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THE KARST AND ITS NEIGHBORS: DIGITAL MAP OF GEOMORPHIC ENVIRONMENTS IN QUINTANA ROO, MEXICO

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Abstract

The Yucatan peninsula is a large, carbonate platform with several geomorphic environments, the largest of which is the karst. The other geomorphic environments have not drawn much scholarly attention. The objective of this work is to spatially identify the geomorphic environments found in Quintana Roo, Mexico. These environments were characterized and defined through their geomorphic and environmental conditions, such as climate and vegetation. The soil types associated with them using cluster statistical analysis, principal components and classification analysis, processed through a GIS system. Seven geomorphic environments were defined for Quintana Roo based on their geomorphological characteristics and types of coverage: littoral, paludal, pseudopaludal, tecto-karstic, karstic, gypsum karst and mixed karst, with 12 subtypes. The karstic and tecto-karstic geomorphic environments occupy the largest surface. The digital map (1:50,000) of geomorphic environments that resulted from this investigation has an accuracy level of more than 80%, which makes it an important tool for developing plans and strategies for the use and management of land in Quintana Roo.

Introduction

The Yucatan Peninsula is a large, calcareous plateau that is often considered a plain because of its low elevation compared to other parts of Mexico, such as the western, eastern and southern sierras. The official maps distinguish only three sub-provinces corresponding to geomorphic environments: Carso Yucateco; Carso and Lomeríos de Campeche; and the lower coast of Quintana Roo (INEGI, 2000a). It is usually believed that the Yucatan Peninsula is mostly environmentally homogeneous in terms of rock type and relief; however, there are large-scale morphometric differences involving karst depressions (Fragoso-Servón et al., 2014a), as well as small karst depressions and altitude variations (Lugo et al., 1992; Bautista et al., 2011).

In the study of the environment, and particularly of relief, the classification system proposed by Zinck (2012), which has been applied and validated in various parts of the world, constitutes an especially useful methodological tool for the identification of geomorphic environments.

The geomorphoedaphic environment (GE) is a category (suborder) of the Zinck (2012) system for the study of relief at a scale of 1:500,000. It is a biophysical medium formed and controlled by certain internal and/or external geodynamic processes (Zinck, 2012).

Characterizing a GE helps to understand and explain spatial distribution of soil-scapes and the pedogenetic processes that take place in it; this, in turn, allows a better understanding of its soil resources and helps evaluate their potential and limitations of use (Bautista et al., 2007; Zinck, 2012; Zinck et al., 2016). However, there is often not enough geographic information to make large-scale maps of geomorphic environments.

These limitations can be overcome through digital soil maps using multivariate techniques, data mining, and geographic information systems, which allow both to handle and infer geographic information, particularly of soils, in unsampled sites (Hartemink and Minasny, 2014; Minasny and McBratney, 2016).

The state of Quintana Roo, Mexico, is part of the karst plateau; it has 12 types of vegetation (Ek, 2011), six climatic subtypes (INEGI, 2008) and 14 soil groups (Fragoso et al., 2017). However, only three geomorphic environments have been reported. This work aimed to identify the diversity of geomorphoedaphic environments that exist in the state of Quintana Roo, Mexico, some of them consisting of karst with neighbors of other types.

Study Area

The state of Quintana Roo, Mexico, is located in the eastern part of the Yucatan Peninsula between 17° 40' and 21° 36' N and between 86° 44' and 89° 24' W. The Peninsula is a karst formation, composed mainly of calcite, dolomite and gypsum, that emerged at the end of the Tertiary or during the early Quaternary (López-Ramos, 1981; Bautista et al., 2011); the oldest geologic formations are located in the south and the most recent to the north and east.

Karst depressions, such as sinkholes, uvalas and poljes, abound in the state (Fragoso-Servón et al., 2014a). The center and north of the state are sub-horizontal and hilly plains, while the southern part is dominated by rolling hills (Fragoso-Servón et al., 2014a).

