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Geodiversity of Mexico

Geodiversidad de México

Jean-François Parrot,* Carolina Ramírez Núñez** y José Luis Palacio Prieto***

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Abstract. Geodiversity is defined by constituents that include geology, geomorphology, soils, surface waters and groundwater. Here, geodiversity sub-indices are calculated in units of 625 km^2 on the basis of three sub-indices, geology (75 types of rock), geomorphology (22 types of landforms) and 29 soil types, expressed in raster images with a resolution of 500 m, and a cell of 25 × 25 km. The number of topics that a cell can contain allows calculating the sub-indices according to the maximum total number of topics contained in each cell in relation with the pixel resolution and the cell size. The sub-index value is directly proportional to the increase in cell size, that is, the larger the cell size, the greater the number of topics contained per cell. The sum of the results concerning the sub-indices is weighted to calculate the Geodiversity index. The results indicate that 1.44% of the Mexican territory has a very high geodiversity and in 19.45% it is high; together, these classes include the northwest and south of the country (Sierra Madre del Sur, states of Guerrero and Oaxaca). 57.56% of Mexico has medium geodiversity and 21.19% has low geodiversity; these medium and low indices are in mountainous areas, the Mexican Altiplano and a considerable portion of the Baja California and Yucatán peninsulas. The very low geodiversity is concentrated in the Yucatán Peninsula. The relatively high degree of geodiversity across a large part of the Mexican territory indicates a high potential for geoconservation and consequently the need for appropriate management.

Keywords: Geodiversity Index, geological diversity, geomorphological diversity, soil diversity, geospatial data management.

Resumen. La geodiversidad se define por componentes que incluyen la geología, la geomorfología, los suelos, las aguas superficiales y las aguas subterráneas. En este artículo, el índice de geodiversidad se calculó en unidades de 625 km^2 considerando solamente tres subíndices: geología (75 tipos de roca), geomorfología (22 tipos de formas del relieve) y 29 tipos de suelos, expresados en imágenes rasterizadas con una resolución de 500 m y una celda de 25 × 25 km. El número de tipos que puede contener una celda corresponde a la base de información que permite calcular los índices. El máximo del número total de tipos que contiene una celda depende de la resolución del pixel y del tamaño de la celda. Por ejemplo, en el caso de la geología, el número máximo de tipos que puede contener una malla de 625 km^2 es igual a 11 (2 500 pixeles es decir 0.03% de la superficie de la República Mexicana); para una malla de 2 500 km^2 el máximo es igual a 12 (30 000 pixeles que representan 0.38%) y para una malla de 10 000 km^2 el máximo es de 16 (120 000 pixeles que corresponden a 1.54%). El valor de diversidad es directamente proporcional al aumento del tamaño de la celda, es decir, cuanto mayor es el tamaño de la celda, mayor es el número de temas contenidos por celda.

* Laboratorio de Análisis GeoEspacial [LAGE], Instituto de Geografía, UNAM. Circuito de la Investigación Científica s/n, 04510, Ciudad de México, CDMX, México. ORCID: https://orcid.org/0000-0001-7528-9054. Email: parrot@geografia.unam.mx
** Escuela Nacional de Ciencias de la Tierra [ENCiT], UNAM. Circuito de la Investigación Científica s/n, 04510, Ciudad de México, CDMX, México. ORCID: https://orcid.org/0009-0000-8130-6420. Email: cramirez@encit.unam.mx. Corresponding author.
*** Departamento de Geografía Física, Instituto de Geografía, UNAM. Circuito de la Investigación Científica s/n, 04510, Ciudad de México, CDMX, México. ORCID: https://orcid.org/0000-0001-6651-0255. Email: palacio@unam.mx

El índice de geodiversidad y los tres subíndices que se utilizan para llegar al resultado final se calculan de la manera siguiente utilizando una malla de celdas cuadradas:

El número de tipo (*nc*) que caracteriza a una variable (por ejemplo, 22 tipos de formas del relieve) permite definir, en el módulo Map_Explor, el número de histogramas (*hist[nc]*) necesarios para calcular el subíndice de esta variable. Antes de ingresar a una celda, todos los histogramas *hist[nc]* se inicializan a cero. Después, se lee la imagen en función del *raw order*; un valor *nc* de pixeles, dentro de cada celda, produce un incremento de 1 del histograma *hist[nc]* correspondiente. De esta manera, se obtiene una distribución de los valores *nc* dentro de la celda y según el número de histogramas cuyo contenido es mayor que cero, se obtiene el valor del subíndice de la variable estudiada; así, este índice corresponde directamente al número de histogramas *hist[nc]* no vacíos.

Finalmente, utilizando el módulo Diversity_Index, el tratamiento suma, en cada celda *k*, el valor de los tres subíndices y distribuye las celdas en cinco niveles de diversidad (muy bajo, bajo, medio, alto, muy alto) utilizando el siguiente proceso (ecuación 2). En cada celda *k*, se suman los rangos alcanzados por todas las variables; esta suma se divide por el valor de la suma del rango máximo alcanzado para cada variable en toda la imagen y, por último, el resultado de esta división se multiplica por el valor *n* que corresponde al número de niveles de diversidad considerado, aquí 5.

Es posible ponderar los tres subíndices de diversidad para saber cuál de estos subíndices juega un papel importante en la definición de la geodiversidad.

Los resultados indican que 1.44% del territorio mexicano tiene una geodiversidad muy alta y en 19.45% es alta; en conjunto, estas clases incluyen el noroeste y sur del país (Sierra Madre del Sur, estados de Guerrero y Oaxaca). Por otro lado, 57.56% de México tiene geodiversidad media y 21.19% tiene geodiversidad baja; estos índices medios y bajos se encuentran en zonas montañosas, el Altiplano mexicano y una porción considerable de las penínsulas de Baja California y Yucatán. La geodiversidad muy baja se concentra en la Península de Yucatán. El grado relativamente alto de geodiversidad en gran parte del territorio mexicano indica un alto potencial para la geoconservación y en consecuencia la necesidad de un manejo adecuado.

Cabe señalar que, para definir una conservación integral de los recursos, se necesitaría contemplar en un análisis posterior no solamente la geodiversidad y accesoriamente la morfodiversidad que requiere de un Modelo Digital de Elevación preciso de la totalidad del territorio mexicano, sino también, la biodiversidad asociada, lo que implica un análisis de la cobertura vegetal, del nivel de protección ambiental, del uso del suelo y su grado de degradación, así como del impacto de la actividad humana, calculando un índice de amenaza para definir la sociodiversidad.

