

Morphodiversity of the Mixteca Alta UNESCO Global (Oaxaca, Mexico)

Carolina Ramírez Núñez

Escuela Nacional de Ciencias de la Tierra [ENCiT], UNAM

Jean-François Parrot

`parrot@geografia.unam.mx`

Instituto de Geografía, UNAM

José Luis Palacio Prieto

Instituto de Geografía, UNAM

Research Article

Keywords: morphodiversity, geodiversity, Digital Elevation Models, primary attributes extraction, Mixteca Alta Geopark

Posted Date: September 16th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10669783/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Morphodiversity of the Mixteca Alta UNESCO Global (Oaxaca, Mexico)

Carolina Ramírez Núñez¹, Jean-François Parrot^{2*}, José Luis Palacio Prieto³

¹Escuela Nacional de Ciencias de la Tierra [ENCiT], UNAM, Ciudad de México, México, ORCID: <https://orcid.org/0009-0000-8130-6420>

²Laboratorio de Análisis GeoEspacial [LAGE], Instituto de Geografía, UNAM, Ciudad de México, México, ORCID: <https://orcid.org/0000-0001-7528-9054>

*Corresponding author parrot@geografia.unam.mx

³Geografía Física, Instituto de Geografía, UNAM, Ciudad de México, México, ORCID: <https://orcid.org/0000-0001-6651-0255>

Abstract

Assessment of geodiversity frequently requires data derived from the interpretation of variables such as geology, geomorphology, soil types, and other components of the natural system. However, this process requires more detailed basic mapping, which is not yet available for all geographical areas. Fortunately, morphodiversity, a component of geodiversity, can be assessed by use of primary attributes extracted from an accurate Digital Elevation Model (DEM). To analyze the morphodiversity of the Mixteca Alta UNESCO Global Geopark, the primary attributes of slope, convexity (analyzed here as slope shape), and roughness (fractal dimension) were used; each attribute was divided into several classes, and their subindices were obtained. Thus, mountainous terrain within the geopark, with rocks of volcanic origin (tuffs and andesites), has high and very high morphodiversity (>54% based on slope values exceeding 9° and on high roughness); intermontane valleys, and limestone hills have an intermediate morphodiversity, and finally, the plains with sedimentary deposits have a low and very low morphodiversity, i.e., low degrees of slope and of roughness. If the subindices of the primary attributes are differentially weighted, convexity (slope shape) appears as the subindex that most confers a heterogeneous pattern in the spatial analysis. Morphodiversity applied to management indicates that areas with high and very high values can be considered priority zones for geoconservation; homogeneous areas (low morphodiversity) are more suitable for infrastructure development or visitor services, reducing pressure on more sensitive zones.

Keywords: morphodiversity, geodiversity, Digital Elevation Models, primary attributes extraction, Mixteca Alta Geopark.

1. Introduction

Geodiversity refers to the natural variety of the Earth's surface, including geological and geomorphological features, soils, surface waters, and systems resulting from both natural processes and human activity. Together with biodiversity, geodiversity constitutes a fundamental component supporting sustainable development (Kozłowski 2004; Lausch *et al.* 2022). In UNESCO Global Geoparks, geodiversity plays a key role in the

identification, conservation and management of geoheritage, where spatial information is essential for decision-making related to conservation, geotourism and environmental education.

Most geodiversity assessments are based on thematic cartographic documents such as geological, geomorphological or soil maps (Bétard and Peulvast, 2019; Parrot *et al.* 2024). However, these documents are not always available at sufficiently detailed scales, particularly in regions such as southern Mexico. This limitation reduces their applicability for fine-scale spatial analysis and geopark management.

In this context, morphodiversity derived from Digital Elevation Models (DEMs) constitutes an alternative approach based on continuous and objective variables obtained directly from the tridimensional surface. In contrast with thematic cartography requiring subjective interpretation, DEM-derived parameters provide quantitative information describing terrain morphology. Although morphodiversity has increasingly been used in geodiversity and geoconservation studies (Bartuś and Mastej, 2023), its operational application in geopark management remains comparatively limited, particularly for spatial planning and territorial management.

The Mixteca Alta UNESCO Global Geopark represents an appropriate study area because of its high geomorphological complexity and the presence of numerous geosites requiring spatial prioritization strategies. Previous studies have addressed the geology (INEGI 1984; SGM 2000; Montes de Oca-Villatoro 2021), geomorphology (Orozco-Ramírez and Bocco, 2021), and vegetation (Ramírez-Santiago *et al.* 2021) of the geopark, and 48 geosites have been identified (Sánchez-Cortez *et al.* 2025). Nevertheless, a detailed spatial characterization based on terrain morphology remains necessary to support integrated management and conservation strategies.

Therefore, this study aims to assess morphodiversity in the Mixteca Alta UNESCO Global Geopark using DEM-derived variables such as slope, convexity and roughness, and to evaluate the contribution of morphodiversity to geopark management, particularly for geoconservation, geotourism planning and spatial zoning.

2. Study area

The Mixteca Alta Geopark is in the physiographic sub province of Western Mountains and Valleys (Ortiz-Pérez *et al.*, 2004) located in the State of Oaxaca; it covers an area of 42,058.32 ha that includes 9 municipalities, each with its own special-historical heritage and its own responsibility within the geopark management (Fig. 1).

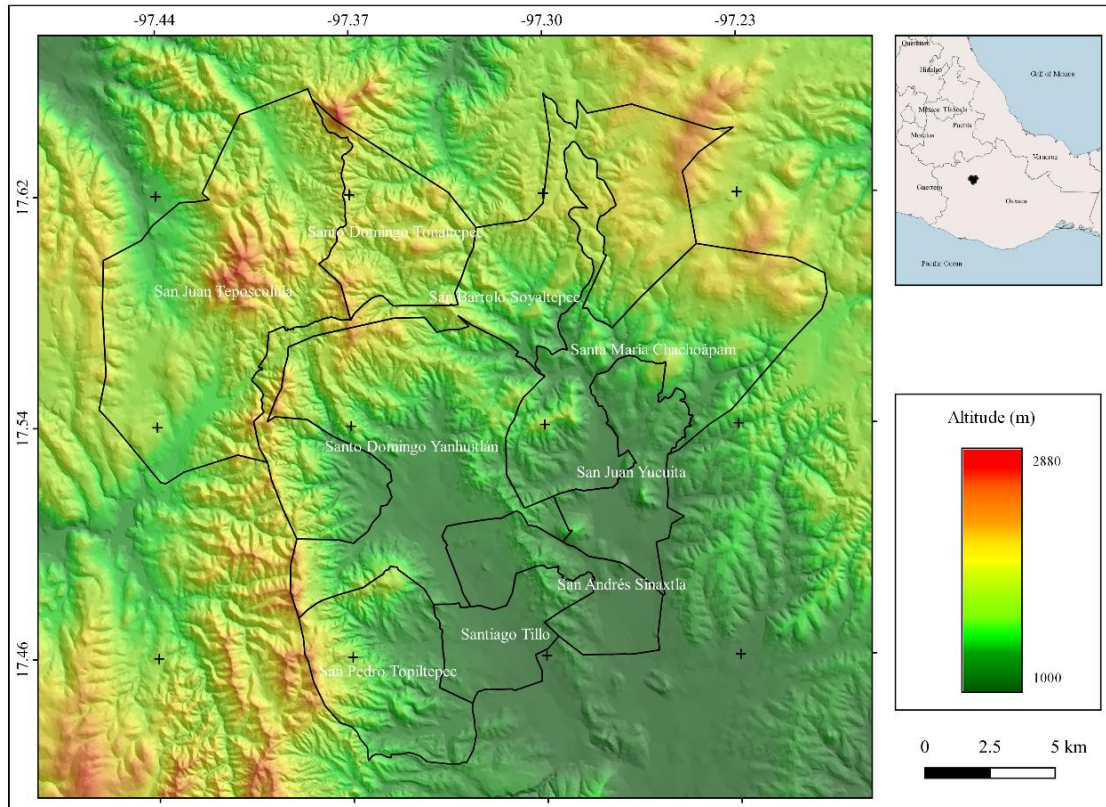


Fig. 1 Location and altimetry of the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico

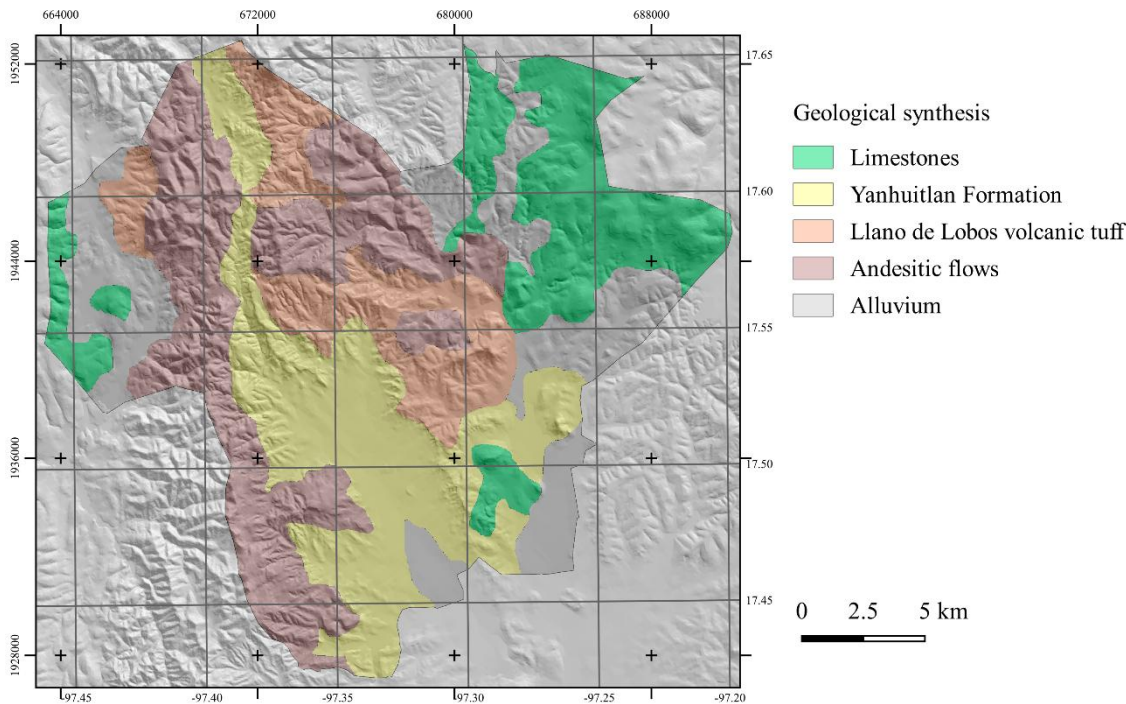
The Mixteca Alta is a rugged region composed of sedimentary, volcanic, and plutonic rocks that date from the Cretaceous to the Miocene, partially covered by Quaternary alluvial deposits.

Cretaceous rocks correspond to the Teposcolula Formation, characterized by cream to dark gray limestones that weather to white. This massive unit contains some fossiliferous horizons with small oyster shells, though most are poorly preserved due to surface erosion. The formation shows both massive and well-stratified sections (Salas 1949).

Overlying it conformably is the Yanhuitlán Formation, composed of thin, rhythmic layers rich in silt and reddish clay, reaching thicknesses of approximately 300-600 meters (Ferrusquía 1976). Deposition of these sediments took place in extensive lacustrine environments during the Paleocene and Eocene, about 40 million years ago (Martiny *et al.* 2000). This formation is one of the most extensive within the geopark, and its poorly consolidated, friable sediments have promoted the development of the distinctive erosional landforms that define the region's landscape.

The Oligocene Llano de Lobos Tuff conformably overlies the Yanhuitlán Formation. It consists of rhyodacitic to andesitic tuffs interbedded with conglomerates containing a sandy matrix and calcareous clasts. Above it lies the Yucudaac Andesite, composed of trachyandesitic to basaltic lavas with a characteristic trachytic texture (Ferrusquía 1970) that correspond to the extensive within the geopark.

Finally, the Quaternary deposits consist of unconsolidated gravel, sand, silt, and clay that form the region's alluvial cover.



Zamudio-Ángeles D, Rosado-González E, Romera-Béjar C (2025) Geological synthesis of the Mixteca Alta Geopark, Oaxaca, Mexico. Modified from Geological Mexican Service (2000), fieldwork in process.

Fig. 2 Geological synthesis of the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico

The schematic geological map of the figure 2 corresponding to the last field observations by Zamudio-Ángeles *et al.* (2025) (field work in process) provides complementary information to the map of the Mexican Geological Service (SGM 2000). Geological surfaces of the five formations have been calculated using the program **Surface JFP Param V2** (Parrot, 2025a).

The folded Neocomian limestone series cover 7454.33 ha (Table 1). They are essentially observed eastwards the geopark and appear westwards in an even more folded group called Zapotec Formation (1103.39 ha). Their rugosity index (2.39) is relatively low.

The Yanhuitlán Formation that covers 10254.23 ha is characterized by a very low roughness (1.86). Volcanic formations are rougher: the bidimensional surface of the Llano de Lobos Tuffs is equal to 5591.47 ha and the roughness index is 4.53; and the Yucudaac Andesite formation covers 10916.67 ha, and its roughness index reaches 7.45.

The surface of the quaternary alluvium is equal to 6969.01 ha and the percentage change when calculating the tridimensional surface is very low (1.54).

Geological formation	Surface 2D (ha)	Surface 3D (ha)	Percentage change
Neocomian Limestones	7454.33	7632.51	2.39
Yanhuitlán Formation	10254.23	10445.30	1.86
Llano de Lobos Tuff	5591.47	5845.06	4.53
Yucudaac Andesite	10916.67	11730.58	7.45
Quaternary Alluvium	6969.01	7076.37	1.54

Table 1. Percentage change from 2D to 3D of the five geological formations

The bidimensional and tridimensional surface measurement of the geological formations leads to calculation of a percentage change P between these two surfaces (Parrot 2007; Parrot 2025b); this determines the percentage of increase that affects the bidimensional surface, percentage that can be likened to a roughness index; it is calculated as follows:

$$P = \left((S_{3D} - S_{2D}) / S_{2D} \right) \times 100 \quad [1]$$

where S_{2D} and S_{3D} correspond respectively to the bi- and tridimensional surfaces.

This percentage change indicates a difference between the Neocomian limestones and the Miocene Yucudaac formation, difference that is not evident from the slope data alone (as will be shown below).

3. Data used

3.1. Digital Elevation Model

The model was generated using the vector file E14D25 provided by INEGI (2013). Various executable modules described in Parrot (2016) allow extracting zones of interest from this file according to its coordinates. In a first step, gray-tone contour lines are created, as well as a table indicating relationships between gray-tone values and the altitude in meters, decimeters, centimeters, or millimeters. The millimetric scale creates the most precise surface representation. Then, after correction of any possible defects, a module transforms the gray-tone image to a 32 bits image (4 bytes) where the contour lines appear with their altitude on a neutral background equal to -99999. This image is used to generate a DEM by means of either a module that applies a contour line dilation (Fig.3A), or a module based on a multidirectional interpolation (Fig. 3B) according to the following equation:

$$A_p = A_i + [(A_s - A_i) \times (d_i/d)] \quad [2]$$

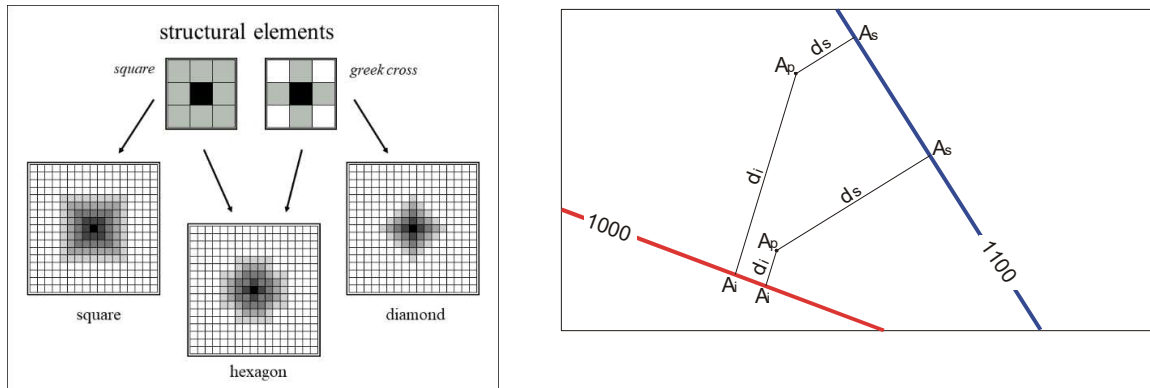


Fig. 3 Interpolation types: A. Contour line dilation (Taud *et al.* 1999); B. Multidirectional interpolation (Parrot 2016)

The first type of interpolation has the advantage of generating a DEM even if local defaults can be observed in the contour lines. The second type needs a complete analysis and an accurate improvement of all the contour lines; generally, this correction requires time, but the result is more precise.