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The climate in Quintana Roo is humid warm (Am(f)) with rain year-round, and warm sub-humid with rain in summer (Aw), with five variants: rainy with rain in winter $Aw_2(x')$, moderately rainy Aw_1, moderately rainy with rain in winter $Aw_1(x')$, the least amount of rain in the summer Aw_0, the least amount of rain in the summer and with rain in winter $Aw_0(x')$ (INEGI, 2008). According to WRB (2014), 14 principal soil groups (WRB) or soil orders (soil taxonomy) have been identified; of these, Leptosols (Entisols), Gleysols (Inceptisols), Phaeozems (Mollisols), Vertisols (Vertisols) and Luvisols (Ultisols) occupy the largest area (Fragoso-Servón et al., 2017). The vegetation is very diverse, including medium forests, low forests, palm groves, mangroves, tular or vegetation of swamps, and lakes (plants 1 m to 3 m high, with narrow leaves and without foliar organs; the representative genera are *Typha, Scirpus, Cyperus, Phragmites* and *Cladium*) and popal (herbs in freshwater marshes rooted in the ground that emerge from the floodwater) (Ek, 2011).

Materials and Methods

Making the map of the geomorphic environments involved three stages (Fig. 1). The first stage consisted in making a morphometric description of the relief and the forms of coverage, based on 1:50,000 topographic information from INEGI, with the support of a Geographic information System (GIS) using the ArcGIS software.

Positive forms of the relief were identified using the vertical dissection coefficient (Priego et al., 2010; Fragoso-Servón et al., 2014b). Thirteen geomorphic units were identified, from sub-horizontal plains to strongly dissected mountains. The information about the negative forms of relief, their characteristics and distribution were taken from Fragoso-Servón et al. (2014a).

Geomorphometric units derived from the previous analyses were classified using geological information from the study Geological-Petrographic Prospection of the Yucatan Peninsula (PEMEX, 1967) and López-Ramos (1981); the information about faults and fractures was obtained from INEGI (2000b).

Then, geomorphometric units identified were classified within the GIS according to their environmental attributes, using climate information from INEGI (2008), vegetation information from INEGI (2009) and CONAFOR-SEMARNAT (2011), and soil information from Fragoso-Servón et al. (2017).

The second stage consisted of three successive analyses: a cluster analysis to reduce the volume of information represented by the polygons of the initial data matrix, a principal components analysis to determine which factors have the greatest weight in determining the existing environments, and a classification decision tree analysis to determine the uncertainty of the obtained results.

Cluster analysis was performed with the unweighted average linkage method using the Goodman-Kruskal Gamma coefficient