Palabras clave: Índice de Geodiversidad, diversidad geológica, diversidad geomorfológica, diversidad de suelos, análisis geoespacial.

INTRODUCTION

"Geodiversity is the natural variety of the Earth's surface, referring to geological and geomorphological aspects, soils, and surface waters, as well as other systems created as a result of both natural processes (endogenous and exogenous) and human activity. Geodiversity and biodiversity are the two elements that determine the possibility of supporting sustainable development" (Kozłowski, 2004).

Recently, this concept has gained international relevance in scientific and political decision-making spheres (Gray, 2008; Gordon et al., 2012; Erikstad, 2013; Comer et al., 2015). Despite a certain initial skepticism about its validity, the concept has demonstrated its usefulness regarding environmental conservation in the current context of climate change (Prosser et al., 2010; Brazier et al., 2012; Brown et al., 2012) and in practical economic aspects related to tourism and the promotion of Geoparks as an alternative model for the protection and conservation of landscapes (Posada Ayala et al., 2014).

Geodiversity in specific territories has been a topic addressed by various specialists. Most of these studies correspond to regions of more or less limited extension of hundreds or thousands of km^2 (Pereira et al., 2013; de Paula et al.; 2015, Bétard and Peulvast, 2019; dos Santos et al., 2020; Dias et al. 2021); although there are also examples at the national level (de Paula Silva, 2021; Alberico et al., 2023; Esmaili, 2024: these three studies refer to Brazil, Italy and Iran, respectively) and even continental (Wolniewicz, 2023, referring to Europe). In all the previous cases, the data consistently include three variables to define geodiversity: geology (rock types), geomorphology (relief units) and soil types. Each of these variables represents a sub-index from which a general Geodiversity index is obtained.

For the purposes of this work, a Geodiversity index was developed based on three main components (geology types of rocks, geomorphological units and main soil types). The information sources used correspond to the most up-to-date maps of Geology, Geomorphology and Soils on a 1: 5 000 000 scale, to be published in the National Atlas of Mexico (ANM, *in press*).

The calculation of the subindices generally uses a grid of square cells within which the number of topics (for example, geological formations) is recorded. Overall diversity is an integer value that indicates how many different topics are observed in each unit area, whether this be a cell, or region or country.

Selection of the cell size will depend on the characteristics of the data and on the purpose of the analysis, whether this be based on lithology and geomorphology (Lopes et al., 2023) or on a variety of physical elements such as geology, geomorphology, hydrology, and soils (Serrano et al., 2007).

The grid system (Pereira et al., 2013) is easy to use, and is the basis of many common tools in Geographic Information Systems (e.g. Raster Calculator in QGIS or ArcGIS).

In this work, a first national map of the Geodiversity of Mexico is created, defined from geological diversity (types of rock), geomorphological diversity (types of landforms) and soil types.

DATA USED

The data are derived from a set of maps of the geology (Ferrari et al., *in press*), geomorphology (Zamorano et al., *in press*) and soils (Cruz-Gaistardo et al., *in press*) of Mexico, which are included in Section III of the National Atlas of Mexico (ANM, *in press*). These data were rasterized to obtain ascii type images; the scale of the source maps is 1: 5 000 000 with a pixel spatial resolution of 500 × 500 meters.

a) Geology

The map of the geology of Mexico (Ferrari et al., *in press*) refers to 75 rock types (see Table 1).

b) Geomorphology

Table 1. Rock types of Mexico.

#	Code	Era	Period	%
Continental sedimentary				
1	Csc	Cenozoic	Miocene	21.723
2	Qc	Cenozoic	Quaternary	10.478
3	Qe	Cenozoic	Quaternary	1.554
4	Jc	Mesozoic	Lower Jurassic	0.304
5	Ksc	Mesozoic	Upper Cretaceous	0.158
6	Pgc	Cenozoic	Paleocene	0.127
7	Jmc	Mesozoic	Middle Jurassic	0.018
8	Psc	Paleozoic	Permian	0.005
		Subtotal		34.37
Continental volcanic igneous				
9	Peov	Cenozoic	Eocene-Oligocene	13.549
10	Qtpv	Cenozoic	Pliocene-Quaternary	5.446
11	Mv	Cenozoic	Miocene	2.452
12	Nmiv	Cenozoic	Miocene	2.325
13	KsPgv	Mesozoic	Upper Cretaceous	1.275
14	Nmb	Cenozoic	Miocene	0.591
15	Tv	Cenozoic	Paleocene	0.149
16	Jv	Mesozoic	Lower Jurassic	0.010
		Subtotal		25.80
Marine sedimentary				
17	K	Mesozoic	Lower Cretaceous	6.033
18	Ks	Mesozoic	Upper Cretaceous	4.145
19	Te	Cenozoic	Eocene	3.736
20	N	Cenozoic	Miocene	2.352
21	Tm	Cenozoic	Miocene	2.127
22	Ki	Mesozoic	Lower Cretaceous	2.083
23	Tpa	Cenozoic	Paleocene	1.690

Table 1. Rock types of Mexico (Part 2).

