoil properties that could be used to explain spatial heterogeneity. Based on the PCA results, a cluster analysis was performed to create soil groups through numerical classification. The three classification modes (MSN, WRB, and NSC) were then compared. Finally, soil attribute maps of the study site were prepared. The different stages of the procedure are described later.

(a) The study site was surveyed with four Mayan farmers from the surrounding area to identify and describe the soil types. The farmers were bilingual (Mayan–Spanish) and had extensive field experience. The soil properties they used to name soil classes were recorded and a soil map in raster format was made with this information using the *Corel Draw* 9 software program.

Table 1. Characteristics of Mayan soil classes and comparison of Mayan soil classes with WRB soil units (% surface area)

Characteristics	*K'ankab*	*Hay lu'um*	*Chaltún*	*Box lu'um*	*Ch'och'ol*	*Tsek'el*	Total %
Geoform	Depression	Depression	Depression-mound	Mound	Mound	Mound	
Color	R	R, RB	R, RB, B	B	B	B	
Stoniness		X		XX	XXX		
Rockiness		XX	XXX		X	XXX	
Depth	XXX	X	ND	ND	ND	ND	ND
Units							
CMle	6	0	0	0	0	0	6
LPeu	11	0	0	0	0	0	11
LPrz	0	0	1	4	0	0	5
LPhsk	1	0	0	3	7	0	11
Lpli	2	5	4	2	5	3	21
Total %	20	5	5	9	12	3	54

Note: R—red, RB—reddish brown, B—black, XXX—high, XX—medium, X—low, ND—not determined.

(b) Soils were classified by quadrant using the *World Reference Base for Soil Resources* (WRB) [21]. Undisturbed soil cores and disturbed soil samples were taken in each quadrant. The soil properties were described, including color, stoniness, rockiness, and depth [18]. Samples were analyzed in the laboratory for particle density [11], bulk density [2], organic carbon using the TSBF colorimeter method [2], water percentage at field capacity [9], particle size distribution [12], and carbonates using HCl reaction. A soil map in raster format was prepared.

(c) To determine patterns of relations between quadrants, a data matrix was created with nine rows representing topsoil attributes and 54 columns for the quadrants. The PCA allowed reduction of the study dimensionality to a few unrelated variables, each of which accounted for a portion of the total variability [1, 16]. Value calculation was done with a correlation matrix, and the Frontier's broken stick model was used as the component selection criterion [1, 16]. The original variables and the generated principal components were compared for correlation purpose [4].

(d) A similarity analysis between quadrants of the experimental area was done for site grouping, and the association was measured with the Gower index (>0.625). A hierarchical classification of the clusters was applied to the resulting matrix using the weighted pair group as a grouping measure, and the results were shown on a dendrogram [16].

(e) Vector maps were made using the nine parameters determined in the identification of site grouping properties, and the SURFER computer program was implemented for kriging [20]. The vector maps provided the foundation for designing soil mapping techniques adapted to karstic areas in the Yucatán. Finally, the maps based on differentiating properties were used to compare soil patches and soil groups. A soil group map in raster format was made.

RESULTS

Mayan Soil Nomenclature

The Mayan farmers identified soil classes based on relief, soil color, stoniness, rockiness, and depth (Table 1). Not all of these properties have the same weight in the WRB classification.

Three soil classes were identified in the depressions: (a) *K'ankab* is a red soil, 10–50 cm deep, with less coarse fragments than the *Hay lu'um* and *Chaltún* soils; this soil class is not flooded and is considered moderately productive for agriculture. (b) *Hay lu'um* has the same characteristics as *K'ankab* but is less than 10 cm deep and contains more fine earth than the *Chaltún* soil class. (c) *Chaltún* soils can be red, reddish brown, or black; contain large amounts of coarse fragments; and are frequently interrupted by rock outcrops of laminar limestone. They occur in depressions as well as on mounds (Fig. 2).

Similarly, three soil classes were recognized on the mounds: (a) *Box lu'um* is a black soil, typical of higher relief portions, with stones of 5–10 cm diameter. (b) *Ch'och'ol* is also a black soil, but with less fine earth than the *Box lu'um* soil; rock outcrops and coarse fragments of 5 cm or more are abundant. (c) *Tsek'el* is a black soil with very little fine earth, though more than in the *Chaltún* class; bedrock outcrops take the form of promontories.

