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Geopedological transects in karst landscapes in Campeche, Mexico

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ABSTRACT

Objective: To determine the spatial variability of landforms and their relationship with the soil geography of the state of Campeche, Mexico.

Design/Methodology/Approach: Two transects were carried out under the geopedological approach, using soil mapping and geomorphology material at landscape level. Geomatic techniques were used for the correction process, mapping the landforms at scale of 1:100,000. Soil profiles were developed westwards, giving priority to the diversity of landforms, resulting in geopedological transects.

Results: Plain landscapes (*e.g.*, P and Lf) feature hydromorphic processes, their soil is deep and rich in organic sediments, and the soil units were classified within the Histosols and Gleysols groups. The transitional EBDe landscape does not have an apparent dissection, presents relatively convex landforms (with a slight slope), and has moderately deep and well-developed soils —classified within the Cambisols group. Finally, the EBPD landscape presents higher elevation and dissection; its soil is mainly shallow with scarce or null pedon development and is related to convex landforms, while the soil units belong to the Leptosols group. For the elevated plains landforms, a relationship with the Luvisols group was determined.

Study Limitations/Implications: Understanding the geomorphology-soil relationships of a given region provides the basis for establishing soil distribution models —which will facilitate soil mapping and territorial planning.

Findings/Conclusions: Campeche's reliefs have a great complexity at landform level. Developing and updating the cartography of the land will help to improve the planning of productive and conservation projects.

Keywords: Geomorphology, plains, toposequences, karstic soils, Yucatan Peninsula.

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INTRODUCTION

Geomorphology is defined as the study of the various landforms of the earth's surface —originated by exogenous and endogenous processes— that constantly form and sculpt the land relief (García and Lugo, 2003). The Yucatán Peninsula is a relatively flat platform that consists of an earth system or morphogenetic environment and geomorphological landscapes (Lugo, 2011) and is typical of the states of Yucatán, Campeche, and Quintana Roo in eastern Mexico (Zavala-Cruz *et al.*, 2016; Fragroso-Servón *et al.*, 2019). Existing

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information points to landscape regionalization at the recognition and median scales, from which the importance for soil survey of the study of relief patterns can be inferred (Bautista-Zúñiga *et al.*, 2005b). According to Porta *et al.* (2003), pedology is the science that studies the soil. Therefore, geopedology sets forth geomorphological and pedological criteria to establish relationships between relief and soils (Zink, 2012; Zavala-Cruz *et al.*, 2016).

The geomorphological evaluation is a useful tool to provide information about the cartographic limits of the geoforms, as well as to determine the pedological characteristics that link them with the different forms of relief (Zinck, 2012; Zavala-Cruz *et al.*, 2016). Porta *et al.* (2003), Krasilnikov *et al.* (2011), and Zink (2012) point out that the relief determines the elevations within a territory and interacts with other landscape-forming factors (*e.g.*, climate and biota) to generate an effect on soil variability.

Nowadays, more emphasis has been given to the study of the relief-soil relationship, as a result of the interest in the implementation of plans with different approaches (Zavala-Cruz *et al.*, 2014; 2016; Aguilar-Rodríguez *et al.*, 2017; Palma-López *et al.*, 2017). Furthermore, the understanding of geomorphological aspects provides a better vision for the management of natural resources and is the basis for small- and medium-scale regionalization (Porta *et al.*, 2003; Zink, 2012; Zavala-Cruz *et al.*, 2016). The objective of this study was to describe the spatial variability of the relief at the landform level and its relationship with soils using geopedological regionalization in transects.