#	Code	Era	Period	%
24	To	Cenozoic	Oligocene	0.869
25	Q	Cenozoic	Quaternary	0.780
26	Js	Mesozoic	Upper Jurassic	0.471
27	Ps	Paleozoic	Permian	0.190
28	Pi	Paleozoic	Cambrian	0.099
29	KiJs	Mesozoic	Upper Jurassic	0.073
30	J	Mesozoic	Lower Jurassic	0.060
31	Ji	Mesozoic	Lower Jurassic	0.035
32	PTs	Proterozoic	Upper	0.019
33	P	Paleozoic	Carboniferous	0.015
34	TR	Mesozoic	Triassic	0.005
		Subtotal		24.78
		Granitic and gabroid intrusive igneous		
35	PgKsgr	Mesozoic	Upper Cretaceous	1.892
36	Pggr	Cenozoic	Paleocene	1.500
37	Ksgr	Mesozoic	Upper Cretaceous	1.396
38	Psgr	Paleozoic	Permian	0.698
39	Tgr	Cenozoic	Paleocene	0.296
40	Ngr	Cenozoic	Miocene	0.055
41	Jgr	Mesozoic	Lower Jurassic	0.024
42	PTmgr	Proterozoic	Middle	0.016
43	Kgb	Mesozoic	Lower Cretaceous	0.006
44	Tgb	Cenozoic	Paleocene	0.003
45	TRgr	Mesozoic	Triassic	0.001
		Subtotal		5.89
		Marine sedimentary igneous volcano		
46	KJsvs	Mesozoic	Upper Jurassic	1.124
47	Mvs	Mesozoic	Triassic	1.050
48	Kivs	Mesozoic	Lower Cretaceous	0.570
49	Jivs	Mesozoic	Lower Jurassic	0.112
50	Mivs	Mesozoic	Triassic	0.048
51	Jmet	Mesozoic	Upper Jurassic	0.007
52	Ksvs	Mesozoic	Upper Jurassic	0.003
53	Psvs	Paleozoic	Permian	0.002
		Subtotal		2.92
		Regional metamorphic		
54	Mmet	Mesozoic	Triassic	0.698
55	Pimet	Paleozoic	Cambrian	0.614
56	Kmet	Mesozoic	Lower Cretaceous	0.508
57	PTmmet	Proterozoic	Middle	0.394
58	TRmet	Mesozoic	Triassic	0.143
59	Psmet	Paleozoic	Carboniferous	0.073
60	Mmil	Mesozoic	Triassic	0.069
61	PTimet1	Proterozoic	Lower	0.040
62	Pmet	Paleozoic	Cambrian	0.024
63	PTimet2	Proterozoic	Lower	0.021
64	Tmet	Cenozoic	Paleocene	0.003
		Subtotal		2.59
		Igneous continental sedimentary volcano		
65	Tmvsc	Cenozoic	Miocene	1.642
66	Pgvsc	Cenozoic	Paleocene	0.632
67	KsPgvsc	Mesozoic	Upper Cretaceous-Paleogene	0.166
68	Tvsc	Cenozoic	Paleocene	0.070
		Subtotal		2.51
		Mixed sedimentary		
69	Temx	Cenozoic	Eocene	0.413
70	Ksmx	Mesozoic	Upper Cretaceous	0.380
71	Tpmx	Cenozoic	Pliocene	1.124
72	Jmmx	Mesozoic	Middle Jurassic	0.117
73	Mimx	Mesozoic	Triassic	0.065
74	Tpamx	Cenozoic	Paleocene	0.009
75	Psmx	Paleozoic	Permian	0.001
		Subtotal		1.15

Source: Ferrari et al. (in press).

Concerning geomorphology, Zamorano et al. (*in press*) refer to 22 topics (Table 2).

c) Soils

Cruz-Gaistardo et al. (*in press*) reports 28 dominant soils and 1 dominant horizon topics in Mexico.

METHODOLOGY

Two specific programs were developed: **Map Explor** (Parrot, 2023a) calculates the value of the subindices using a grid of square cells, or a moving square or circular window; **Diversity_index** (Parrot, 2023b) follows the scheme proposed by various geographic information systems, calculates the sum of the three subindices that make up geodiversity (in this case geology, geomorphology and soils) and normalizes the result based on the user-defined number of classes.

An essential notion in the raster world establishes the relationship that exists between the range *R* and the size *m* of the side of a square element (cell or moving window). This side corresponds to and the range *R* depends on the size *m* of the pixel side and the desired viewing surface *S* as follows:

$$R = \left(\left(\sqrt{S'/_{side^2}}\right) - 1\right)/2 \qquad (1)$$

Table 2. Relief units of Mexico.

	Relief units	%
1	Cumulative proluvial ramps	15.69
2	Mountains and plateaus of volcanic origin with intense erosive-fluvial modeling	14.33
3	Proluvial-aeolian plains	9.80
4	Folded sedimentary mountains	9.78
5	Volcanic and sedimentary relief	8.79
6	Sedimentary hills	8.01
7	Recent cumulative volcanic relief	7.00
8	Complex detrital ramps	5.60
9	Block mountains	3.57
10	Karst platform with high development of surface and underground relief	3.40
11	Marginal plains	3.05
12	Fluvio-deltaic plains	2.75
13	Complex marine plains	2.23
14	Karst platform with heterogeneous deltaic covers	1.55
15	Cumulative plains with limited fluvial dissection	1.20
16	Karst platforms with structural control	1.15
17	Intermontane proluvial cumulative ramps	1.04
18	Lacustrine-aeolian endorheic basins	0.37
19	Monogenetic volcanic fields	0.31
20	Composite volcanoes and products associated with moderate-severe river erosion	0.20
21	Tectonic trenches	0.09
22	Composite volcanoes and products associated with incipient to moderate river erosion	0.08

Source: Zamorano et al. (in press).

with m in meters, S in km^2 and $S' = S \times 1\,000\,000$

In the present case, m is 500 m and the observation area in each cell is 625 km^2 (25 km × 25 km). The results were compared on the basis of two greater sizes: 2 500 km^2 (50 km × 50 km) and 10 000 km^2 (100 km × 100 km). In the case of geology, for example, the maximum number of types that a 625 km^2 cell can contain is 11 (2 500 pixels, or 0.03% of the surface of the Mexican Republic); for a 2 500 km^2 cell, the maximum is 12 (30 000 pixels, representing 0.38%) and for a 10 000 km^2 cell, the maximum is 16 (120 000 pixels, corresponding to 1.54%). As expected, the diversity value in each element of the grid grows in relation to the increase in cell size (see Figure 1), that is, the larger the cell size, the greater the number of topics contained per cell.

The values presented above come from the application of the following variables:

R = 25 (with m = 500 and S = 625); and $c = (R \times 2) + 1 = (25 \times 2) + 1$; and according to the cell size c (in pixels), the surface (in pixels) = R^2 = 51 × 51 = 2 601, that is to say a cell surface in km^2 = 650.250 with a pixel of 500 × 500 meters.

Thus, the recalculated area is close to the value defined by the user, namely 625 km^2 (25 km × 25 km).

The number of topics (nc) that characterize a variable (i.e., 7 classes [segments] for the slope) allows defining the number of histograms (*hist[nc]*) needed to calculate the diversity subindex In_{div} of this variable. Before entering a cell, all the *hist[nc]* histograms are initialized to zero. Then, by scanning the image within each cell, a pixel nc value produces an increment of 1 of the corresponding *hist[nc]* histogram. Thus, a distribution of the nc values within the cell is obtained and according to the number of histograms whose content is greater than zero, the value of the diversity subindex In_{div} is obtained; this index corresponds directly to the number of not empty *hist[nc]* histograms.