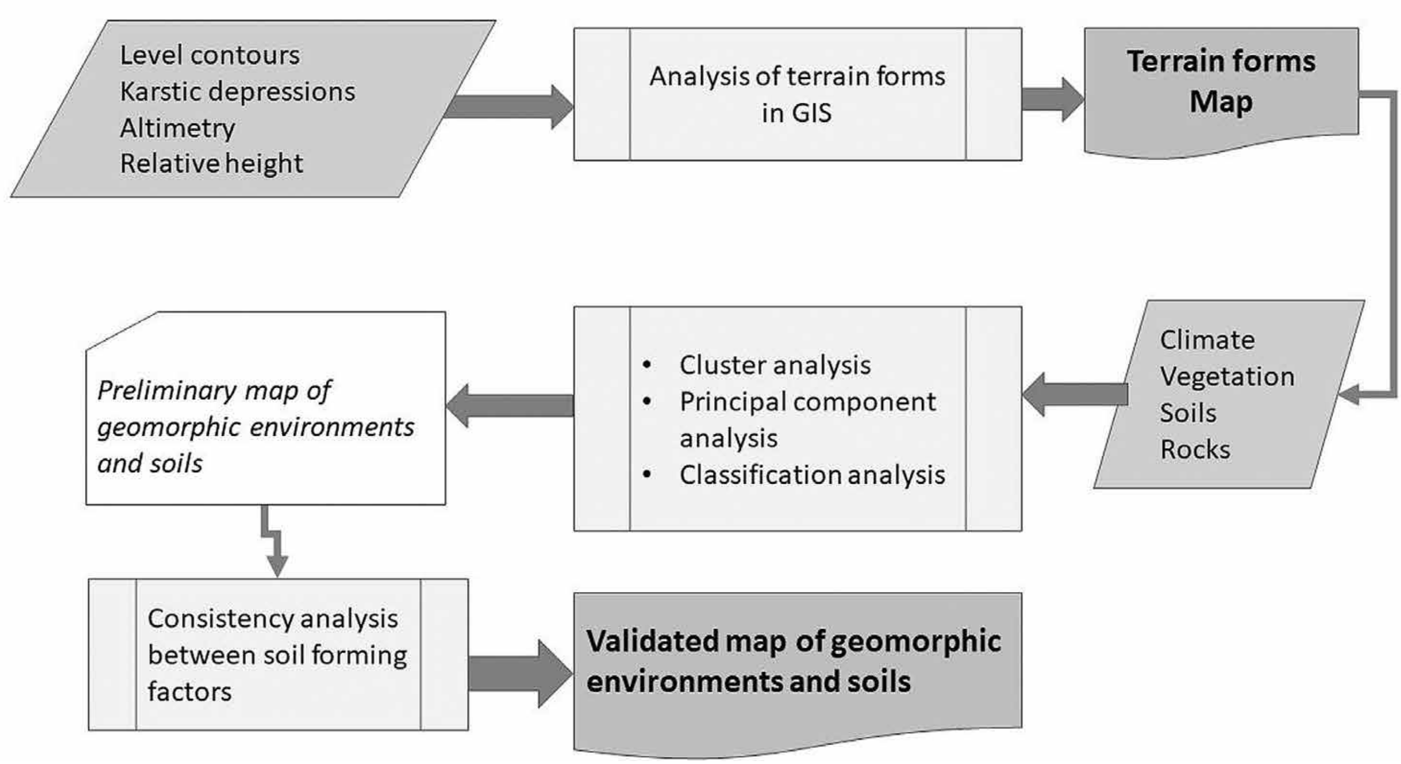

Figure 1. Methodological diagram.

$$D = 1 - \left(\frac{N_s - N_d}{N_s + N_d}\right), \quad (1)$$

where: D is the distance between pairs of objects, N_s is the number of objects with matching attributes and sequences, and N_d is the number of objects with different attributes and sequences.

This estimator is known as one of maximum similarity that is useful to handle large volumes of hierarchical data that have matches in order and value (Nelson, 1986). This analysis was validated using the Pseudo-F test, the Pseudo-T test, and Dunn's test (Halkidi et al., 2002; Havens et al., 2008; Omran et al., 2007) to verify the resulting cluster.

The Pseudo-F test yields a probability value for each node based on the probability of all the nodes that form the cluster

$$F = \left(\frac{U_1 / d_1}{U_2 / d_2}\right), \quad (2)$$

where U_1 and U_2 follow a chi-square distribution with d_1 and d_2 degrees of freedom, and U_1 and U_2 are statistically independent. The Pseudo-T test compares the mean distances and the intra and intergroup variances to estimate the dispersion of the nodes

$$T = \frac{\bar{X}_1 / \bar{X}_2}{s_{\bar{X}_1} / s_{\bar{X}_2}}, \quad (3)$$

where $\bar{X}_1 - \bar{X}_2$ is the mean intragroup and intergroup distances and $S_{\bar{X}_1} - S_{\bar{X}_2}$ is the difference in variances according to the size of the clusters. Dunn's Consistency or Distortion test is used to validate the cluster (Halkidi et al., 2002; Havens et al., 2008; Omran et al., 2007)

$$D = \frac{d_{\min}}{d_{\max}}, \quad (4)$$

where $d_{\min}$ is the minimum intercluster distance and $d_{\max}$ = maximum intracluster distance.

The resulting classes or clusters were subjected to principal component analysis to identify the sources of data set variability and the relative importance of each of them (Jongman et al., 1995).

Additionally, the result of the principal components analysis was subjected to a classification decision tree analysis, using the software WEKA to estimate the uncertainty of the classification (Bouckaert et al., 2009; Hall et al., 2009). Three different algorithms were used in four runs, and the results were compared to determine the consistency of the classification: a) Classification by decision tables with simple and exhaustive search (Kohavi, 1995; Mukerjee, 2012); b) Classification by exceptions to the initial rule (RIDOR or RIpple-Down-Rules) (Gaines and Compton, 1995); c) Classification by partition rules (Frank and Witten, 1998).

In the third stage, a preliminary map of the geomorphic environments was obtained; it was simplified by merging adjacent polygons with the same characteristics into each of the five resulting categories (structural, depositional, erosional, dissolutional, residual or mixed).

For each of these simplified units, we verified that the relationships between geomorphology, soils, vegetation, and climate were congruent with the field data and with the existing bibliographic references. This was done to validate the map of the geomorphic environments of Quintana Roo.

Results

As a result of the cluster analysis, it was possible to reduce the 16,456 polygons to 869 clusters of units that had identical attributes. The subsequent merger of clusters with minor differences reduced the total to 188 clusters with different geomorphometric conditions. The results of the statistical tests used on the clustering output gave to the estimated morphometric structure of clustering tree an uncertainty of less than 5 %.