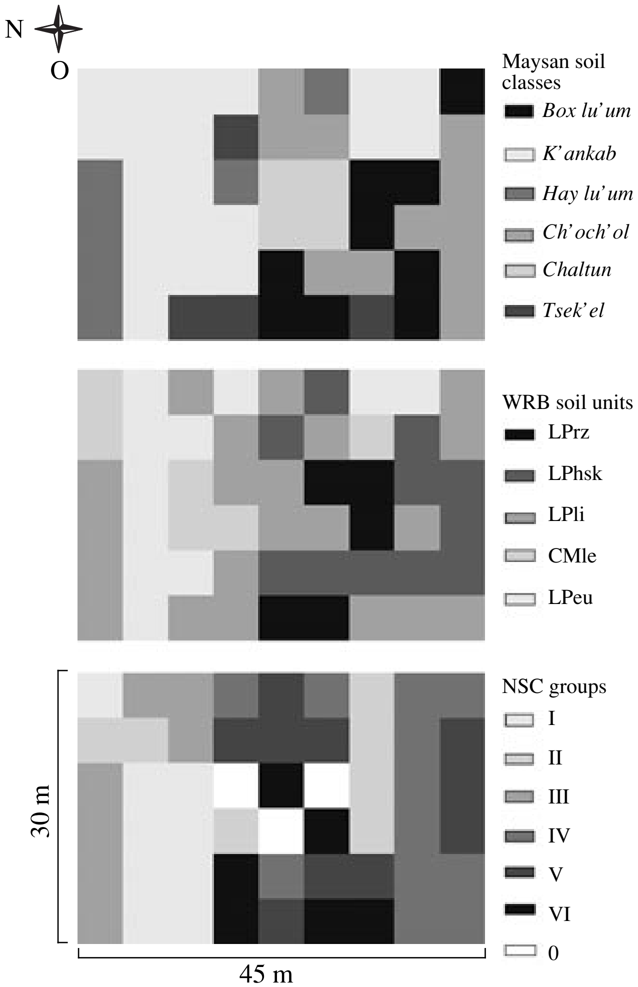

Fig. 2. Distribution of Mayan soil classes, WRB soil units and numerical classification soil groups.

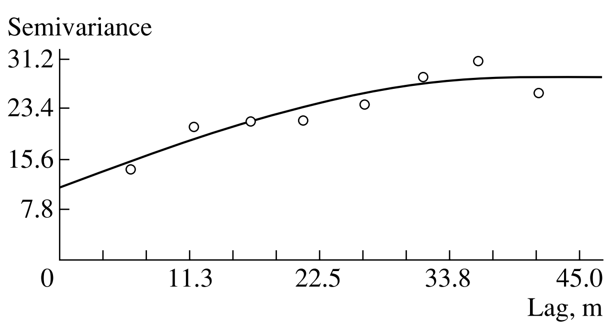

Fig. 3. Variogram of soil organic carbon.

According to Barrera's Maya Dictionary, the Mayan terms used to label soil classes mean: *K'ankab*, red or yellow earth; *Chaltún*, calcareous surface bedrock; *Hay lu'um*, shallow soil; *Lu'um*, earth or soil; *Box*, black; *Ch'och'ol*, place full of loose rock fragments; and *Tsek'el*, rock outcrop or rocky soil unsuitable for cultivation [3].

The farmers also named other soil classes not found in the study area but occurring in the surroundings, such as *Chich lu'um*, a soil with abundant gravel content; *Pus lu'um*, soft black earth; and *Chak lu'um*, deep red soil.

WRB Soil Classification

The largest part of the study area (89%) is covered by shallow stony Leptosols, including 37% of very surficial soils, having continuous limestone bedrock within 10 cm from the soil surface (Lithic Leptosols), and 52% of surficial soils, having continuous limestone bedrock within 10–25 cm from the soil surface (other kinds of Leptosols). The rest of the study area (11%) corresponds to pockets of somewhat deeper Endoleptic and Epileptic Cambisols (CMle).

The Lithic Leptosols (LPli) include four subunits: (a) Lithic-chromic Leptosols (LPli-cr), red soils in low portions of the relief; (b) Lithic-skeletic Leptosols (LPli-sk), soils having 40–50% surface stone content; (c) Lithic-hyperskeletic Leptosols (LPli-hsk), soils with more than 90% stone cover; and (d) Lithic-humic Leptosols (LPli-hu), black soils with 40–70% surface rock cover.