MATERIALS AND METHODS

Study area

The state of Campeche is located in the west and southwest of the Yucatan Peninsula, Mexico. It is located between the parallels 17° 40' 30" and 20° 50' 30" (N) and 89° 10' 30" and 92° 30' 00" (W). It has three climates which are distributed in different regions of the state: A(m), warm humid with rainfall in summer; A(w), warm sub-humid with rainfall in summer; and B(s), which refers to a dry steppe climate (García-Cruz, 2004). The precipitation captured in the different basins of the state is quickly evacuated by the prompt infiltration of the limestone rock; the dissolution of the rock creates underground rivers that flow into the sea through *petenes* (Bautista-Zúñiga *et al.*, 2005a). The geology of most of the territory is made up mainly of sedimentary rocks (limestone, marl, and gypsum) and, to a lesser extent, by sandstone and shales, as well as alluvial and marsh sediments (SGM, 2005; Zavala-Cruz *et al.*, 2016). The relief was classified under the approach of Zink (2012), arranged by morphogenetic environments —whose origin lay in endogenous and exogenous geodynamic processes—, controlling the modeling of geomorphological landscapes (which are characterized by their physiographic expression). Their differentiation was carried out with the following morphometric information: shape, slope, altitude, geomorphological or geodynamic process, and type and age of the rock (Ortiz-Pérez *et al.*, 2005; Zavala-Cruz *et al.*, 2016).

Geopedological regionalization of the relief

The present study was carried out through the interpretation and analysis of the geomorphological map at the landforms (LF) level, with a scale of 1:100,000. The map was developed with the Geographic Information System (GIS) and the ArcView 9.3 software, at the Laboratorio de Geomática del Colegio de Postgraduados, Campus Tabasco. The maps generated are based on regionalization studies at the earth system level, which refers to the morphogenetic environment and geomorphological landscapes described by Bautista-Zúñiga *et al.* (2005a) and Ortiz-Pérez *et al.* (2005). The limits of the said landscapes were perfected through the photo-interpretation and analysis of a Digital Elevation Model (DEM) (INEGI, 2011) and SPOT-type satellite images, generating a relief/modeling and LF repetitive pattern (Zink, 2012). Geomorphological processes and rock types were also identified to differentiate detrital, karstic, and marshy landscapes (SGM, 2005; Ortiz-Pérez *et al.*, 2005), among others.

First, we differentiated the LF-level reliefs for each geomorphological landscape; subsequently, we analyzed the distribution arrangement of the LFs, through two transects that were in an eastward direction (Figure 1): the AA1 and the BB1 transects.

Information about the soils of each geomorphological landscape was collected by describing soil profiles in the field, located according to the LF spatial distribution (Cuanalo, 1990; USDA, 2017). Each profile was described in terms of horizon, color, texture, consistency, structure, transition, presence of nodules, cutanes, waterlogging, and permeability, among others. Additionally, the description of the physical environment included the following elements: relief, slope, elevation, surface drainage, parent material, vegetation, and/or land use, as well as the dominant formation process. Subsequently, the soils were physically and chemically analyzed according to NOM-021-RECNAT-2000 (DOF, 2002), which establishes the regulations that oversee the analysis methodologies used for soil classification. In this way, through the world reference soil resource base of IUSS and WRB Working Group (2014), the soil mapping and classification was carried out.

RESULTS AND DISCUSSION

Geomorphological landscapes and landforms

Eight out of 23 differentiated geomorphological landscapes (Figure 1) were analyzed and characterized. They are located within the following systems or morphogenetic environments: SFP (Fluvial-Marshes System) and the SKT (Karst-Tectonic System). Figure 1 shows the list of geomorphological landscapes, as well as the spatial distribution of each unit, along with the location of the transects. The AA1 transect includes the P, Fp, and EBDe landscapes, up to the EBPD landscape —*i.e.*, it covers both morphogenetic or earth systems. Meanwhile, the BB1 transect covers the PRA, EBPD, and ADPC landscapes, up to the denudation highlands (DH), located at >200 m.a.s.l. Unlike AA1, this transect only represents the geomorphology-soil relationship of the SKT.

The LFs of the SFP morphogenetic environment, as well as of the SKT, have a depositional nature, with geomorphological landscapes of plains. For relief/modelling, two types were found in both environments: depression and floodplains. Being depositional, they are classified as unconsolidated materials (Zink, 2012); consequently, the facie in both environments is marshy and alluvial. Table 1 shows the morphometric information of the geomorphological landscapes and their respective LFs.