To carry out the following calculations, only the hypsometric values located in the geopark area are used.

3.2. Primary attributes

Three attributes extracted from the DEM have been used to calculate the tridimensional morphodiversity: a) slope, b) convexity and c) roughness. The process requires a previous segmentation of these attributes.

For slope, field observations are considered to define the segments.

The convexity is segmented according to the pyramidal distribution of the values to emphasize the minimum (thalwegs) and maximum (watershed boundaries) values.

The surface roughness is calculated using the tridimensional local fractal dimension (Taud and Parrot 2005) and the result is segmented by means of equipopulation.

a. Slope

The slope of the surface corresponds to its inclination with respect to a horizontal plane. Slope calculation uses Sobel operators that correspond to an efficient treatment, because, in a simple way, are obtained both the magnitude of the slope and the direction of the slope using horizontal and vertical gradients. These quick and simple calculations are especially useful for analyzing relief. There are many alternative treatments, such as Gaussian derivatives or methods based on Fourier Transforms or wavelets. But in fact, these treatments are only stopgap measures that seek to compensate for the irregularities of the documents on which they are applied. For this reason, Taud *et al.* (1999) and Parrot (2016) developed interpolations that generate perfectly smoothed

DEMs, without pits or peaks, artifacts or noise, and which therefore require no tools other than Sobel operators S_x and S_y .

These operators calculate the *Slope* and this result corresponds to the value of the inclination (0-90°).

$$Slope = atan(\sqrt{S_x^2 + S_y^2}) \times (180/\pi) \quad [3]$$

<i>Slope class</i>	%
Extremely steep (>35°)	1.54
Very steep (21-35°)	14.53
Steep (13-20°)	22.15
Moderately steep (9-12°)	16.76
Sloping (4-8°)	22.16
Gently sloping (2-3°)	9.99
Flat or almost flat (0-1°)	12.87

Table 2. Occurrence (%) of slope classes in the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico.

Seven slope classes have been defined: 1) flat or almost flat (0 – 1°); 2) gently sloping (2 - 3°); 3) sloping (4 – 8°); 4) moderately steep (9 – 12°); 5) steep (13 – 20°); 6) very steep (21 - 35°); 7) extremely steep (> 35°). The percentage of each slope class in the geopark is reported in Table 2. According to these results, 54.98% of the area comprises mountainous zones with slope > 9°.

This parameter is segmented according to field observations and measurements (Fig. 4).

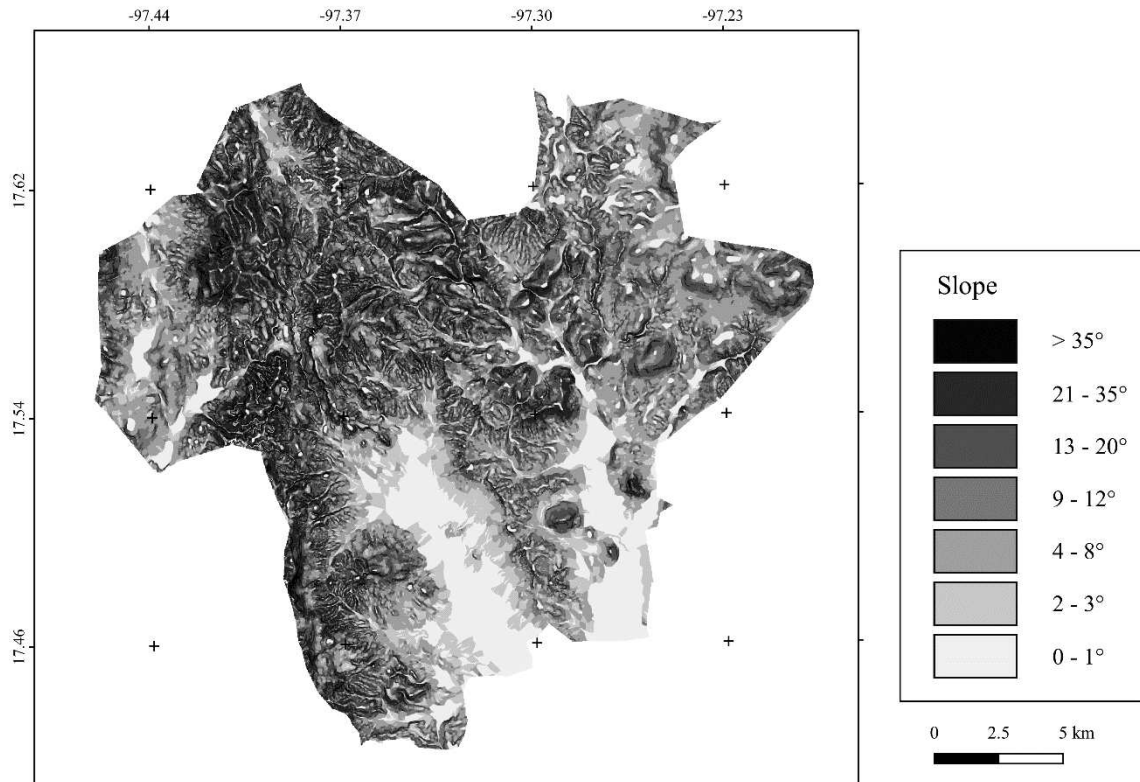


Fig. 4 Slope classes in the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico.

Flat and gently sloping gradients correspond to Quaternary alluvial deposits in valleys located in the south-central zone, as well as in the intermontane valleys to the northeast and northwest of the geopark. The moderately steep and steep slopes characterize the elevations of Paleocene-Middle Eocene conglomerates and sandstones, as well as Neocomian limestones. Finally, the very steep and extremely steep gradients correspond essentially to the Upper Eocene - Miocene tuffs.

b. Convexity

The shape of the slopes or slope profile (Douglas 1977) reflects the irregularities of the earth's surface. In the Ruhe (1960) model, the geometric classification is based on five classes: concave, convex, two inclined surfaces and one horizontal plane.

Depending on the resolution of the DEM, calculation of convexity requires definition of the size of the moving cell used (i.e., 5×5), as well as the dynamic scale (0-100 or 0-255). The histograms in Figure 5 show the results for these two scales, where the maximum value (100 or 255) corresponds to the pixels of convex surfaces, while the minimum value (0) corresponds to the concave areas. The intermediate values around the peak of the pyramidal curve correspond to the flat areas and their transitions.

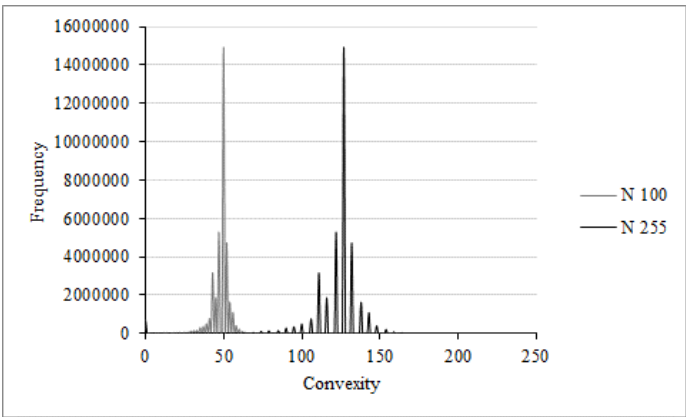


Fig. 5 Convexity expressed in percentage ($N = 100$) or normalized gray tones ($N = 255$)

In fact, a stretching based on the PINS algorithm (Parrot 2011) is required to emphasize the concave and convex surfaces at the extremities of the histograms; the lowest values characterize the channels and the highest values the watershed boundaries.

This treatment saturates the extreme values and normalizes the results between 0 and 255, using a saturation rate applied to the two extremities of the diagram. Inside a 3×3 moving window is obtained the sum of all pixels belonging to this window. The histogram of these sums (Fig. 6) allows calculation of the number of

pixels N_{SAT} comprised between 0 and the lower sum value, as well as the distance between 2295 and the upper sum value; 2295 is the maximum theoretical value (9×255). Thus, the saturation limits min_{SAT} and max_{SAT} are obtained and finally, it is only necessary to normalize between 0 and 255 the values bounded by those limits min_{SAT} and max_{SAT} . Then, segmentation of the stretched image is performed.