Adding soil information to polygons of those 188 clusters allowed the identification of 123 clusters with complete soil information, which represent more than 99.5 % of the surface of the state.

The main components analysis allowed the identification of the groups of variables that are the source of the system's variability; they can be grouped into: relief conditions (vertical dissection, karsticity and faults), type and distribution of soils and rainfall, and temperature and flood regime. Relief conditions, constituted by the vertical dissection, shape, distribution and flood regime of the karst depressions and faults, explained approximately 51 % of the variation in the geographical distribution of soils. These relief conditions, together with the resulting soil distribution and the climatic conditions of precipitation and temperature, explain approximately 65 % of the observable environmental variability.

Certainty of these results was calculated using the confusion matrix from the classification analysis. Simply put, this matrix shows how many polygons were correctly classified and how many were not. It yielded a result that was consistent with the determination of the variance explained by the principal components analysis; for the three algorithms considered, the percentage of polygons correctly classified was above 83 %, which indicates that the environments were correctly identified using this procedure (Table 1). The results indicate that the identification of the environments, based on the selected variables, has an uncertainty between 14 % and 16 % associated with inaccuracies in the data (Table 1).

Based on the variables analyzed and the definition of morphogenetic environments (Zinck, 2012), seven geomorphic environments were identified for Quintana Roo (Table 2), two of them were depositional (paludal and pseudopaludal), one was erosional (litoral), one was structural (tecto-karst), two were dissolutional (karst and gypsum karst) and one was mixed.

Littoral Environment

This geomorphic environment is the most recent; it formed at the end of the Tertiary (Pliocene) or during the early Quaternary (López-Ramos, 1981); it is located in the coastal area, at the transition between the mainland (karst) and the sea, and it is, therefore, influenced by both environments (Fig. 2).

There are two types of littoral environments: erosive-accumulative littoral and erosive littoral (Table 2). The first is located in the northern coastal areas, where sandy and rocky beaches alternate at short distances. Southern Quintana Roo is the locale of the second type. Both occupy 1.24 % and 1.06 % of the state's surface, respectively (Table 3).

In the northern part of the state, where the littoral environment is erosive-accumulative, the most common soils are Arenosol/Gleysol/Histosol; on these soils grow coastal scrub vegetation, low deciduous forest and halophytic plants. In some places it is possible to find soil associations such as Regosol/Gleysol/Histosol and Regosol/Arenosol, on which xerophytic plants grow. It is also possible to find Leptosols in rocky coastal areas.

In the south, the coastal environment is mainly accumulative and the soils that developed are Gleysol/Histosol/Regosol/Arenosol and the mangrove vegetation occupies the largest area.

A conjunction of factors determine the presence of the littoral environment. For example, the Chetumal Bay, despite being a coastal area, has different characteristics than the rest of the coast. Its innermost part has low salinity (between 7 ppm and 10 ppm), since it is the mouth of the Hondo River and the Bacalar Lagoon system; it is more similar to a river bank or a lagoon than to a coastline. From the ecological point of view, it shows an estuarine behavior; for that reason, the areas bordering the bay present paludal and pseudopaludal environments. The characteristics of a littoral environment appear only at the mouth of the bay, where salinity increases, and the conditions are similar to those of the seafront.

In the southern coastal zone, the influence of the Caribbean marine current creates cumulative environments, while the northern zone shows an alternation between erosive and cumulative environments, depending on the profile of the coast (geological history). The characteristics of the soils in the coastal area of Quintana Roo are linked to the dynamics of the marine currents and the transport of sediments. This causes Gleysols and Histosols to be more frequent in the cumulative environments of the south, in the area corresponding to Bahías de Ascensión and Espíritu Santo, while Regosols and Arenosols are more frequent in the central zone (Costa Maya); the northern zone, where the geomorfoedaphological environment is erosive-accumulative, favors the presence of different mixtures of Arenosols, Gleysols and Histosols. In these conditions, the vegetation is influenced by two factors: the amount of subsurface (fresh water) and underground water (saline water) and the depth at which it is found. Mangrove areas dominate in the south and coastal scrub in the north, where it alternates with low forest formations.

Paludal Environment

Toward the west coast, in the sub-horizontal plains, the proximity of the water table, the abundant rainfall and the frequency of the salt wedge penetration have favored the presence of a paludal environment, where flood conditions have produced soils such as Gleysols and Solonchaks, with the characteristic vegetation of mangrove, popal and tular.