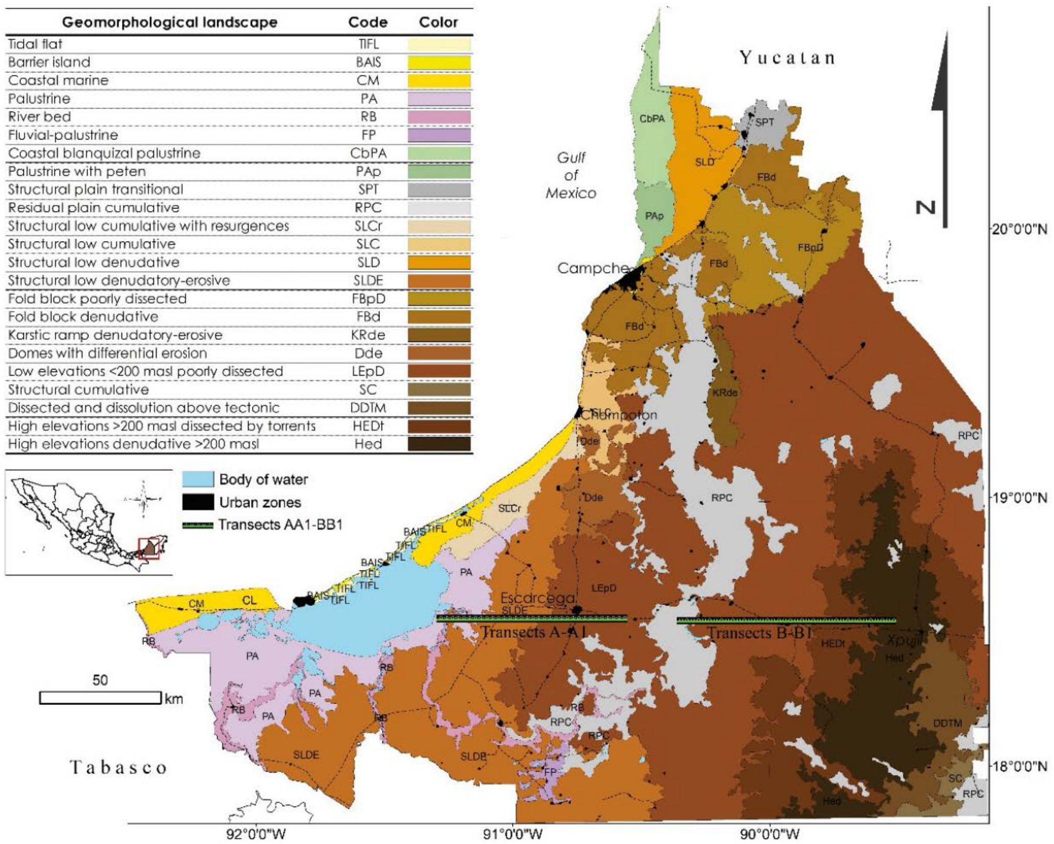

Figure 1. Map of geomorphological landscapes of the state of Campeche and geographical location of geopedological transects. Adapted from Lugo (2011), Bautista-Zúñiga *et al.* (2005b), and Ortiz-Perez *et al.* (2005).

Morphogenetic environment: SFP (Fluvial-Marshes System) and SKT (Karst-Tectonic System). **Geomorphological landscape**: P (marsh), Lf (river bed), EBDe (denudation-erosive low structural), EBPD (scantly dissected low elevations, <200 m.a.s.l.), PRA (cumulative residual plain), ADPT (highlands dissected by torrents, >200 m.a.s.l.), AD (denudation highlands, >200 m.a.s.l.). *Landforms*: Pbil (low lagoon floodplain), Llab (low floodplain), Llai (floodplain), T (terrace), Tc (karst terrace), Piac (wide cultivated inland plains), Piav (wide inland plains with vegetation), Ccxlo (slightly-undulating convex ridges), Ccxmo (moderately-undulating convex ridges), Ccxfo (strongly-undulating convex ridges), Prbdc (cultivated well-drained residual plain), Vt (torrent valley), Piacclo (broad inland plains and slightly-undulating convex ridges), Ccxlmo (slightly- to moderately-undulating convex ridges), Ccxmfo (moderately- to strongly-undulating convex ridges), Apbdv (highlands with well-drained plains with vegetation), and Alali (highlands with slightly-sloped isolated hills). **Geomorphological process**: A (accumulation), D (denudation), I (weathering), E (erosion), and K (karstification). **Rock type and age**: pa (marsh), al (alluvial), Ar (sandstone), Lu (shale), Cz (limestone), Mg (marl), Y (gypsum), Oho (Holocene - Quaternary), Opl (Pleistocene - Quaternary), Te (Eocene - Tertiary), and Tpa (Paleocene - Tertiary).