The other kinds of Leptosols include three subunits: (a) Eutric-chromic Leptosols (LPeu-cr), surficial (10–25 cm) red soils occurring in the low-lying portions of the relief (17% of the area); (b) Rendzic Leptosols (LPrz), soils deeper than 10 cm, with a mollic horizon (11% of the area); and (c) Hyperskeletic Leptosols (LPhsk), 10–25 cm deep (24% of the area).

LPli-cr, LPeu-cr, and CMle soils are found in the lower positions of the meso-relief (i.e., depressions) and constitute together a soil evolution sequence. Luvisols, not present in the study area but occurring in the region, are the most developed end-member of this sequence.

The soils in the higher positions of the meso-relief (i.e., mounds) may follow one of two possible soil development sequences: (a) LPli-hu-LPli-sk-LPrz, with Epipetric and Endopetric Calcisols as evolution end-members; or (b) LPli-hsk-LPlisk-LPhsk, with deep Endopetric or Endoskeletic Calcisols as evolution end-members.

Lithic Leptosols cover a large part of the study area but form also the most diverse unit. To reach some correlation with the Mayan soil classes, LPli must be subdivided into subunits, or the differentiating properties of the Mayan classes, such as rock type (promontory or laminar bedrock), amount of surface stones, and soil characteristics (e.g., soil color), must be introduced in the WRB classification. Conversely, the WRB classification helped identify two subunits within the *K'ankab* soil class (Table 2).

Hay lu'um and *Tsek'el* are two Mayan soil classes corresponding to LPli. K'ankab soils mainly corre-

Table 2. Differentiating soil properties according to first principal components EV—explained variation; PC—principal components

Soil property	PC I Organic material	PC II Texture	E V (%)
Stoniness, %	0.4361	0.1100	54.6
Rockiness, %	0.1080	0.3326	44.1
Organic carbon, %	0.6839	0.0123	69.6
Bulk density, MG m^{-3}	0.6586	0.0044	66.3
Particle density, MG m^{-3}	0.4905	0.0945	58.5
Clay, %	0.0952	0.4814	57.7
Silt, %	0.2416	0.5224	76.4
Depth, cm	0.4186	0.0878	50.6
Water at field capacity, %	0.4191	0.0055	42.5

Table 3. Descriptive statistics of numerical classification groups (mean ± standard deviation)

	Group I	Group II	Group III	Group IV	Group V	Group VI
Stoniness, %	16 ± 12	20 ± 5	40 ± 12	63 ± 12	66 ± 10	22 ± 4
Rockiness, %	9 ± 2	10 ± 0	14 ± 16	10 ± 0	15 ± 5	44 ± 17
OC, %	5.7 ± 2.5	7.4 ± 3.7	9.2 ± 2.8	12.6 ± 4.4	12.5 ± 3.0	13.4 ± 5.9
BD, Mg m^{-3}	0.87 ± 0.07	0.81 ± 0.07	0.83 ± 0.09	0.68 ± 0.08	0.64 ± 0.06	0.65 ± 0.05
PD, Mg m^{-3}	2.17 ± 0.12	1.81 ± 0.46	2.17 ± 0.22	1.62 ± 0.37	1.63 ± 0.39	1.84 ± 0.36
Clay, %	42 ± 7	51 ± 9	41 ± 4	46 ± 23	29 ± 10	25 ± 14
Silt, %	34 ± 5	21 ± 9	34 ± 6	12 ± 13	22 ± 10	32 ± 5
Sand, %	24 ± 5	28 ± 4	25 ± 5	42 ± 20	45 ± 10	40 ± 12
Depth, cm	23.8 ± 13.4	20.2 ± 7.1	9.5 ± 3.4	11.5 ± 4.7	9.9 ± 2.9	6.8 ± 4.2
WFC, %	33.0 ± 4.0	34.9 ± 5.0	36.8 ± 4.2	38.0 ± 4.6	38.8 ± 5.7	39.9 ± 3.1

Note: OC—organic carbon, BD—bulk density, PD—particle density, WFC—water at field capacity.

spond to CMle and LPeu. The Leptosol group can be ameliorated with MSN, and the *K'ankab* concept can be separated into two groups on the basis of soil depth. *Box lu'um* is still a poorly defined concept (Table 2).