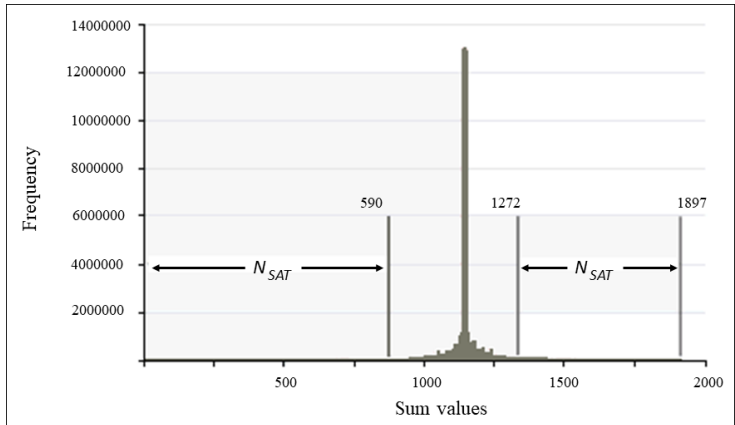


Fig. 6 Stretching parameters and calculation (In: Ramírez-Núñez *et al.*, 2026)

As seen in figure 8, the result corresponds to a Gaussian distribution despite the absence of information for some values. The segmentation considers that the peak value must correspond to horizontal surfaces.

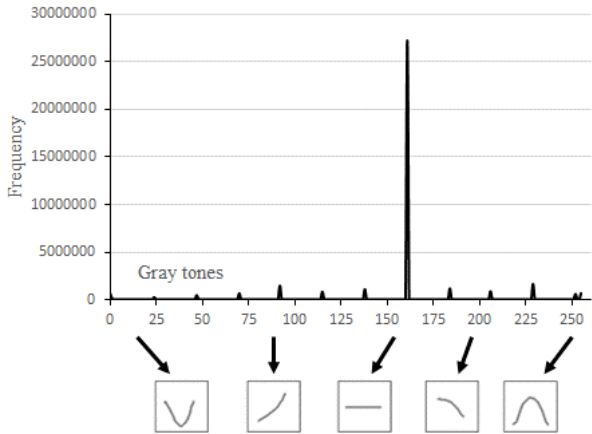


Fig. 7 Distribution of the slope shapes based on the calculation of convexity

Figure 8 illustrates the distribution of the classes of surface shapes in the geopark; high concavity (black) corresponds to riverbeds and high convexity (white) to watershed boundaries (Table 3). Transition surfaces and flat areas are shown in gray.

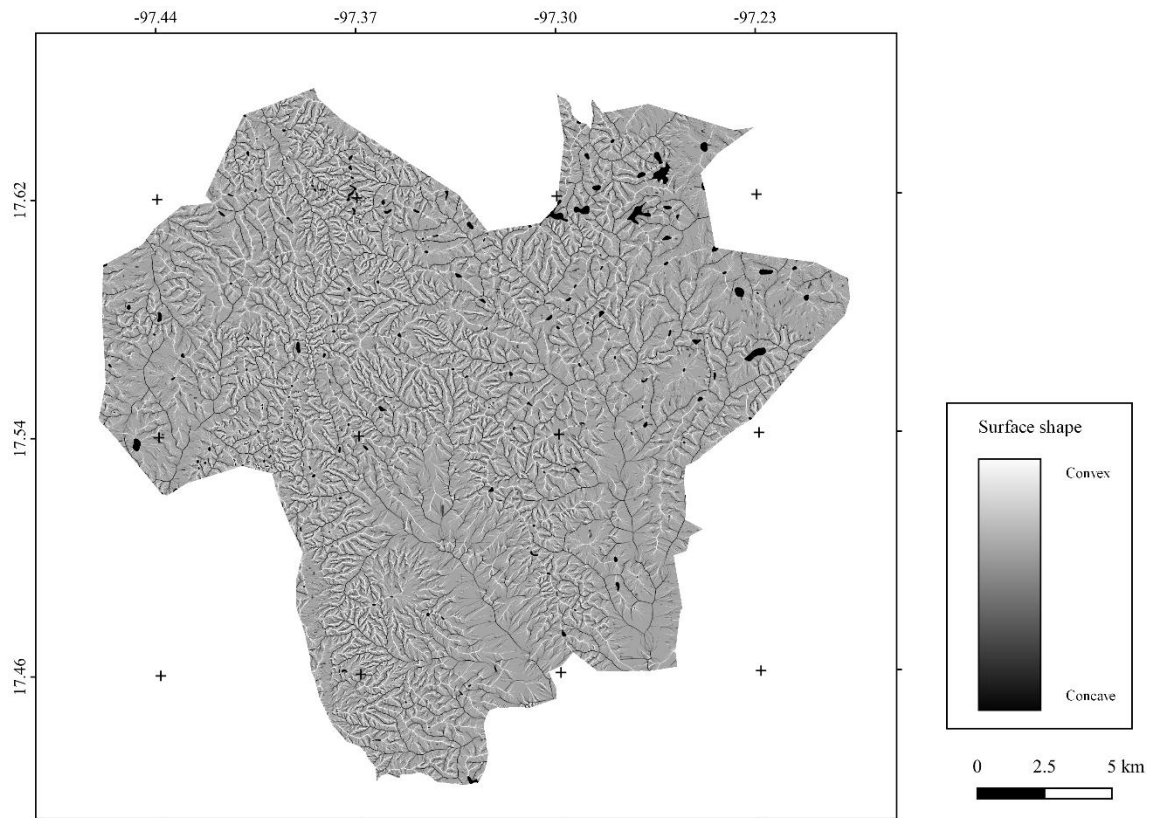


Fig. 8 Convexities and concavities in the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico.

<i>Shape class</i>	<i>%</i>
Strong Concavity	2.01
Concavity	25.24
Flat	69.82
Convexity	2.92
Strong Convexity	0.01

Table 3. Area (%) occupied by each shape class in the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico.

c. Roughness

The DEM roughness is the third criterion used to calculate here the morphodiversity. This parameter corresponds to differences in elevation data, and it is calculated as an absolute standard deviation of all values inside a moving window or as the calculated deviation from a fitted plane (Hobson 1972; Evans 1984; Haneberg *et al.* 2005; Wilson *et al.* 2007; Olaya 2009; Pike *et al.* 2009; Parrot and Ramírez-Núñez 2021).

We use here the local Fractal Dimension (*FD*), a surface roughness parameter developed by Taud and Parrot (2005). The *FD* of each pixel describing the DEM surface is calculated within a moving box $s \times s \times s$ and uses a tridimensional method derived from box-counting. In this treatment, the voxels that describe the volume at a local level are directly related to the altitude values of the pixels defining the DEM surface.

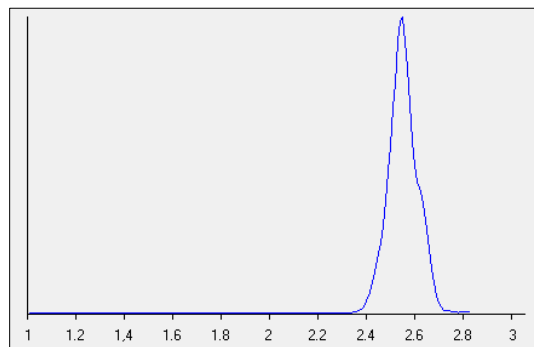


Fig. 9 Local Fractal Dimension with a *window* = 12 and a coefficient $h = 0.25$

209

210 The resulting tri-dimensional *FD* values lie between 2 and 3 (Fig. 9). As the studied central point is located, by
 211 definition, in the center of the cube, a horizontal surface will fill one-half of the test cube.

212

213 When the surface is irregular, each column of voxels belonging to the tridimensional portion of terrain that is
 214 taken locally in the moving box $s \times s \times s$ reaches a level greater or lower than the horizontal surface that fills
 215 one-half of the test cube and the result thus obtained indicates the magnitude of roughness of this surface. Thus,
 216 when the irregularity of the surface increases, its *FD* grows in the direction of dimension 3.

217 Then, a single equipopulation process is applied to the result to obtain only 5 classes (Fig. 10 and Table 4). A
 218 subsequent inversion of the resulting scale yields a comprehensive view of the result.