Table 1. Morphometric information of the geomorphological landscapes and landforms (LFs), in Campeche, Mexico.

Morphogenetic region	Geomorphologic landscape	TF	Altitude (masl)	Slope (%)	Geomorphologic process	Stone and age
SFP	P	Pbil	2-9	<1	C	pa, Qho
		Llab	9-10	<2	C	pa, Qho
	RB	Llai	10-11	<1	C	al, Qho
SKT	SLDE	T	11-40	1-6	W, E, C	Sn-Sh, Te-Qpl
		Tc	30-90	1-6	K, C	Ls-Lm, Te
		Piac	30-70	<2	C, K	Ls-Lm, Te
		Ccxlo	30-120	1-3	K, E, C	Ls-Lm, Te
	LEpD	Piac	30-140	<2	C, K	Ls-Lm, Ct, Te, Tpa
		Piav	35-140	<2	K, C	Ls-Lm, Ct, Te, Tpa
		Ccxlo	35-190	3-6	K, E, C	Ls-Lm, Ct, Te, Tpa
		Ccxmo	35-190	6-10	E, K, C	Ls-Lm, Ct, Te, Tpa
		Ccxfo	30-190	>25	E, K, C	Ls-Lm, Ct, Te, Tpa
	RCP	Prbdc	10-60	<1	C	al, Qho
	HEDt >200 masl	Vt	150-240	<3	C	Ls-Ct, Tpa
		Piacclo	200-250	1-6	C, K	Ls-Ct, Tpa
		Ccxlmo	200-250	3-10	K, E	Ls-Ct, Tpa
		Ccxmfo	200-250	10-25	E, K	Ls-Ct, Tpa
	HEd >200 masl	Apbdv	200-260	<2	C, K, D	Ls-Ct, Tpa
		Alali	200-260	3-6	K, E, D	Ls-Ct, Tpa

Each of the transects has an eastward altitudinal ascent. Baptist *et al.* (2005a), Ortíz-Pérez *et al.* (2005), SGM (2005), and Zavala-Cruz *et al.* (2016) point out that these landscapes —which correspond to SKT— have developed within a morphogenetic environment (earth system), where the dissolution of limestone rock and marls from the Tertiary Oligocene-Miocene prevails. Meanwhile, in the P and Lf plains, which correspond to the SFP morphogenetic environment, the parent material corresponds to unconsolidated sediments from the Quaternary - Holocene, mostly transported by the San Pedro and San Pablo River.

AA1 geopedological transect

Figure 2 and Table 2 shows the relationship between the relief and the soil of the AA1 transect, indicating that the SFP environment with depositional character has deep soils, with slight alkalinity, rich in organic materials. The said soils have poor to very poor internal drainage —which give rise to hydromorphic processes— and are classified as Histosols and Gleysols. They are related to concave LFs.

Soils in the SKT environment are mostly shallow, have high $CaCO_3$ concentrations and scarce or no soil development. They have been classified within the Leptosols group and were mainly related to convex LFs. To a lesser extent, deep, developed, and well-

Table 2. Soil units according to the landform in the AA1 transect.