The paludal environment is found in areas of sub-horizontal plains that are close to the coast, where the water is permanently or semi-permanently stagnated due to the almost complete absence of slope, the abundant rainfall,

Table 1. Quality of the classification of polygons in the map of geomorphic environments.

Method	No. of Polygons Examined	No. of Rules	Polygons Correctly Classified, %	Polygons Incorrectly Classified, %
Decision table corresponding to a simple search	16353	1119	83.26	16.74
Decision table corresponding to an exhaustive search	15353	1119	83.26	16.74
Exceptions (Ripple-Down-Rules)	16456	357007	84.19	15.81
Partition rules (PART)	16456	389	85.69	14.31

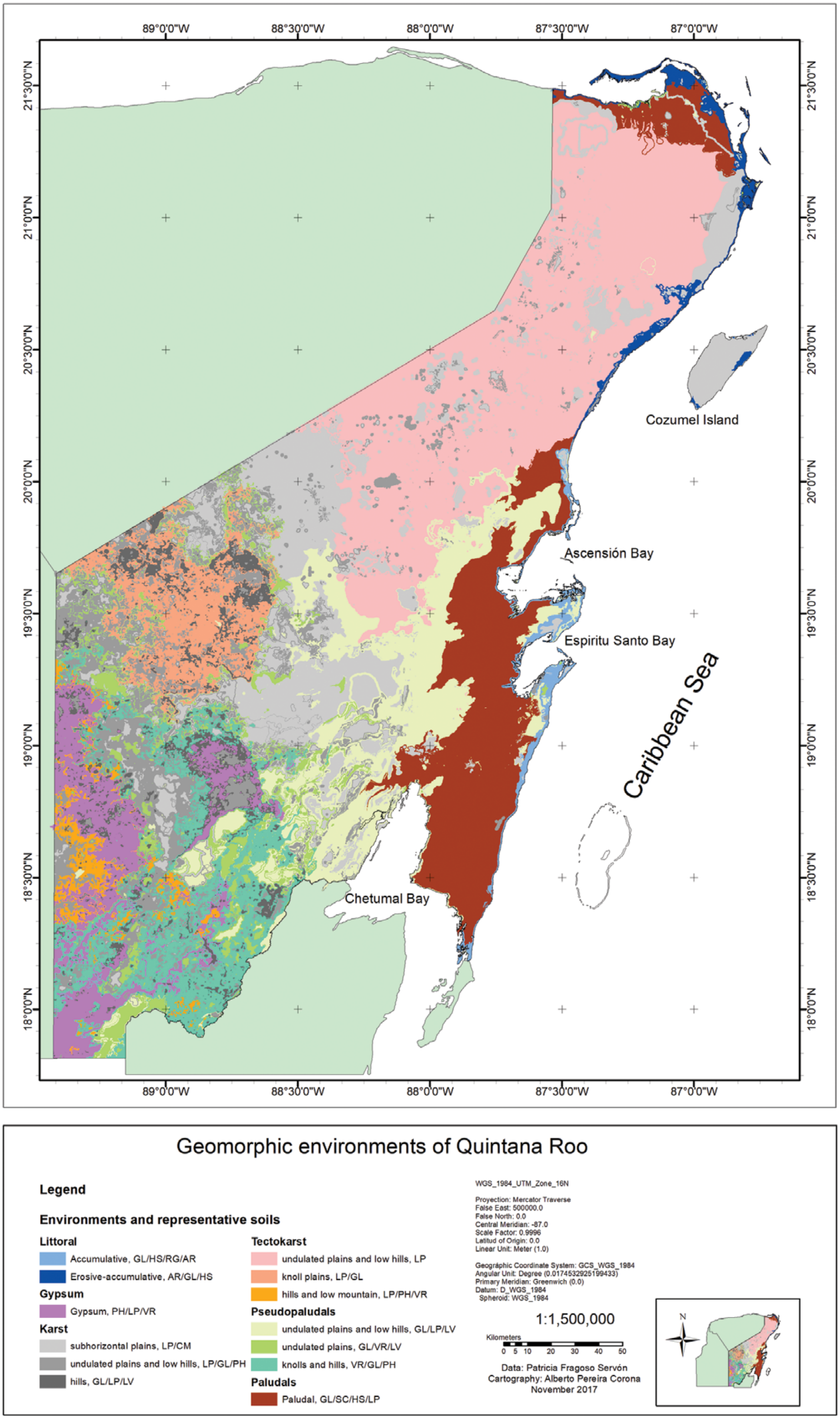

Figure 2. Map of the geomorphic environments of the state of Quintana Roo.

the frequent penetration of the salt wedge in coastal areas, the upwelling of underground water or the rise and fall of the water table, all of which can produce periods of flooding (Bonacci, et al., 2006; Hughes, et al., 2011; Pereira, et al., 2016) (Fig. 2).