Numerical Soil Classification

According to principal components analysis, the two first components explain more than 57% of the variation of the soil cover. The first component is determined by organic material (organic carbon, bulk den-

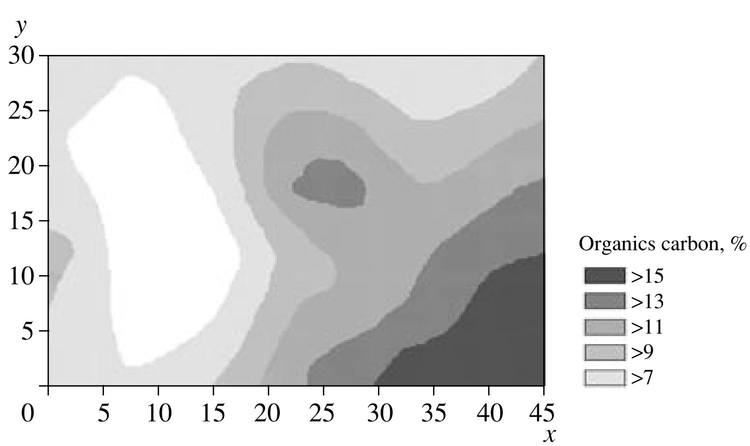

Fig. 4. Interpolation map of soil organic carbon using kriging.

Table 4. Correlation between numerical classification groups, WRB soil units and Mayan soil classes (per quadrant)

WRB soil units	NSC Groups					
	I	II	III	IV	V	VI
CM	4	2		2		
LPeu	5	2	2			
LPrz		2			1	1
LPhsk				6	5	
LPli	1		6	4	3	5
Mayan soil classes						
K'ankab	9	4	3	3		1
Hay lu'um			4			
Chaltún			1			2
Box lu'um		2		5	1	1
Ch'och'ol				4	8	
Tsek'el	1					2
Total	10	6	8	12	9	6

sity, and particle density), and the second one is determined by soil texture (clay and silt) (Table 3).

The differentiating properties included organic carbon, bulk density, and particle size distribution. As these parameters can easily be determined, they are useful for preparing low-cost soil attribute maps at the farming plot level. They also contributed to qualify the WRB units with additional information and to split them into subunits for soil management purpose. For instance, the Lithic-chromic Leptosols were subdivided on basis of silt content and particle density (groups I and II), and the Hyperskeletic Leptosols were subdivided on basis of particle size distribution (clay and silt contents).

NSC led to the formation of six groups (Table 4). The first group had a similarity index value of 0.75; the second, 0.72; the third, 0.66; the fourth, 0.68; the fifth, 0.70; and the sixth, 0.63.

According to the results generated by NSC, the minimum data set for the soil survey in the Yucatán karst condition includes organic carbon, bulk density, particle density, and soil texture (clay and silt) (Table 3).

Spatial Soil Distribution

Organic carbon showed a spatial dependence (isotropic model), and the spherical model was the best for describing the data ($r^2 = 0.854$). The range was 39 m, which is smaller than the maximum distance value of 45 m. The maximum semivariance value was 28 m^2.

The organic carbon map shows a gradient in which lower concentrations are found in the *K'ankab* soils, together with lower stoniness and rockiness, and higher concentrations occur in the *Ch'och'ol* soils, together with high stoniness, and in the *Chaltún* soils, together with high rockiness. Organic carbon largely coincided with the Mayan soil class map (Fig. 2), principally in the mineral-material topsoils. This was not the case for the soils with high organic carbon content, because other differentiating properties were included, such as surface stoniness and rockiness.

DISCUSSION

Mayan Soil Nomenclature and WRB Classification

Terrain position is a very important feature in soil survey. Soil groups as well as soil units vary according to their position on the landscape [6, 13]. Soil color is usually considered an accessory property, but in karstic conditions, it becomes a differentiating one as it reflects chemical and mineralogical conditions that allow estimating organic matter and the Fe and Mn contents [5]. Stoniness is a relevant property to build hierarchy in MSN (e.g., *Ch'och'ol*), as well as in the WRB classification at the unit level (e.g., Hyperskeletic and Skeletic Leptosols).

In the study area, rockiness can take different forms that are reflected in two major classes in MSN: *Chaltún* soils have a smooth laminar bedrock with surface dissolution channels, while in *Tsek'el* soils bedrock outcrops are large, rugged promontories with cracks. The WRB classification does not include this property as diagnostic. On the map obtained with the numerical classification groups, surface rockiness is greatest in the center of the study site (the *Chaltún* area) and lesser in the west (the *Tsek'el* area) (Table 2).