Geomorphologic landscape	Terrain forms	Soil unit
PA	Low plain of lagoon flooding (Pbil)	Salic Histosols (Eutric) HS-sa.eu
	Low abyssal plain (Llab)	Molic Gleysols (Eutric, Clayic) GL-mo.eu.ce
RB	Flood abyssal plain (Llai)	Molic Gleysols (Eutric, Clayic) GL-mo.eu.ce
SLDE	Terrace (T)	Gleyic Cambisols (Humic, Clayic) CM-gl.hu,ce
	Karstic terrace (Tc)	Rendzic Leptosols LP-rz
LEpD	Wide cultivated interior plains (Piac)	Haplic Luvisols (Humic, Hipereutric) LV-ha-hu.he
	Wide interior plains with vegetation (Piav)	Leptic Luvisols (Hiperutric, Clayic) LV-lp.he.eu
	Slightly undulating convex crests (Ccxlo)	Hiperesqueletic Leptosols LP-hk.
	Moderately undulating convex tops (Ccxmo)	Hiperesqueletic Leptosols LP-hk.
	Strongly undulating convex crests (Ccxfo)	Hiperesqueletic Leptosols LP-hk.

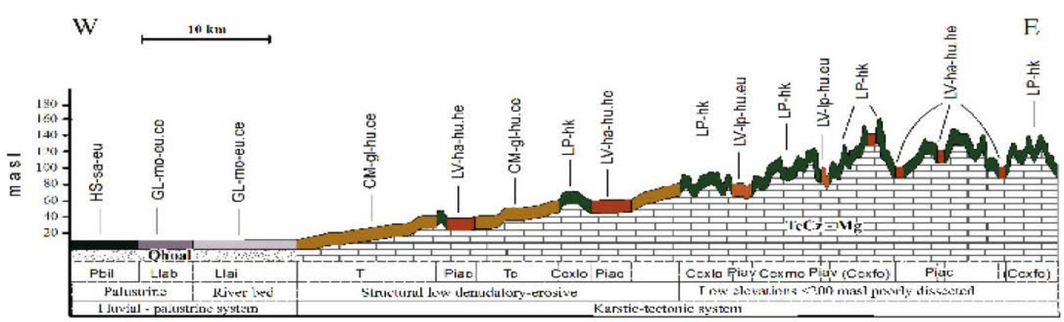

Figure 2. Geopedological toposequence of transect AA1. **Soil units**: HS-sa.eu Salic Histosols (Eutric), GL-mo-eu.ce Molic Gleysols (Eutric, Clayic), CM-gl-hu.ce Gleyic Cambisols (Humic, Clayic), LV-ha-hu.he Haplic Luvisols (Humic, Hipereutric), LP-hk Hiperesqueletic Leptosols, LV-lp-hu.eu Leptic Luvisols (Hiperutric, Clayic); **Terrain forms**: Pbil Low plain of lagoon flooding, Llab Low abyssal plain, Llai Flood abyssal plain, T Terrace, Tc Karstic terrace, Piac Wide cultivated interior plains, Ccxlo Slightly undulating convex crests, Piav Wide interior plains with vegetation, Ccxmo Moderately undulating convex crests, Ccxfo Strongly undulating convex crests.

drained soils have been recorded; they have been classified within the Luvisols group and are related to flat LFs. Unlike the above examples, the Terrace LFT —which is located in the transition area with the SFP— has a convex-concave to flat shape, with an extensive spatial arrangement, and is related to a deep soil with imperfect drainage. It has been classified within the Cambisols group. Similarly, the Tc with thin soil has been classified as

LP-rz. Specifically, the Ccxlo, Ccxmo, and the Ccxf LFs are directly related to the LP-hk soil unit, while the LV-ha-hu.he and LV-lp-hu.eu units —which are mainly located within the EBPD landscape, with some isolated remnants in the EBDe landscape— are connected with the Piac and Piav LFs, respectively.

BB1 geopedological transect

Figure 3 and Table 3 show the geomorphology-soil relationship of the BB1 transect for the SKT environment with dissolution and karstification processes. It is subdivided into four representative geomorphological landscapes: PRA, EBPD, ADPT >200 m.a.s.l., and AD >200 m.a.s.l. These landscapes have similar characteristics in terms of the repetition of LFs: the EBPD landscape has Piac and Piav, as well as Ccxlo, Ccxmo, and Ccxfo; the ADPT landscape includes Ccxlmo, Ccxmfo, and Vt; and AD >200 m.a.s.l. has Apbdv and Alali. This last landscape has the highest elevation in the study and extends into the state of Campeche (Bautista-Zúñiga *et al.*, 2005b).