Regarding geology, application of this calculation to the 75 rock types (Table 1) results in 8 groups or classes that correspond to the number of topics per cell (Table 4).

Regarding geomorphology, application to the 22 relief units (Table 2), results in 6 classes (Table 5).

Regarding soils, application to the 29 types (Table 3) results in 12 classes; classes 11 and 12 that only contain one soil type per cell are not reported in the Table 6.

The most frequent number of topics per cell was 3 for geology, 2 for geomorphology and 4 for soils (27.38% for geology, 42.62% for geomorphology and 29.40% for soils) (Figure 2).

The **Map_Explor** module generates, for each variable, a map of the number of topics per cell according to the cell size. It is possible to superimpose the grid of cells if necessary.

The **Diversity_index** module that sums the subindices also draws the grid of square cells and generates a detailed report on the treatment and results.

Finally, the treatment distributes the cells into 5 levels of diversity (very low, low, medium, high,

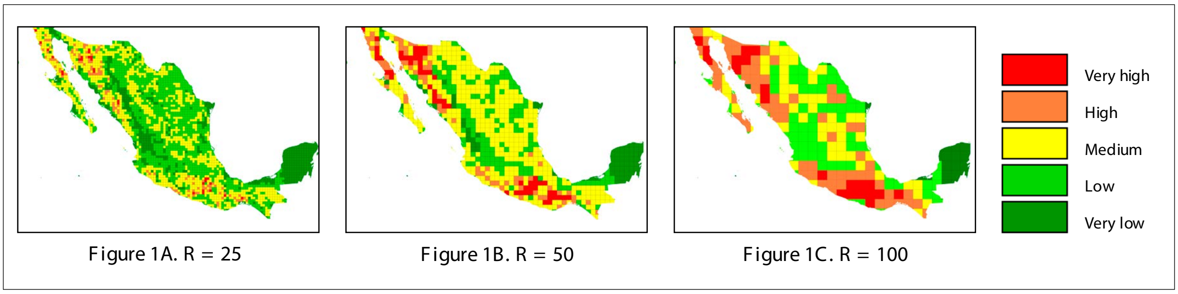

Figure 1. Influence of cell size on the number of topics per unit area (cell) used in maps of Mexico. In general, the larger the cell the greater the number of topics contained (the diversity index, In_{div}).

Table 3. Soil topics of Mexico.

	Soil type	%
1	Leptosols	29.375
2	Regosols	13.425
3	Calcisols	10.982
4	Phaeozems	10.944
5	Luvisols	8.877
6	Vertisols	7.641
7	Cambisols	4.154
8	Arenosols	1.834
9	Solonchaks	1.831
10	Kastanozems	1.703
11	Andosols	1.393
12	Gleysols	1.330
13	Chernozems	1.176
14	Fluvisols	0.890
15	Umbrisols	0.865
16	Acrisols	0.585
17	Durisols	0.558
18	Solonetz	0.514
19	Nitisols	0.475
20	Planosols	0.446
21	Histosols	0.308
22	Gypsisols	0.291
23	Alisols	0.129
24	Tecnosols	0.097
25	Stagnosols	0.087
26	Lixisols	0.067
27	Ferralsols	0.011
28	Natric horizon	0.007
29	Plinthosols	0.003

Source: Cruz-Gaistardo et al. (in press).

very high); for each cell k, this process uses the following normalization:

$$Val_{(k)} = \left({}^{Val_{Sum(k)}} / {}_{Val_{Max}} \right) \times n \qquad (2)$$

where $Val_{(k)}$ is the normalization value of the cell k, $Val_{Sum(k)}$ is the value of the sum of the ranks reached by all the variable in the cell k, Val_{Max} is the value of the sum of the maximum rank reached

Table 4. Number of classes (rock types per cell).

Topics per cell	Number of classes	Surface (pixels)	Surface (km²)	Percentage %
1	278	722,898	18,0724.5	9.33
2	743	1,931,345	482,836.25	24.95
3	815	2,121,071	530,267.75	27.38
4	547	1,423,748	355,937.00	18.38
5	338	879,032	219,758.00	11.37
6	154	400,891	100,222.75	5.17
7	76	196,649	49,162.25	2.53
8	19	48,733	12,183.25	0.63
9	6	15,606	3,901.50	0.20
10	1	2,601	650.25	0.03
11	1	2,601	650.25	0.03

Table 5. Number of classes (relief units per cell).

Topics per cell	Number of classes	Surface (pixels)	Surface (km²)	Percentage (%)
1	469	1,219,413	304,853.25	15.74
2	1269	3,300,658	825,164.50	42.62
3	938	2,440,227	610,056.75	31.51
4	265	689,553	172,388.25	8.90
5	33	84,943	21,235.75	1.10
6	4	10,381	2,595.25	0.13

Table 6. Number of classes (Soil type per cell).

Topics per cell	Number of classes	Surface (pixels)	Surface (km²)	Percentage (%)
1	56	145,805	36,451.25	1.88
2	347	902,006	225,501.50	11.65
3	831	2,160,149	540,037.25	27.89
4	876	2,277,416	569,354.00	29.40
5	534	1,387,793	346,948.25	17.92
6	235	611,633	152,908.25	7.90
7	72	187,972	46,993.00	2.43
8	21	54,440	13,610.00	0.70
9	6	15,431	3,857.75	0.20
10	1	2,530	632.50	0.03

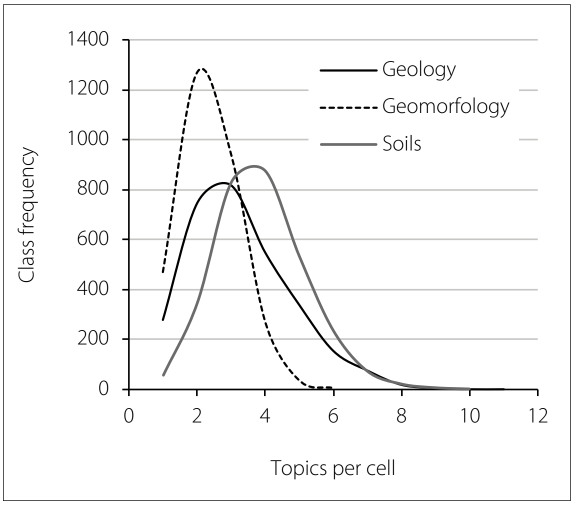

Figure 2. Number of topics per cell for each subindex.

for each variable in the whole image and *n* is the diversity levels, here 5.