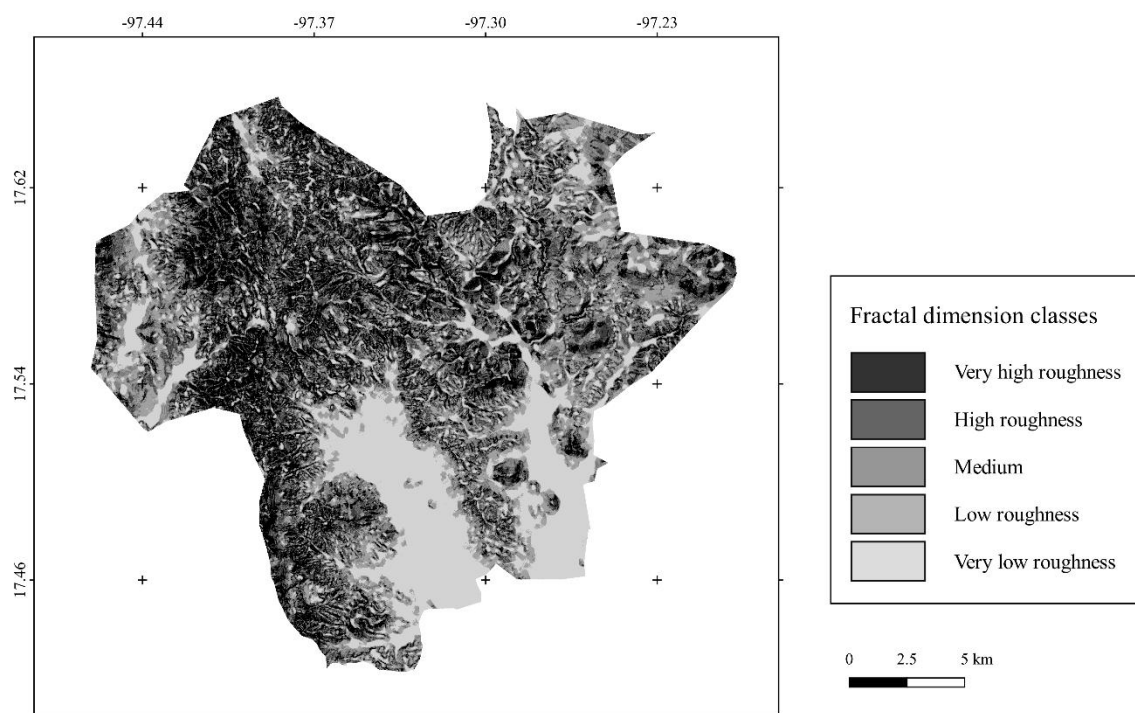


Fig. 10 Fractal dimension classes in the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico.

<i>Fractal Dimension class</i>	<i>%</i>
Very High Roughness	20.11
High Roughness	20.83
Medium	18.97
Low Roughness	19.84
Very Low Roughness	20.35

Table 4. Percentage of the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico for each fractal dimension class.

The Quaternary alluvium has the least roughness; the conglomerates and sandstones from Paleocene to Middle Eocene and Neocomian limestones have intermediate roughness; and the upper Eocene to Miocene tuffs have the greatest roughness.

4. Subindices calculation

Calculation of subindices and morphodiversity index rests on the number of topics present in each cell of a grid of squared cells. Grid size depends on the regional scale (Serrano and Ruiz-Flaño 2007), but its selection is generally empirical (Lopes *et al.* 2023).

Here, morphodiversity has been measured in terms of three subindices: slope, convexity, and roughness. The segmented images presented in the previous section have been processed in **Map Explor** (Parrot 2023a) and **Diversity Index** (Parrot 2023b).

4.1. Generalities

The value of each subindex (In_{div}) is calculated using a grid of squared cells. The size $c \times c$ of the cells of this grid results from the application of a range R which depends on the size m of the pixel side and the desired viewing surface S (Parrot *et al.*, 2025). In the present case, the size m of the pixel side is 5 meters and various values of S have been used to retain only the most significant. The range R is calculated as follows:

$$R = \left(\left(\sqrt{S'/m^2} \right) - 1 \right) / 2 \quad [4]$$

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

The number of cells containing only a single theme decreases as cell size increases. It is thus possible to objectively and non-empirically define a cell size for calculating subindices. The **Objective Window Size** module we developed (Parrot and Ramírez-Núñez 2025) addresses this issue by tracking the decrease in the percentage of cells c containing only a single theme as cell size increases. It can be estimated that if this percentage is only 5%, the document under study will present a valid response. For example, Figure 11, which

247 corresponds to a processing applied to the slope class (Fig. 4), shows that for a range R equal to 20 (i.e., a cell
 248 of 41×41 pixels, or 205×205 m), only 5% of these cells contain only a single theme (Fig. 12).

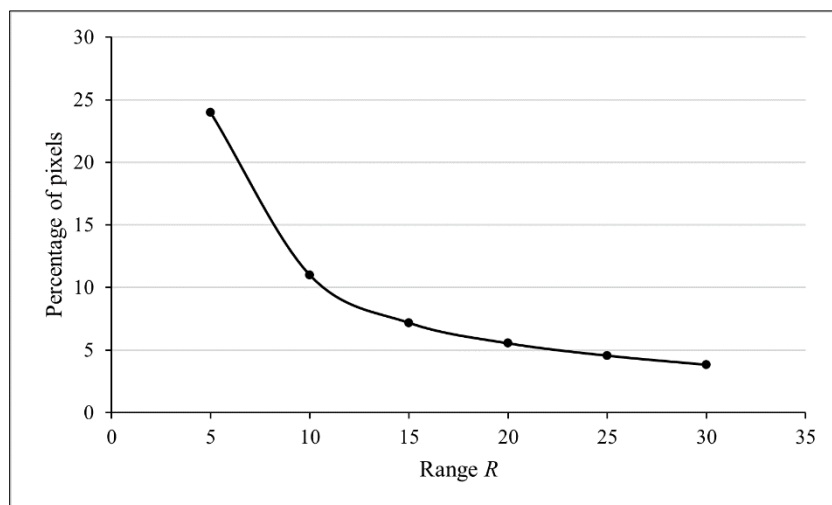
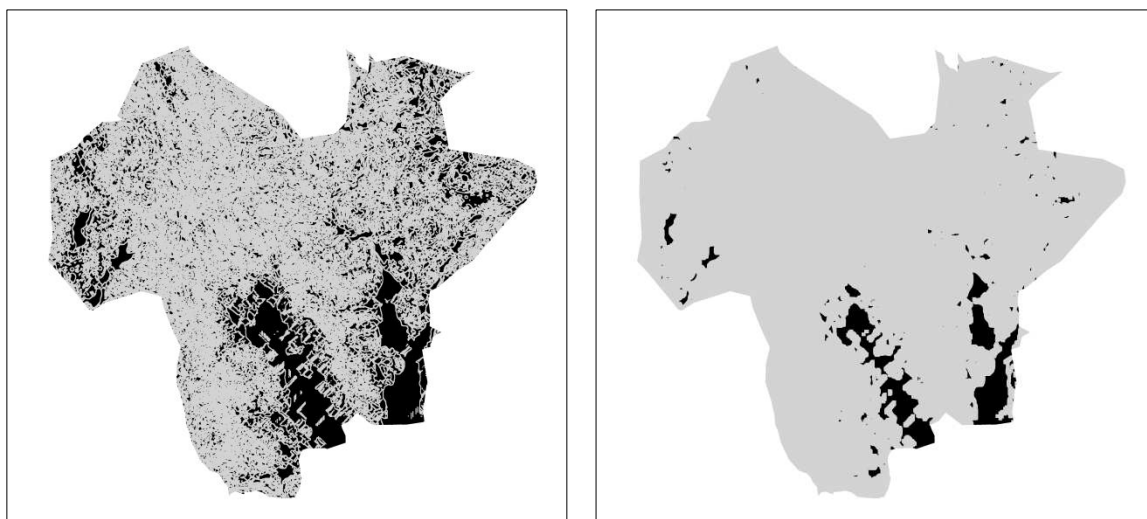


Fig. 11 Percentage of monothematic cells according to the range values

249



A. Range $R = 5$

B. Range $R = 20$

Fig. 12 Distribution of monothematic cells in a grid applied to the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico according to the *range*.

250

251 Conversely (Fig. 13), a treatment on the geological map presented in figure 2 shows that for a R value of 5 (Fig.
 252 14A), the percentage of monothematic cells is 96.81%. This percentage decreases only slightly when the value
 253 of R increases and remains above 78% for $R = 35$ (Fig. 14B). Cells with a value greater than 1 are only found
 254 on or near the boundaries of the geological zones.

255 This explains why we chose to conduct our research by focusing on morphodiversity and not on geodiversity
 256 which would require a level of cartographic detail that is not yet available.