The PRA landscape does not have isolated peaks or remains; the soil variability in this low-altitude landscape is residual and cumulative. Deep, developed, and well-drained soils predominate in these plains; they belong to the Nitisols group. At the same time, it is related to other groups of lower position that have not been included in the transect. The

Table 3. Soil units according to the shape of the terrain in the BB1 transect.

Geomorphologic landscape	Terrain forms	Soil unit
RPC	Well-drained and cultivated residual plain (Prbdc)	Molic Nitisols (Eutric, Rodic) NT-mo.eu.ro
LEpD	Wide cultivated interior plains (Piac)	Nitic Luvisols (Ferric, Hipereutric) LV-ni-fr.he
	Wide interior plains with vegetation (Piav)	Haplic Luvisols (Hipereutric, Esqueletic) LV-ha-he.sk
	Slightly undulating convex crests (Ccxlo)	Hiperesqueletic Leptosols (Rendzic) LP-hk-rz
	Moderately undulating convex tops (Ccxmo)	Hiperesqueletic Leptosols (Calcaric, Humic) LP-hk-ca.hu
	Strongly undulating convex crests (Ccxfo)	Hiperesqueletic Leptosols (Molic, Humic) LP-hk-mo.hu
HEDt >200 masl	Wide interior plains and slightly undulating convex crests (Piacclo)	Rendzic Leptosols (Humic) LP-rz-hu
	Stream valley (Vt)	Molic Gleysols (Calcaric, Humic, Clayic) GL-mo-ca.hu.ce
	Slightly to moderately wavy convex crests (Ccxlmo)	Litic Leptosols (Calcaric) LP-li-ca
	Moderately convex to strongly wavy crests (Ccxmfo)	Litic Leptosols (Calcaric) LP-li-ca
HEd >200 masl	High well-drained plains with vegetation (Apbdv)	Rendzic Phaeozems (Clayic) PH-rz-ce
	High with slightly sloping isolated hills (Alali)	Rendzic Leptosols (Clayic) LP-rz-ce