Depth is used in both classifications as an indicator of effective soil volume. The MSN is more precise than the WRB classification, establishing a clear difference between *Hay lu'um* and *Chaltún* soils within the Lithic Leptosols. The WRB, in contrast, differentiates between Leptosols (<25 cm) and Cambisols (>25 cm), a distinction that is not taken into account in MSN. Although a 25-cm depth may be an arbitrary threshold, it is a useful indicator of the soil volume available for root development. Similarly, the *K'ankab* soil class can be divided into two subclasses based on depth, resulting in a shallow (10–25 cm) *K'ankab* and a deep (>25 cm) *K'ankab*. Cambisols, the deepest soils in the area, were identified in the north and northwest portions of the parcel.

The MSN needs more diffusion among extension agents and researchers to increase communication efficiency with local producers, as the latter do the actual agricultural work, whether or not they own the land. The MSN and the WRB classifications are complementary. It is recommended that both systems be used at a maximum level of detail, as together they offer a good vision of the soil resource in the study area.

Numerical Soil Classification, MSN Nomenclature, and WRB Classification

Organic carbon can be used to identify a gradient according to micro-relief [5, 6]. Bulk density separates Leptosols into two large groups: a group with lower values (0.64–0.68 Mg m^{-3}), corresponding to topsoils with organic material (groups IV, V, and VI), and a group with higher values (0.81–0.87 Mg m^{-3}), corresponding to topsoils with mineral material (groups I, II, and III).

Group III fully matches MSN classes in identifying soils with moderate organic carbon content and stoniness, typical of the *Hay lu'um* soils. Group IV partially coincides with MSN and WRB units, as most of the soils included in this group are stony, but discrepancies exist with the WRB classification, which does not consider depth as a differentiating property. Group V, including soils with high organic carbon content, low bulk density and low stoniness, coincides with the *Ch'och'ol* soils. Group VI matches the WRB unit of the Lithic-humic Leptosols but none of the Mayan soil classes (Table 4).

Once the differentiating soil properties are identified and selected, categories and classes can be established according to the number of groups. The spatial location and surface area of the groups can be determined precisely, both of which are vital for the management of agricultural and forest systems, including application of fertilizers, manure, and herbicides; seeding and planting density; as well as cost estimates for weeding, planting, and harvesting, among others. However, the diagnostic properties of the soil groupings generated via NSC are usually site-specific and can therefore not be extrapolated to other areas.

A comprehensive data set for a soil survey in the karst condition should include qualitative (terrain position, topsoil color, rock type), semiquantitative (stoniness, rockiness, and HCl reaction) and quantitative (organic carbon, particle size distribution, and depth) soil properties [4, 19].

Spatial Soil Distribution

All soil property maps, including organic carbon, bulk density, particle density, carbonate content, stoniness, and depth, are related to the elevation gradient within the study area. This validates the use of relief as the main criterion for naming and classifying soils and making soil maps, as is done in the Mayan nomenclature and the WRB classification.

Rockiness, stoniness, and depth maps can be useful for land evaluation, soil management, and land use planning. Using geostatistics for soil cartography has become handier with recent advances in information technology and the appearance of low-cost, easy-to-use software. If no access to information technology is available, raster-type maps can be made using grid paper. This would lower the accuracy level but without seriously harming the management of the agricultural and forest production systems in the region. Polygons can be characterized in terms of organic carbon, bulk density, and particle size distribution for the preparation of detailed soil maps, in raster or vector format, useful for the use and management of small agricultural and agro-forestry plots.

CONCLUSIONS

The MSN nomenclature should provide subdivisions of *K'ankab* and *Box lu'um* according to soil depth and of *Ch'och'ol* according to stoniness.

The WRB classification system should provide subdivisions of Leptosols to cope with soil and landscape features that strongly influence land management and use, such as soil depth (e.g., extreme soil shallowness), types of bedrock (e.g., promontory bedrock, laminar bedrock), surface stoniness (e.g., 26–50%, 51–75%, and >75% coarse fragments), and soil color.

NSC is complementary to both the MSN and WRB classifications. However, as NSC gives the same weight to all soil properties, this may result in the formation of numerous groups without a spatial relationship.

The soil organic carbon map prepared using geostatistics contributes to the identification of property gradients along the landscape. Soil organic carbon showed a spatial dependence, and its variance could be fully represented in the map.

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