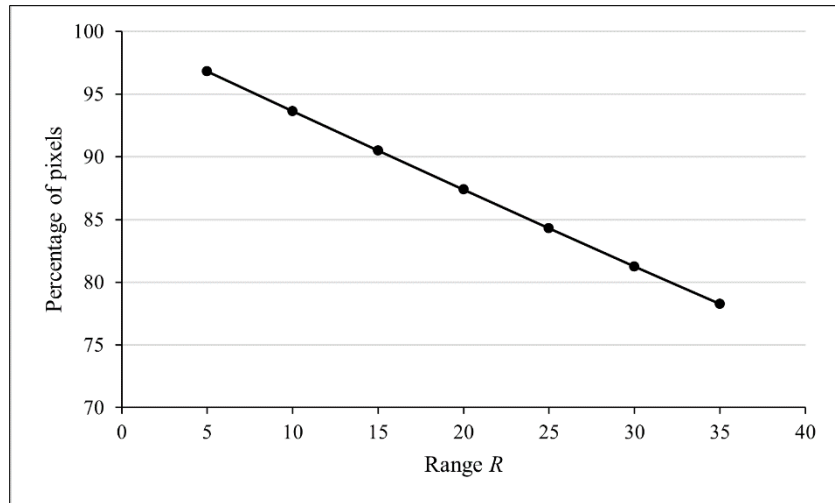


Fig. 13 Percentage of geological monothematic cells according to R values

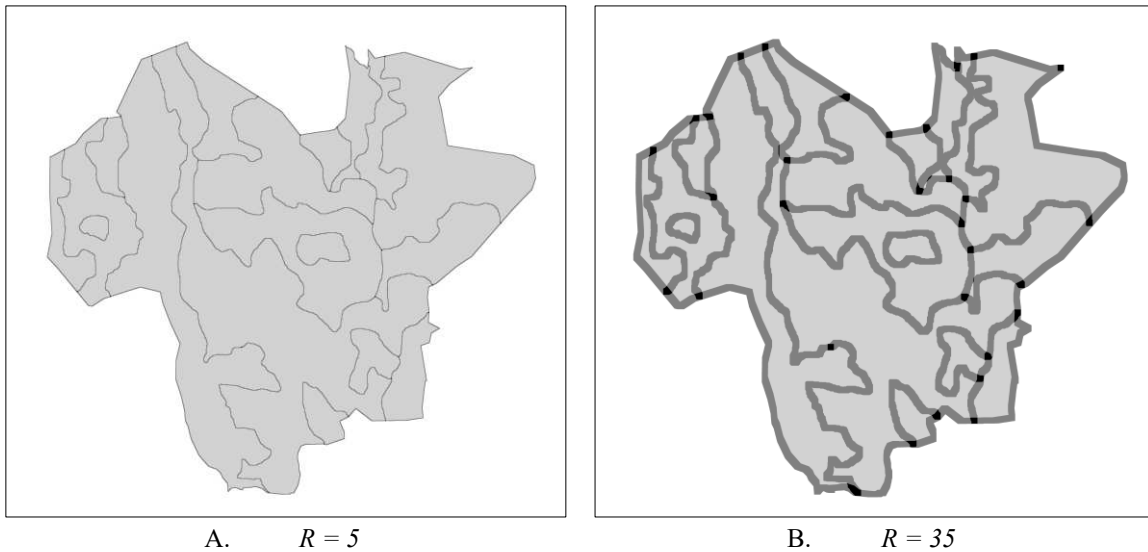


Fig. 14 Treatment applied to the geological map (monothematic cells in clear gray; bi-thematic cells in dark gray; tri-thematic cells in black)

4.2. Map Explor

This executable module calculates the value of each subindex (In_{div}) using a grid of squared cells. This study has tested four values of R . With $R = 22$, using a pixel size 5×5 m and a cell side c of 225 m, the 2025 pixels describing the surface S correspond to 0.050625 km^2 (5.0625 ha). Three other sizes have been tested: R 31 [$c = 315$; $S = 0.099225 \text{ km}^2$ (9.923 ha)], R 38 [$c = 385$; $S = 0.148225 \text{ km}^2$ (14.8225 ha)], R 44 [$c = 445$; $S = 0.198025 \text{ km}^2$ (19.8025 ha)].

Each cell can contain a given number (nc) of classes (i.e., 7 classes for the slope). This number leads to definition of the number of histograms ($hist[nc]$) that the program requires to calculate the diversity subindex In_{div} of this variable. Beginning the process, all histograms $hist[nc]$ are initialized to zero. During the scanning, the nc value

of a pixel that belongs to the cell produces an increment of 1 of the corresponding *hist[nc]* histogram. The distribution of the *nc* values within the cell is thus obtained and the subindex *In_{div}* corresponds directly to the number of not empty *hist[nc]* histograms.

The module generates for each variable (slope, surface shape, and roughness) a map of *In_{div}*, superimposing the drawing of the squared cell grid on the resulting image if required by the user.

To illustrate the behavior when using increasing *c* values, we present here the results obtained in the case of the slope subindex. The diversity value in each element of the grid grows in relation to the increase in cell size (Fig. 15). For *R* = 22, the pixel edge size *m* is 45 and the window size in pixels 45 × 45; according to the pixel size in meters (5 × 5), a cell surface corresponds to 5.0625 ha (0.051 km²); in this case, 8213 cells are required to cover the geopark surface that corresponds to 44.45% of the image. To cover this surface, it is necessary to use 4190 cells of 9.923 ha when *R* is 31, 2805 cells of 14.8225 ha when *R* is 38, and 2100 cells of 19.8025 ha when *R* = 44 has been chosen.

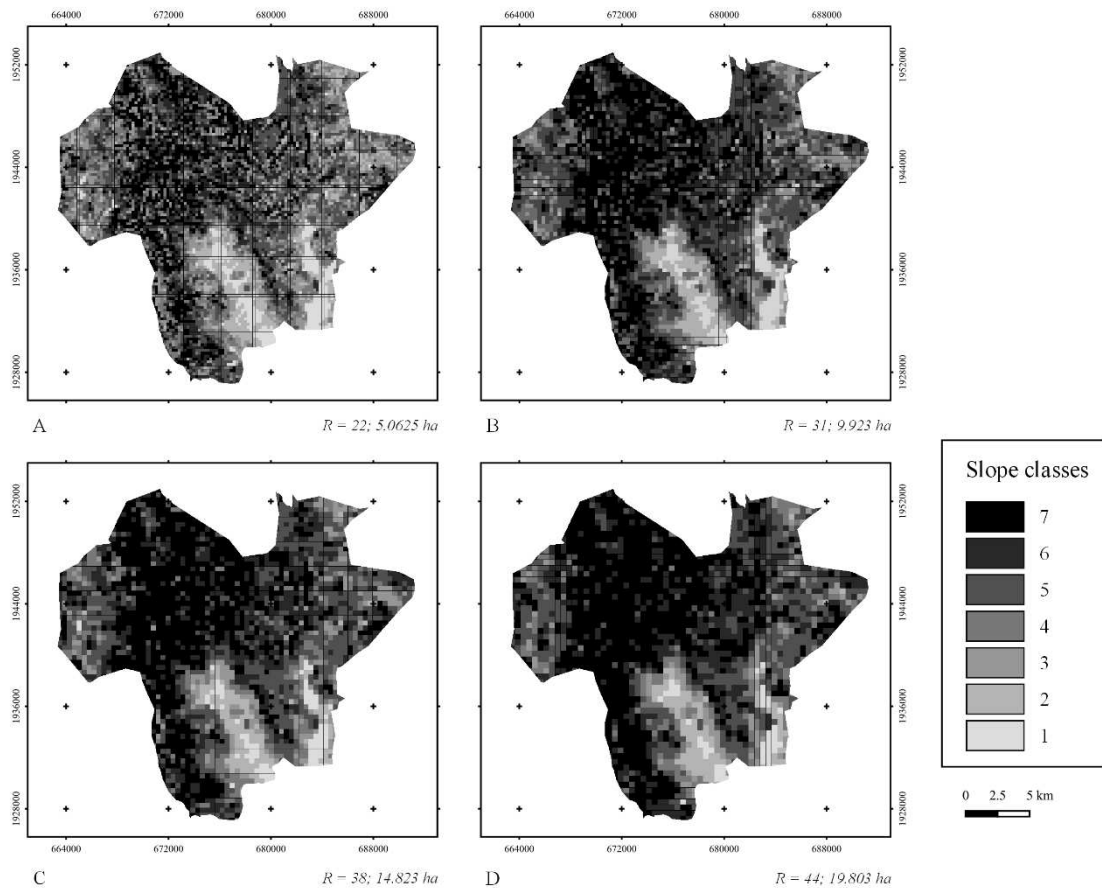


Fig. 15 Slope subindex for the Mixteca Alta UNESCO Global Geopark, Oaxaca, Mexico according to cell size

The relative percentages of the seven slope classes (Table 2) evolve as a function of cell size (Table 5); this allows us to specify the dominant character of each of these classes (Fig. 16), with the aim of defining the cell size most appropriate to study the area.