It is possible to weight the three diversity subindices to know if one of these subindices plays a major role in defining the geodiversity.

RESULTS

As mentioned above, subindices were obtained for the diversity of rocks, relief units and soil types, derived from the corresponding maps contained in the National Atlas of Mexico (Ferrari et al., *in press*; Zamorano et al., *in press*; Cruz-Gaistardo et al., *in press*).

Geological diversity (Figure 3) is greatest in the northwest and south of the country. The first region includes parts of the states of Baja California, Sonora, and Sinaloa, while the second includes portions of the Sierra Madre del Sur and the Sierra de Chiapas (states of Guerrero, Oaxaca and Chiapas). The diversity is lower in the Sierra Madre Occidental, the Mexican Altiplano, the Trans-Mexican Volcanic Belt and part of the Gulf Coastal Plain and is markedly low in the Yucatán Peninsula. Lithology and tectonics determine much of the geological diversity.

Geomorphological diversity (Figure 4) is very low in the Baja California Peninsula, the Sierra Madre Occidental, the Trans-Mexican Volcanic

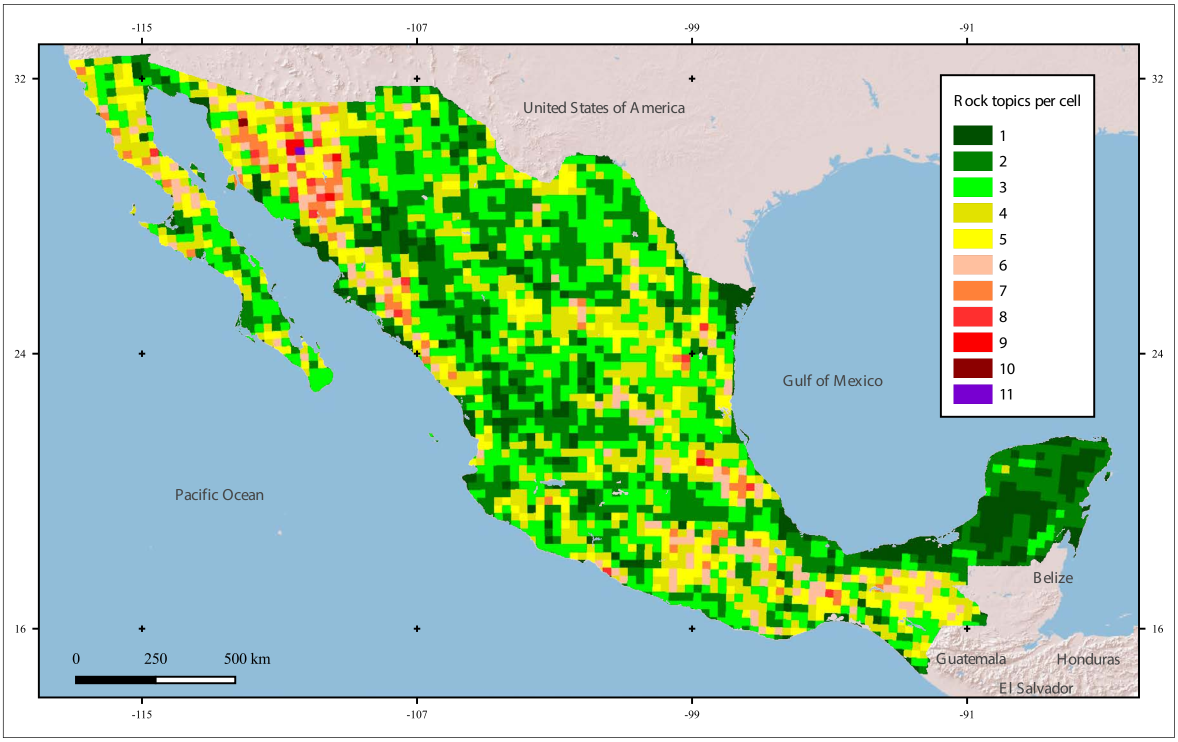

Figure 3. Geological diversity across Mexico.

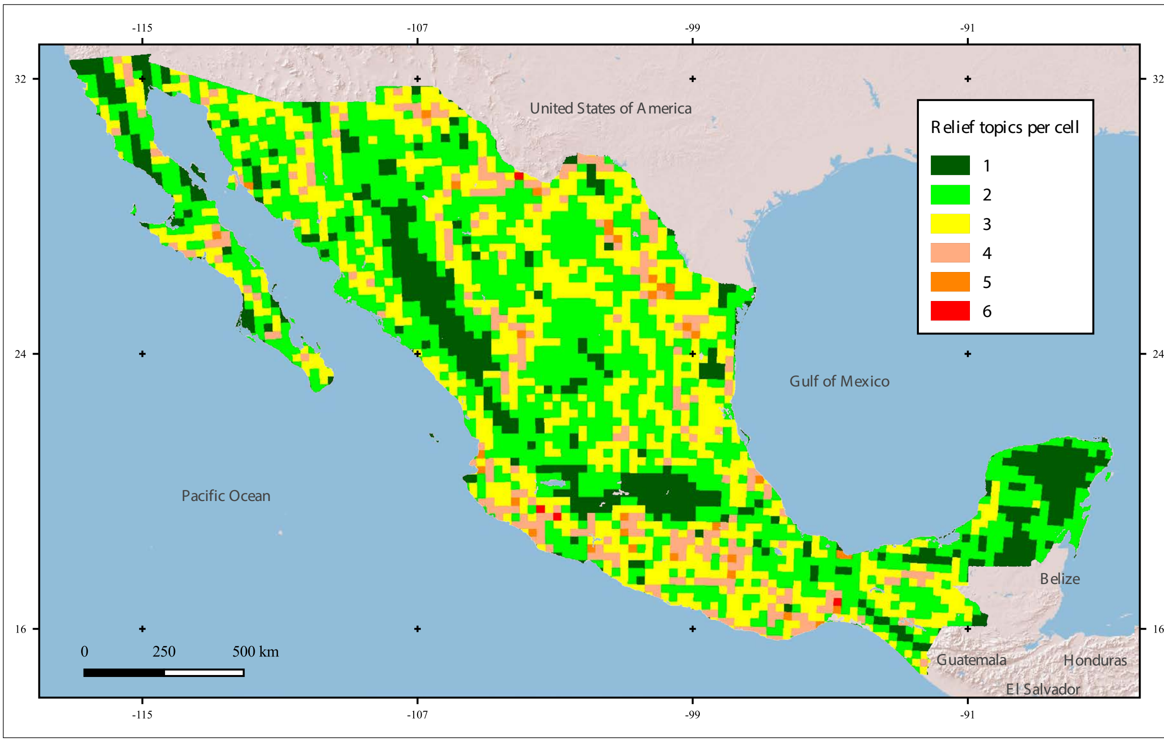

Figure 4. Geomorphological diversity across Mexico.