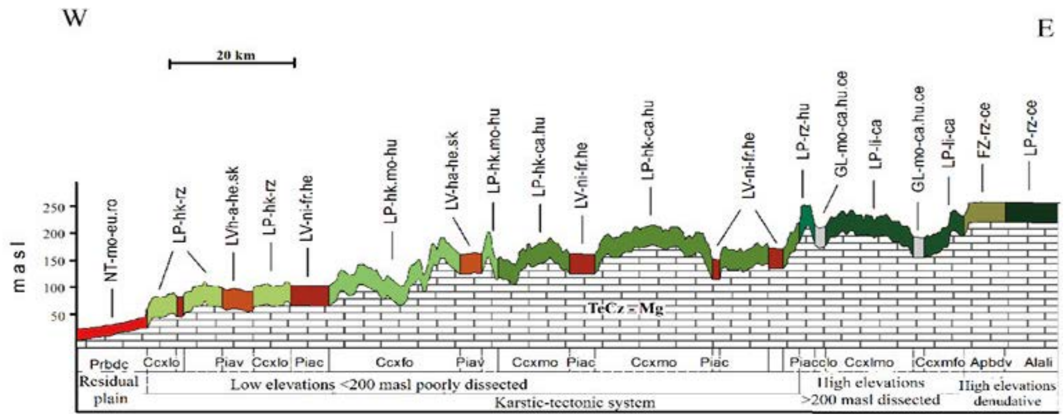

Figure 3. Geopedological toposequence of transect BB1. **Soil units**: NT-mo.eu.ro Molic Nitisols (Eutric, Rodic), LP-hk-rz Hiperesqueletic Leptosols (Rendzic), LV-ha-he.sk Haplic Luvisols (Hipereutric, Esqueletic), LV-ni-fr.he Nitic Luvisols (Ferric, Hipereutric), LP-hk-mo.hu Hiperesqueletic Leptosols (Molic, Humic), LP-hk-ca.hu Hiperesqueletic Leptosols (Calcaric, Humic), LP-rz-hu Rendzic Leptosols (Humic), GL-mo-ca.hu.ce Molic Gleysols (Calcaric, Humic, Clayic), LP-li-ca Litic Leptosols (Calcaric), PH-rz-ce Rendzic Phaeozems (Clayic), LP-rz-ce Rendzic Leptosols (Clayic). **Terrain forms**: Prbdc Well-drained and cultivated residual plain, Ccxlo Slightly undulating convex crests, Piav Wide interior plains with vegetation, Piac Wide cultivated interior plains, Ccxfo Strongly undulating convex crests, Ccxmo Moderately undulating convex tops, Piacclo Wide interior plains and slightly undulating convex crests, Ccxmlo Slightly to moderately wavy convex crests, Ccxmfo Moderately convex to strongly wavy crests, Apbdv High well-drained plains with vegetation, Alali High with slightly sloping isolated hills.

interior plains were related to the Luvisols group and they have a direct relationship to land-use: the plains with secondary vegetation (for example, the LV-ha-he.sk unit) were related to stony soils. Unlike these, the cultivated plains are not stony and are related to the LV-ni-fr.he unit. The convex LFs are related to the Leptosols group, which was previously described as shallow. Given that the slope is a determining factor in the development of the soil, the slightly-convex LFs are less stony than the LFs with a steeper slope. The units correspond to the LP-hk-rz, LP-hk.mo.hu, and LP-hk-ca.hu units.

The ADPT landscape had similar results for the convex LFs, as well as the LP-rz-hu and LP-li-ca soil units. Meanwhile, the GL-mo-ca.hu.ce soil unit is related to the Vt landform. This landform has a flat-concave, narrow, and poorly drained relief, located on the slopes of the higher elevation landscape. It acts as a drainage area that unloads in the interior plains of the EBPD landscape. Finally, the LFs of the plains and hills of the AD >200 m.a.s.l. are related to the PH-rz-hu and LP-rz-hu soil units and they are the deepest for the plain.

Legates *et al.* (2010) point out that the topological shape of the earth's surface impacts the accumulation of moisture within the soil profile. Convex LFs have low infiltration and high internal drainage, which reduces moisture within the soil profile (Sener and Oztürk, 2019; López-Castañeda *et al.*, 2017). In flat FTs, the infiltration speed and internal drainage depend on the gradient of the slope. Concave LFs have greater infiltration and lower internal drainage, which favors a longer period of humidity within the soil (Sener & Ostürk, 2019), as in the cases of marsh and fluvial-marshes landscapes.

Based on an analysis of the catenas, it can be inferred that, in sites with convex relief, the aeration within the soil profile is greater than in flat or concave LFs. In addition, the humidity conditions in the latter allow a better development of the vegetation, which influences the *in situ* development of the soil (Krasilnikov *et al.*, 2011).

The quantity and variation of the geomorphological landscapes found in the toposequences of this study were greater than those registered in other states located in the same morphogenetic environment (Yucatán Peninsula). For this study, we found 23 geomorphological landscapes in Campeche, while Bautista-Zúñiga *et al.* (2015) only identified five landscapes in Yucatán and Zavala-Cruz *et al.* (2016) described 12 landscapes in Tabasco, a state adjacent to the peninsula.

CONCLUSIONS

The two catenas studied showed a strong correlation between relief and soil types, both at the geomorphological landscape level and at the landform level. The catenas provided the basis for the cartographical definition of the distribution of soils in the state of Campeche. This definition will be incorporated into a proposal for the sustainable management of soils in Mexico. By controlling the distribution of the masses and the energy of the relief zone, it was possible to distinguish each landscape's accumulation, erosion, and karstification areas. Understanding the geomorphology-soil relationships in a given region lays the foundations for the establishment of soil distribution models, which facilitates soil cartography and territorial planning.

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