Map Symbology	Slope class	<i>R</i> 22	<i>R</i> 31	<i>R</i> 38	<i>R</i> 44
		45 × 45	63 × 63	77 × 77	89 × 89
1	Flat or almost flat (0-1°)	4.74	3.42	2.86	2.17
2	Gently sloping (2-3°)	7.91	5.22	4.46	4.60
3	Sloping (4-8°)	12.45	7.80	5.82	4.32
4	Moderately steep (9-12°)	17.61	12.73	9.70	8.27
5	Steep (13-20°)	22.73	24.44	23.04	20.21
6	Very steep (21-35°)	15.06	17.77	19.27	20.03
7	Extremely steep (>35°)	19.50	28.32	34.85	40.40

Table 5. Values of slope classes according to the cell size

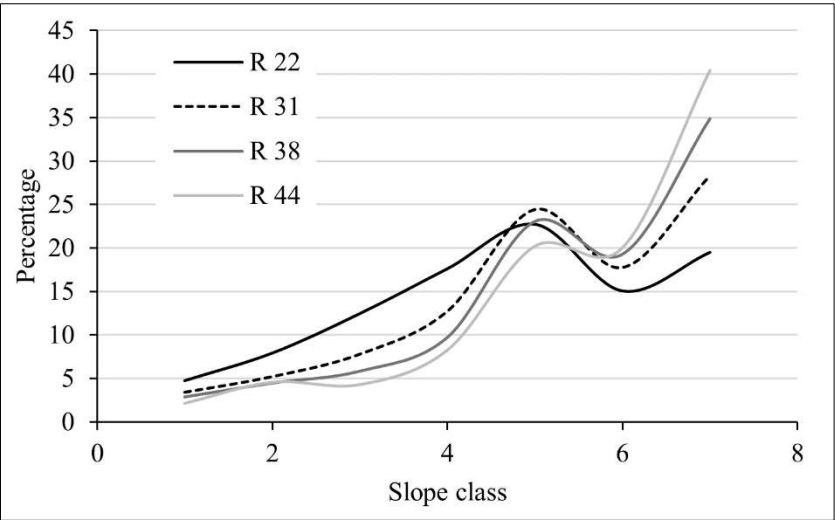


Fig. 16 Percentage of slope classes according to cell size

In this first example, the number of cells with high diversity naturally increases when the size of the cell increases; this behavior does not modify the general trend; this indicates that the morphodiversity value results from an objective analysis of the different morphologic zones.

For convexity and concavity, it is difficult to visualize the differences. Table 6 and figure 17 show the evolution of the surface shapes with the increasing of the range *R*.

Surface shape class	<i>R</i> 22	<i>R</i> 31	<i>R</i> 38	<i>R</i> 44
	45 × 45	63 × 63	77 × 77	89 × 89

Strong concavity	1.54	0.81	0.64	0.33
Concavity	14.37	8.51	6.17	4.7
Flat	70.35	65.92	60.04	55.07
Convexity	13.74	24.73	33.11	39.85
Strong Convexity	0	0.03	0.04	0.05

Table 6. Values of surface shape classes according to the cell size

Note that the tridimensional fractal dimension is a factor that measures roughness regardless of the altitude range; a plain or a plateau (both smooth surfaces) will have the same roughness index, which will result in a high value because in this case all the voxels will be filled. On the other hand, the fractal dimension will be low when the morphology of the area cannot fill the tridimensional space, for example a canyon or a mountain ridge. In fact, the scale of values is here reversed to facilitate visual understanding of the results offered by this parameter.

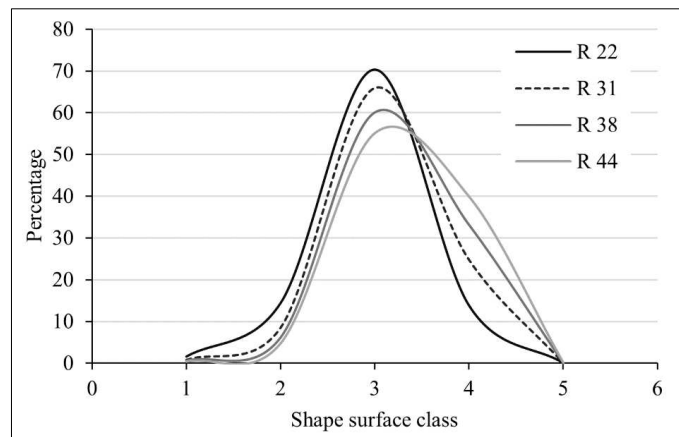


Fig. 17 Evolution of the surface shape classes according to range *R*

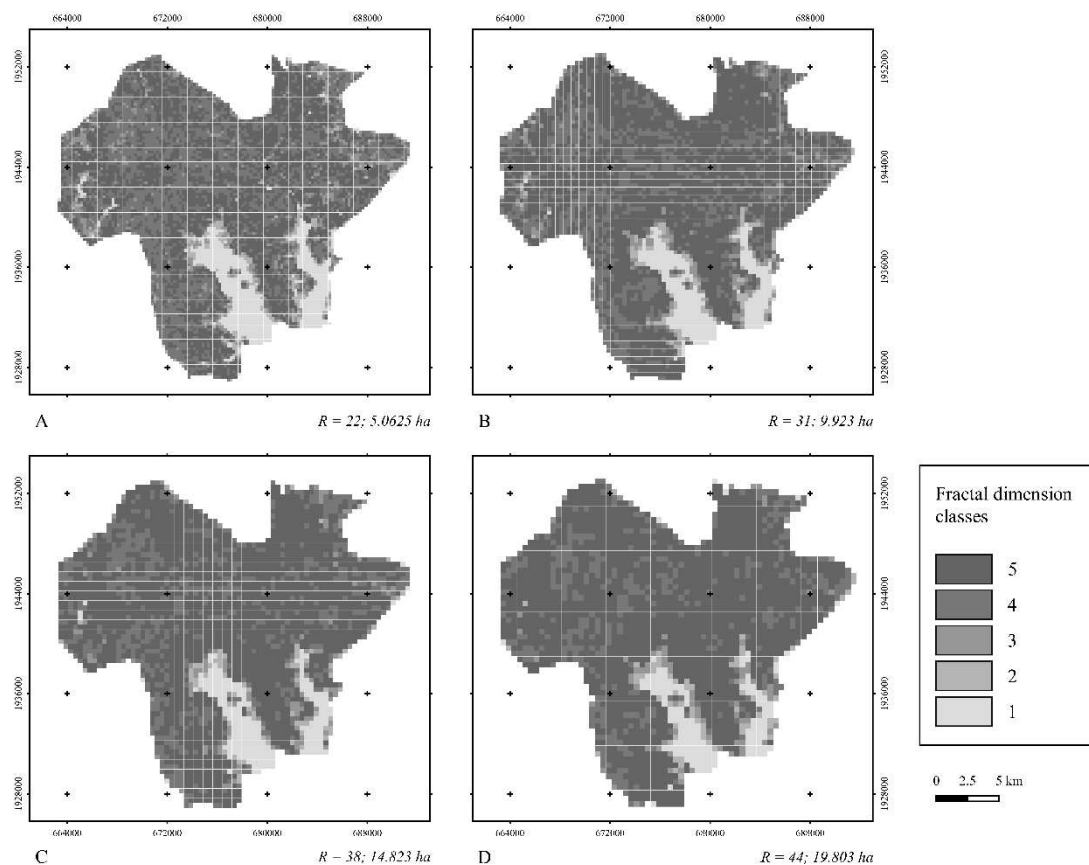


Fig. 18 Fractal dimension subindex according to the cell size

The fractal dimension is only partially influenced by the observation scale (Fig. 18); the areas of greatest slope are characterized by strong roughness. Table 7 and figure 20 show the evolution of the fractal indices related to the range R .