This environment occupies 11.28 % of the state; it is found over the Pliocene formation in two zones, one involving a large area parallel to the coast, where rainfall is abundant (Aw_2), and another smaller area in the north with a drier climate (Aw_0), but with the presence of subsurface water flows. The soils that occur in this environment are Gleysol, Solonchak, Histosol and Leptosol; the vegetation that grows on them is mainly mangrove and tular-popal, with low forest in high relief formations (on hills and knolls).

Pseudopaludal Environment

As the vertical dissection of the relief increases, a transition zone between paludal environments and karstic and tecto-karstic environments emerges; this zone corresponds to pseudopaludal environments, where a large amount of water accumulates during the rainy season and stays there most of the year. In some areas, the water infiltrates quickly (Luvisols), while in other areas, it accumulates (Gleysols and Vertisols), resulting in a permanent flooding.

Medium forests and even high forests can develop in this environment with deeper soils. It is the area with the largest sur-

Table 2. Geomorphic environments in the state of Quintana Roo, Mexico.

Geomorphoedaphic Environments	Subtypes	Soils	Vegetation
Littoral	erosive-accumulative	AR/GL/HS	Scrub
	accumulative	GL/HS/RG/AR	Mangrove
Paludal	accumulative	GL/SC/HS/LP	Mangrove, tular, popal, low semi-evergreen forest
Pseudopaludal	undulated plains and low hills	GL/LP/LV	Low and medium semi-evergreen forests
	undulating plains	GL/VR/LV	Low and medium semi-evergreen forests, agriculture, cultivated pasture
	hill-billies and hills	VR/GL/PH	Medium semi-evergreen forest, agriculture, cultivated pasture
Tectokarst	Undulated plains and low hills	LP	Medium semi-deciduous and semi-evergreen forests
	Hill-billie plains	LP/GL	Medium semi-evergreen forest and cultivated pastures
	hills and low mountain	LP/PH/VR	Low and medium semi-evergreen forests, cultivated pastures
Karst	subhorizontal plains	LP/CM	Low deciduous forest, medium semi-evergreen forest, agriculture
	undulating and hilly plains	LP/GL/PH	Low semi-deciduous forest, medium semi-deciduous forest, agriculture
	Hills	LP/LV/GL	Low semi-evergreen forest, medium semi-evergreen and semi-deciduous forests, cultivated pastures
Gypsum karst	No Subtypes	PH/LP/VR	High and medium semi-evergreen forest
Mixed	Data depend on place and observability at scales of 1:50,000		

face dedicated to agriculture in the state and also the one with the greatest heterogeneity of soils. The pseudopaludal environment occupies 21.89 % of the state surface. It shows three main types of geoforms: sub-horizontal rolling plains that are slightly dissected, rolling plains, and areas of knolls and mountains.

The first type, which has lower vertical dissection and higher precipitation (Aw^1x'), can be found next to the paludal environment, on the formations of the Miocene, Oligocene and Pliocene (Bacalar, Estero Franco and Carrillo Puerto). The low slope favors hydromorphic conditions and the development of soils such as Gleysol/Leptosol/Luvisol, with low and medium semi-evergreen forests.

The second type of geoforms, to the west, in the oldest formations of the late Mesozoic, upper Cretaceous (Peten Limestone), over rolling plains, the accumulation of materials has allowed the development of deeper soils. The most common are an association between Gleysols, Vertisols and Luvisols, with medium and low semi-evergreen forests, in addition to agricultural areas and cultivated grassland.

The third type of geoform can be found on the plains with hills and knolls slightly dissected, located in the south of the state; the representative soils are Vertisols, Gleysols and Phaeozems. The most important agricultural activity of the state is carried out on this area (Fig. 2).

Tecto-Karstic Environment

This environment appears where two simultaneous characteristics occur: a medium or high density of faults and a high density of karst depressions (sinkholes, uvalas and poljes). Depending on the vertical dissection, the geology and soils, three subtypes of tecto-karstic environment can be identified: sub-horizontal and undulating plains, plains with hills and knolls, and mountains.