Belt and the plain of the Yucatán Peninsula. The areas with low diversity are in the Mexican highlands, the hilly areas in the south of the Yucatán Peninsula, and in some of the coastal plains of the Gulf of Mexico such as the low plain of the Coatzacoalcos and Grijalva rivers. Intermediate and high values of geomorphological diversity are mainly in the Sierra Madre del Sur and portions of the Sierra Madre Oriental. In general, the geomorphological variable introduces a pattern of heterogeneity in most of the country's physiographic provinces.

Soil diversity (Figure 5) is more generally dispersed. In general, it is very high and high in the central-eastern zone of the Trans-Mexican Volcanic Belt, in the Sierra de Chiapas and in the north of Chihuahua. Diversity is low or very low in the Baja California Peninsula, northern Nuevo León and Coahuila, the Mesa del Centro, areas of the Balsas Depression and the Gulf Coastal Plain and the Yucatán Peninsula.

A geodiversity map of Mexico was derived from the sum of the three subindices (Figure 6, Table 7). It is very high across 1.44% of the land and high across 19.45% and reflects a wide variety of rock types (sedimentary, igneous, and metamorphic of diverse ages) in the northwest and in the south (generally corresponding to the Sierra Madre del Sur in the states of Guerrero and Oaxaca).

Areas of medium geodiversity are scattered across 57.56% of the land area. When this is considered together with the 21.19% of the land with low geodiversity, this ~79% forms a continuum that includes most of the mountainous areas of the country, as well as the Mexican Altiplano and a considerable area of the two peninsulas (Baja California and Yucatán).

Geodiversity is very low across only 0.36% of the land, all of it on the Yucatán Peninsula, a low-altitude platform lacking notable geomorphological contrasts and with a lithological composition dominated by marine sedimentary rocks.

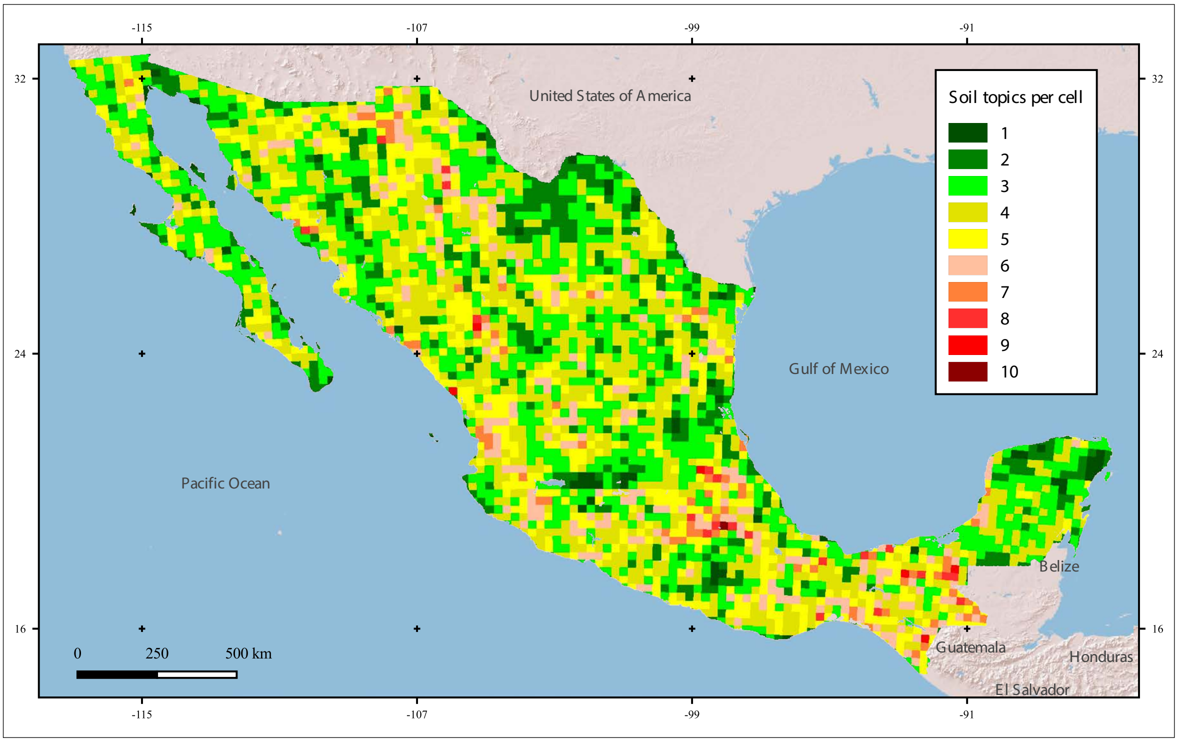

Figure 5. Soil diversity across Mexico.

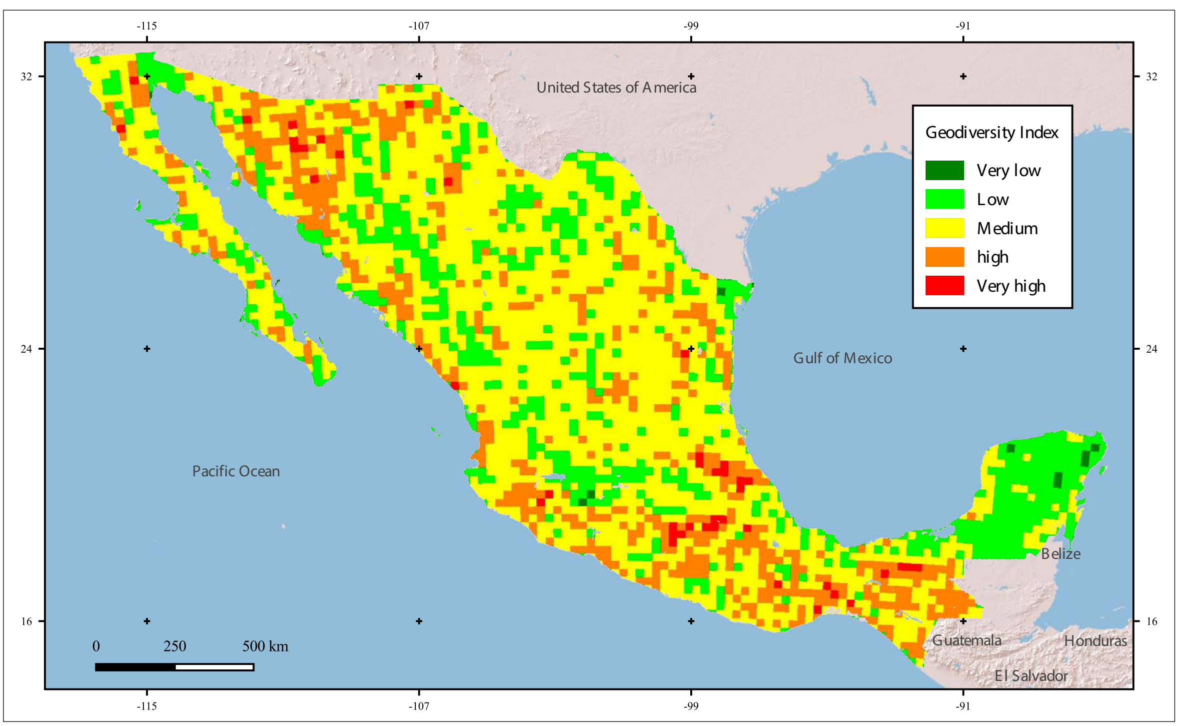

Figure 6. Geodiversity across Mexico, derived from the subindices for geology, geomorphology, and soils.

GEODIVERSITY IN MEXICO

The geological diversity of Mexico results from a long and complex history associated with the interaction between tectonic plates and diverse geological environments. A mosaic of tectonostratigraphic terranes assembled during the Paleozoic and Mesozoic as a result of the complex interaction between Laurentia, Gondwana and the Paleo-Pacific plate (Centeno-García, 2017). Strong activity continues through the interaction of five main plates: North American, Pacific, Cocos, Caribbean and Rivera.

Because of this long geological history, there are rocks of diverse characteristics and ages (see Geology maps of Mexico in Section III of the National Atlas of Mexico, *in press*). In general, the most abundant are those of sedimentary origin (continental and marine), followed by magmatic (intrusive and extrusive) and metamorphic (see Table 1), and their ages range from the Precambrian to the present.

The oldest rock outcrops in Mexico, metamorphic rocks, are few and are mainly in the states of Sonora and Oaxaca (Ferrari et al., *in press*), two regions with the high and very high values of geodiversity referred to above. Precambrian metamorphic outcrops of the Caborca area of Sonora are represented by igneous and sedimentary rocks metamorphosed to greenschist and amphibolite facies (Anderson et al., 1978; Anderson and Silver, 1978). Precambrian rocks are also present in the State of Oaxaca.

The sedimentary rocks of the Cretaceous and to a lesser extent the Jurassic (mainly limestones, marls, shales) are distributed throughout the Sierra Madre Oriental, Sierra Madre del Sur, and the Yucatán Peninsula. Finally, igneous rocks (both intrusive and volcanic) are preferentially distributed along the Sierra Madre Occidental (extensive Paleogene pyroclastic deposits) and along the Trans-Mexican Volcanic Belt (Neogene to the present).

Table 7. Geodiversity of Mexico.

Geodiversity	Percentage of land area covered
Very low	0.36
Low	21.19
Medium	57.56
High	19.45
Very high	1.44

As a consequence of geological evolution, the diversity of rock types and the exogenous processes that shape the relief (see Geomorphologic Map of the National Atlas of Mexico, *in press*), the geomorphological diversity of Mexico includes units that are grouped into endogenous relief forms (e.g. mountains of folded, blocky or volcanic rocks, generally young, relatively well preserved) and exogenous relief forms (e.g. various forms derived from fluvial, aeolian, marine and, to a lesser extent, glacial activity), karst, relief and mixed landforms (see Table 2).

Lithology and relief are two of the most important factors involved in the formation of different types of soil. Here, the diversity of rocks and relief units partly explains the diversity of soils across Mexico.

CONCLUSION

The Geodiversity map of Mexico, based on rock types, landforms and soils, constitutes a first approach to the country's abiotic natural diversity. The methodology is adjustable and capable of being applied in specific, smaller areas to achieve greater detail. A further characterization of the country's geodiversity will depend on the availability of data regarding other variables such as climate, morphometry, and underground water resources. Results must be contextualized according to the scale of origin of the data used, in this case national level (1:5,000,000). The relatively high degree of geodiversity across a large part of the Mexican territory indicates a high potential for geoconservation and consequently the need for appropriate management. The results and methods addressed are of interest in various basic and applied fields of Earth Sciences and Geography, not least in geoconservation, the promotion of natural heritage for various purposes and the creation of Geoparks.

It should be noted that, in order to define comprehensive conservation of resources, a subsequent analysis would need to consider not only geodiversity and, additionally, morphodiversity, which requires an accurate Digital Elevation Model of the entire Mexican territory, but also the associated biodiversity, which implies an analysis of vegetation cover, the level of environmental protection, land use and its degree of degradation, as well as the impact of human activity.

REFERENCES

Alberico, I., Casaburi, A. & Matano, F. (2023). Mapping Geodiversity at a National Scale: the Case Study of Italy. *Geoheritage, 15*, 121. https://doi.org/10.1007/s12371-023-00889-8

Anderson, T. H., Eells, J. H. & Silver, L. T. (1978). Rocas precámbricas y paleozoicas de la región de Caborca, Sonora, México. In J. Roldán-Quintana y G. A. Salas (Eds.), Libreto Guía. In *Primer Simposio sobre la Geología y Potencial Minero en el Estado de Sonora* (pp. 5-34). Instituto de Geología, Universidad Nacional Autónoma de México.

Anderson, T. H. & Silver, L. T. (1978). The nature and extent of precambrian rocks in Sonora, Mexico. *Primer Simposio sobre la Geología del Estado de Sonora y su potencial minero* (pp. 9-10). Instituto de Geología, UNAM.