The tecto-karstic environment found in sub-horizontal plains occupies the largest area (29.76 %); it is located in the northernmost part of the state of Quintana Roo, over recent geological formations (Pliocene and Quaternary); the dom-

Table 3. Surface occupied by different geomorphic environments.

Geomorphic Environments	Surface Area, km^2	Surface Area, %
Erosive-accumulative littoral	627.63	1.24
Accumulative littoral	534.33	1.06
Paludal	5708.04	11.28
Pseudopaludal, undulating plains and low hills	5424.13	10.72
Pseudopaludal, undulating plains	2201.61	4.35
Pseudopaludal, knolls and hills	3448.34	6.82
Tectokarst, undulating plains and low hills	11948.51	23.62
Tectokarst, knoll plains	2323.02	4.59
Tectorkarst, hills and low mountains	784.25	1.55
Karst of subhorizontal plains	7684.82	15.19
Karst, undulating plains and low hilly	5464.91	10.80
Karst, hills	1653.00	3.27
Gypsum	2753.51	5.44
Reefs	37.61	0.07
Total	50593.71	100.00

inant vegetation is medium sub-evergreen forest growing on Leptosols. However, there are also areas with presence of Leptosols/Luvisols (negative tecto-karst like sinkholes, uvalas, caves and underground rivers) (Fig. 2). A second zone with tecto-karstic environment is found on the hilly plains of the central-western part of the state over the Eocene formation (Chichen Itza); this zone is dominated by Leptosols and Gleysols, which are used for man-induced grasslands. The third zone occupies the smallest area and is located over the oldest formations of Quintana Roo (Icaiché), on knolls and mountains located in the western region of the state (dissolution formations associated to faults and fractures or positive tecto-karst), where deeper soils have developed in the lower parts. The dominant soils are Leptosols, Phaeozems and Vertisols, with medium semi-evergreen forest.

Karstic Environment

This environment is produced by the dissolution processes of limestone, involving rainfall, halo-phreatic mixing of groundwater and vegetation, which produce negative exokarstic (sinkhole, uvalas and poljes) (Fig. 2) and endokarstic (caves and caverns) relief formations. This environment occupies 29.26 % of the surface of the state of Quintana Roo, similar to the tectokarstic environment.

The karstic environment has three subtypes: in the sub-horizontal plains to the north of Quintana Roo; in the undulated and hilly plains of the central part; and in the knolls located to the west. The sub-horizontal plains of the karstic environment to the north of the state occupy small areas scattered among tecto-karstic zones. The karstic zones to the south and the central part of the state occupy large areas, where the relief starts to get higher. Representative soils are Leptosols and Cambisols, with low and medium semi-evergreen forests.

Karsticity decreases toward the west, as well as the size of the areas occupied by this environment. The undulating and hilly plains have deeper soils, the most common of which are Leptosols, Gleysols and Phaeozems, with low and medium semi-deciduous forests. Leptosols, Luvisols and Gleysols can be found among knoll areas with both medium semi-evergreen and semi-deciduous forests, as well as in some places with low semi-evergreen forest.

Gypsum Karstic Environment

This environment occurs in the oldest geological formations of the state of Quintana Roo (Upper Cretaceous and Paleocene), in the extreme west, which is the highest area, containing gypsum bedrock, where mountains, knolls and undulating plains are formed (Fig. 2). It has Leptosols on the slopes and Vertisols in the valleys, where materials accumulate under the influence of a strong karstification process. The dominant soil association is Phaeozem/Leptosol/Vertisol, with high and medium semi-evergreen forests.

Mixed Environment

This environment can be identified in some areas of the state when working at a scale of 1:50,000 or more detail. These are small areas that contain several geomorphoedaphic environments. In the north of the state, for example, these areas contain coastal, paludal, pseudopaludal and karstic environments.

Discussion

Geomorphic Environments

Quintana Roo has a great diversity of environments; however, maps of the Yucatan Peninsula with a scale of 1:500,000 do not show this (INEGI, 2000a; Bautista et al., 2011). A physiographic approach with which these maps were made, based on the types of rock and relief, distinguish only three physiographic subprovinces in the state of Quintana Roo (INEGI, 2000a). Using the traditional geopedological approach, Bautista et al. (2011) identified six geomorphic environments (coastal, fluvio-paludal, tecto-karstic and three karst subtypes). On the other hand, using a combined geomorphological and digital approach, seven environments and 12 subtypes were identified.