Atlas Nacional de México (ANM, *in press*). *Atlas Nacional de México*. Instituto de Geografía, UNAM.

Bétard, F. & Peulvast, J. P. (2019). Geodiversity hotspots: Concept, method and cartographic application for geoconservation purposes at a regional scale. *Environmental management*, 63(6), 822-834. https://doi.org/10.1007/s00267-019-01168-5

Brazier, V., Bruneau, P. M., Gordon, J. E. & Rennie, A. F. (2012). Making space for nature in a changing climate: the role of geodiversity in biodiversity conservation. *Scottish Geographical Journal,* 128(3-4), 211-233. https://doi.org/10.1080/14702541.2012.737015

Brown, E. J., Prosser, C. D. & Stevenson, N. M. (2012). Geodiversity, conservation, and climate change: key principles for adaptation. *Scottish Geographical Journal*, 128(3-4), 234-239. https://doi.org/10.1080/14702541.2012.725859

Centeno-García, E. (2017). Mesozoic tectono-magmatic evolution of Mexico: An overview. *Ore Geology Reviews*, 81, 1035-1052. https://doi.org/10.1016/j.oregeorev.2016.10.010

Comer, P. J., Pressey, R. L., Hunter Jr, M. L., Schloss, C. A., Buttrick, S. C., Heller, N. E., Tirpak, J. M., Faith, D., Cross, M. S. & Shaffer, M. L. (2015). Incorporating geodiversity into conservation decisions. *Conservation Biology*, 29(3), 692-701. https://doi.org/10.1111/cobi.12508

Cruz-Gaistardo, C., Ramos, Zavala et al. (*in press*). Diversidad Geográfica del Suelo. *Atlas Nacional de México*. Instituto de Geografía, UNAM.

de Paula Silva, J., Rodrigues, C. & Pereira, D. I. (2015). Mapping and analysis of geodiversity indices in the Xingu River basin, Amazonia, Brazil. *Geoheritage,* 7, 337-350. https://doi.org/10.1007/s12371-014-0134-8

de Paula Silva, J., Alves, G. B., Ross, J. L. S. Soares de Oliveira, F., Leite do Nascimento, M. A., Grochoski Felini, M., Manosso, F. C. & Ínsua Pereira, D. (2021). The Geodiversity of Brazil: Quantification, Distribution, and Implications for Conservation Areas. Geoheritage, 13, 75. https://doi.org/10.1007/s12371-021-00598-0

Dias, M. C. S. S., Domingos, J. O., dos Santos Costa, S. S., do Nascimento, M. A. L., da Silva, M. L. N., Granjeiro, L. P. & de Lima Miranda, R. F. (2021). Geodiversity index map of Rio Grande do Norte State, Northeast Brazil: cartography and quantitative assessment. *Geoheritage*, 13, 1-15. https://doi.org/10.1007/s12371-021-00532-4

dos Santos, F. M., de La Corte Bacci, D., Saad, A. R. & da Silva Ferreira, A. T. (2020). Geodiversity index weighted by multivariate statistical analysis. *Applied Geomatics*, 12, 361-370. https://doi.org/10.1007/s12518-020-00303-w

Erikstad, L. (2013). Geoheritage and geodiversity management - the questions for tomorrow. *Proceedings of the Geologists' Association*, 124(4), 713-719. https://doi.org/10.1016/j.pgeola.2012.07.003

Esmaili, R. (2024) Quantitative Evaluation and Spatial Clustering of Geodiversity in Iran. *Geoheritage*, 16, 13. https://doi.org/10.1007/s12371-024-00914-4.

Ferrari, L. Morán, D. Ortega et al. (*in press*). Geología de México. Atlas Nacional de México. Instituto de Geografía, UNAM.

Gordon, J. E., Barron, H. F., Hansom, J. D. & Thomas, M. F. (2012). Engaging with geodiversity - why it matters. *Proceedings of the Geologists' Association*, 123(1), 1-6. https://doi.org/10.1016/j.pgeola.2011.08.002

Gray, M. (2008). Geodiversity: the origin and evolution of a paradigm. *Proceedings of the Geologists' Association*, 300(1), 31-36. https://doi.org/10.1144/SP300.4

Kozłowski, S. (2004). Geodiversity. The concept and scope of geodiversity. *Przegląd Geologiczny, 52*(8/2), 833-837.

Lopes, C., Teixeira, Z., Pereira, D. I. & Pereira, P. (2023). Identifying Optimal Cell Size for Geodiversity

Quantitative Assessment with Richness, Diversity and Evenness Indices. *Resources*, 12(6), 65. https://doi.org/10.3390/resources12060065

Parrot, J.-F. (2023a). Map_Explor. Número de registro del INDAUTOR: 03-2023-091810372800-01. https://www.geografia.unam.mx/geoigg/investigacion/lage/Metodos_espacial/intro.html

Parrot, J.-F. (2023b). Diversity_Index. Número de registro del INDAUTOR: 03-2023-091810384900-01. https://www.geografia.unam.mx/geoigg/investigacion/lage/Metodos_espacial/intro.html

Pereira, D. I., Pereira, P., Brilha, J. & Santos, L. (2013). Geodiversity assessment of Paraná State (Brazil): an innovative approach. *Environmental Management*, 52, 541-552. https://doi.org/10.1007/s00267-013-0100-2

Posada Ayala, I.H., García Gastélum, A. Bruschi, V. & Téllez Duarte, M.A. (2014). Geodiversidad y paisaje: un análisis de su potencial en Baja California, México, *Investigaciones Geográficas*, (48), 19-40. https://doi.org/10.5354/0719-5370.2014.36674

Prosser, C. D., Burek, C. V., Evans, D. H., Gordon, J. E., Kirkbride, V. B., Rennie, A. F. & Walmsley, C. A. (2010). Conserving geodiversity sites in a changing climate: management challenges and responses. *Geoheritage*, 2, 123-136. https://doi.org/10.1007/s12371-010-0016-7

Wolniewicz, P. (2023). Quantifying geodiversity at the continental scale: limitations and prospects. *Resources*, 12(5), 59. https://doi.org/10.3390/resources12050059

Zamorano, J.J., Quijada, Salinas et al. (*in press*). Geomorfología. Atlas Nacional de México. Instituto de Geografía, UNAM.