The geomorphic environments reported in this study were identified based on the dominant soil-forming processes in each of them, and their combinations within a defined hierarchical model. This hybrid approach, based on a hierarchical classification system, allows creation of accurate definitions of the environment types, and even allows assessment of each definition's accuracy (Zinck, 2012; Hall et al., 2009).

At the scale used in this study, the variable "vegetation" does not allow determination of the soil distribution; only some extremely particular types of vegetation, such as mangrove, can identify a soil group. Nevertheless, it is not a determining factor (Peris et al., 1994; Leyva et al., 2009). Additionally, vegetation serves to confirm the congruence between relief and soils, as in the case of plains with karst depressions, Gleysols and low semi-evergreen forest, or Arenosols and xerophilous scrub (Leirana-Alcocer et al., 2004), or Solonchack and halophilic scrub (Leirana-Alcocer et al., 2004).

The karst terrain gives the geomorphic environments reported in this study certain characteristics, such as, the presence of calcium carbonate, the presence of Leptosols, soils with pH values ranging from neutral to basic, and abundance of calcium ions. Arenosols and Regosols had particles with abundant calcium carbonate, which make these soils very different to Arenosols and Regosols from other parts of the country.

One of the greatest advantages of the method used in this study is its replicability. Being based on a hierarchical system, its categories are well defined, excluding subjective assessments. New information technologies, that can manage and analyze large volumes of information in a short time, make it possible to use this method in other areas and at different scales, in a relatively straightforward manner (Gessler et al., 1995; MacMillan et al., 2005; Hartemink et al., 2013).

The statistical analysis used in this study (cluster analysis, principal components analysis and classification analysis) indicated that, of the variables considered, vertical dissection, karstic formations, climate and geology have the greatest weight in the distribution of geomorphic environments.

Soils

According to Hall and Olson (1991; in Bautista et al., 2007), the variability of soils is both systematic and random. Systematic variability is predictable and associated with relief (edaphic landscapes), while random variability occurs when one of the soil-forming factors exerts its influence with greater intensity (Bautista et al., 2011; Mulder et al., 2011; Hu, 2013; Lagacherie et al., 2013).

Systematic variability, for example, can be observed in the presence of Arenosols in the littoral environment, originating and depicting an identifiable pattern. An example of random variability is the presence of Leptosols across the entire study area in markedly different geoforms and climatic conditions and no identifiable distribution pattern.

The characterization of the landscape formations allows both to understand the existing relationships between geoforms and soils and to identify the degree of development of landscape. For instance, the presence of Leptosols is more frequent in the lower part of the system of slightly inclined and incised hilly plains. Whereas in the south, where hills are found in greater density and with greater inclination, Leptosols are less frequent and the presence of richer and deeper soils, such as Phaeozems and Luvisols, increases. This could indicate that the wideness of the intermontane valleys is related to these soil formations in a similar way that the extension of catenae in the state of Yucatan is related to the soils associated with them, as reported by Bautista et al. (2004, 2015), by Berg and Oliveira (2000a, 2000b) in Brazil, by Fonseca (2010) in Portugal, Hennemann and Nagelhout (2004) in Kenya, by Lo Curzio (2009) in Italy and Möller et al. (2008) in Germany.

Time as a soil-forming factor is spatially expressed; thus, the oldest karst zones are in the south and west of the state of Quintana Roo, while the more recent zones are located on the coast (north and center) not considering Quaternary deposits as rocks. In the same way, the most frequent and predominant soil groups in the most recent (or with the shortest exposure time) karst area, are the less developed ones (those with AC horizons), while the more developed soils (those with ABC horizons) are in the center and south of the state, as reported by Bautista et al., (2011).

The relief irregularities produced by the karstification process, when the depressions were formed, explains the presence of different soils within small areas located in other parts of the Yucatan Peninsula, as reported by Bautista et al. (2003, 2004, 2015 , Kueny and Day (2002), Day (2010) and Aguilar et al. (2016).

Conclusions

This new hybrid, methodological proposal, which includes the classical approach to the study of geomorphic environments and reliefs and a method based on digital soil maps, has made it possible to: a) increase the identification of seven geomorphic environments and 12 variants, while also representing the interaction of its components and dynamics; b) identify the environmental factors that explain spatial variability; c) infer soil information in unsampled geomorphic environments; d) validate the generated map by calculating that the uncertainty of geomorphic environmental representation, for which there is no soil information, is 16%.

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