	$R \ 22$	$R \ 31$	$R \ 38$	$R \ 44$
Fractal dimension class	45×45	63×63	77×77	89×89
Very High	9.01	7.44	7.04	6.18
High	3.17	2.64	2.11	2.49
Medium	7.71	4.51	3.47	2.78
Low	39.55	29.12	22.14	16.69
Very Low	40.56	56.29	65.24	71.86

Table 7. Fractal dimension classes according to the cell size

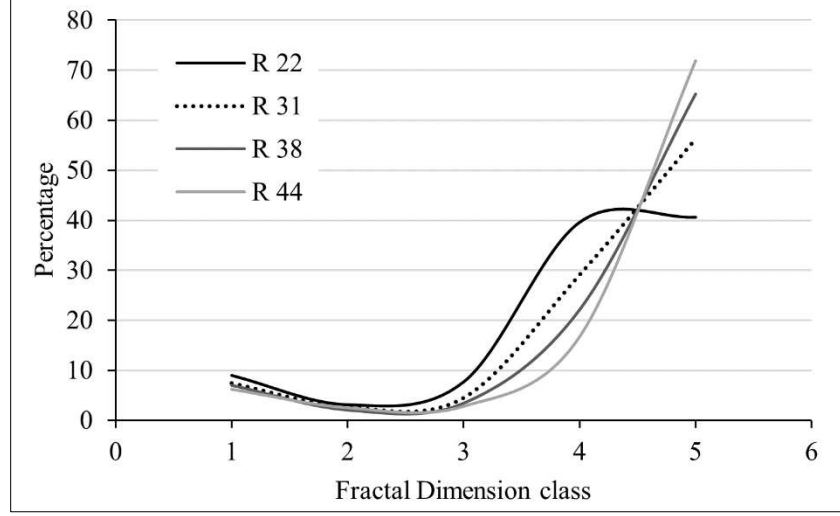


Fig. 19 Occurrence (%) of the fractal dimension classes related to the range R

The sum of these observations at the local level validates the results obtained at the general level.

4.3. Morphodiversity Index

The **Diversity Index** module sums the three sub-indices (slope, surface shape, and roughness) used to define morphodiversity. In addition, the algorithm considers the relative weight of each of these sub-indices to determine which one is dominant. This weight depends on the chosen scale, the type of moving window used for calculation (square or circular), and the resolution of the input data; all these variables are corroborated by field observations. This program also draws the square cell grid, if desired, and generates a detailed report concerning the results.

In a final phase, the algorithm distributes the different cells into 5 classes of morphodiversity (very low, low, medium, high and very high). For each cell k , the process is as follows: considering that Val_{Max} corresponds to the sum of the maximum ranks reached by each variable in the whole image, the normalization value $Val_{(k)}$ of the cell k is calculated as follows:

$$Val_{(k)} = \left(Val_{Sum(k)} / Val_{Max} \right) \times n \quad [5]$$

where $Val_{Sum(k)}$ is the sum of the ranks reached by all the variables in the cell k , and n is the number of morphodiversity classes, here 5.

Various tests define which of the three subindices is dominant (Fig. 20, Fig. 21 and Table 8). Considering the visibility, $R = 38$ has been chosen, that means a cell size of ≈ 15 hectares. The following four images result from the combination of the subindices slope, convexity, and fractal dimension, assigning an identical weight to each

in figure 20A and giving them differential weighting in each of the other images: 2-1-1 (Fig. 20B), 1-2-1 (Fig. 20C), and 1-1-2 (Fig. 20D).

Whereas the morphodiversity shown in figures 20A, 20B and 20D is comparatively homogeneous, the dominance assigned to the convexity subindex has introduced a greater dispersion in figure 20C; hence, the slope and the fractal dimension (which is a good indicator of geological limits) tend to homogenize the result.

Overall, figure 20 reveals three main distributions within the geopark: 1) a southern homogeneous area of the alluvial flat zones of the lower reaches of the Rio Grande and Rio Blanco (greens for very low and low morphodiversity), surrounded by transition zones of medium morphodiversity (yellow); 2) polygenic conglomerate sandstones of Oligocene age covered by remnants of Neogene andesitic tuffs and andesites (orange and red for high and very high diversity), where this disrupted cover leads to scattered abrupt changes of the convexity value from weak to intense, as can be observed when the convexity subindex is dominant; 3) Neocomian limestones located eastwards and westwards with a smoother surface and intermontane valleys (yellow and orange for medium morphodiversity).

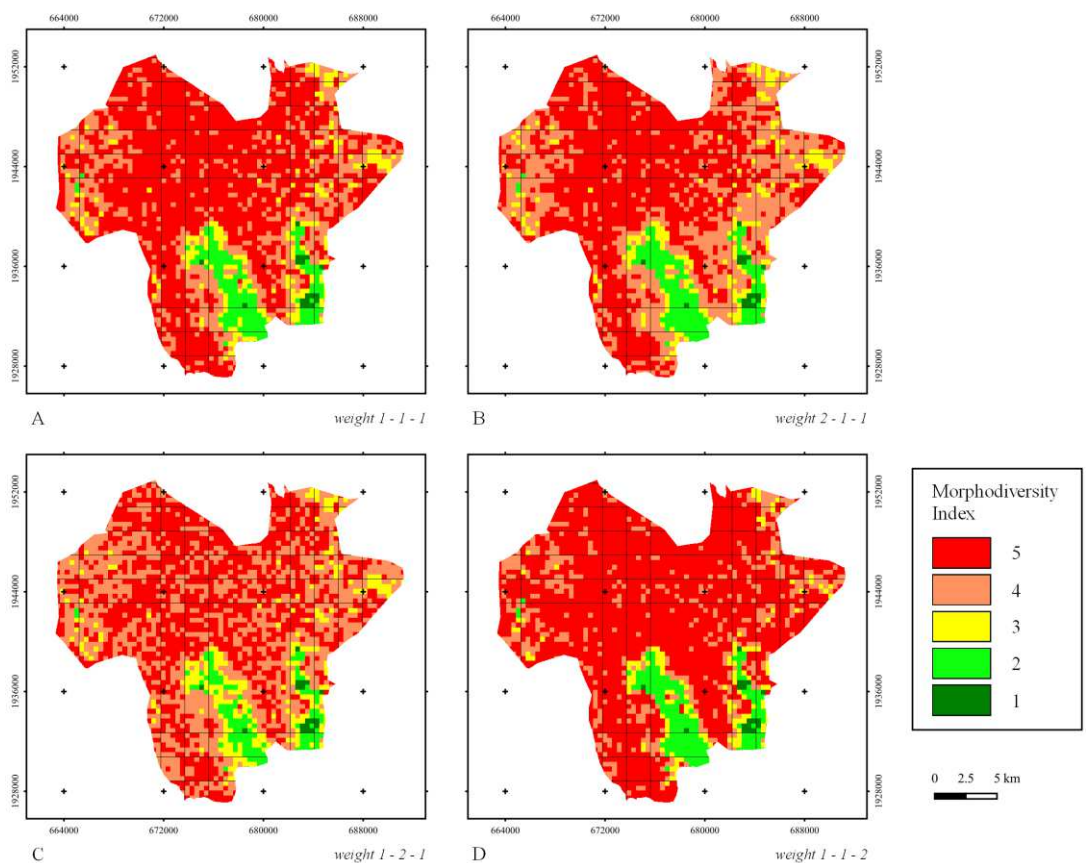


Fig. 20 Morphodiversity assessment (from 1 – very low morphodiversity, to 5 – very high morphodiversity) according to the relative weighting assigned to the subindices: slope - convexity - fractal dimension, respectively

Morphodiversity Index	Weighting			
	1-1-1	2-1-1	1-2-1	1-1-2
1 – Very low	0.64	0.64	0.64	0.64
2 – Low	6.13	6.66	4.46	6.63
3 – Medium	7.68	7.52	9.04	4.97
4 – High	27.02	35.31	42.88	18.15
5 – Very high	58.53	49.87	42.98	69.61

Table 8. Morphodiversity Index according to differential weighting assigned to the subindices slope - convexity – fractal dimension, respectively

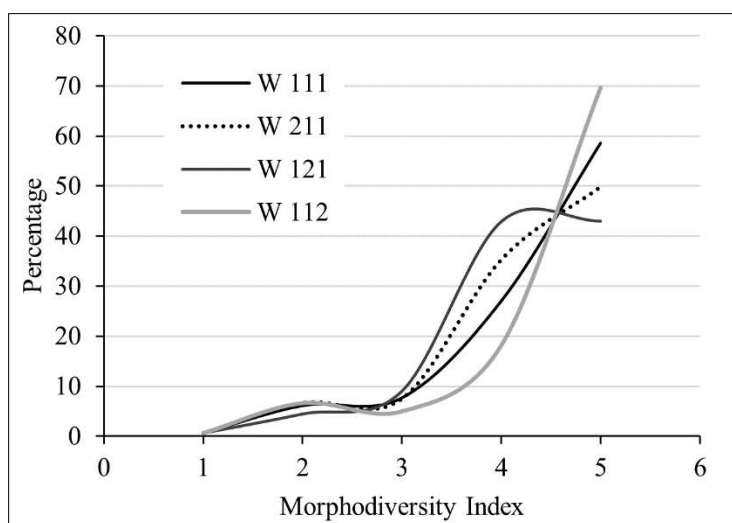


Fig. 21 Index distribution according to the weight

353

354 5. Results

355 This section presents the quantitative outcomes of the morphodiversity assessment carried out in the Mixteca
 356 Alta UNESCO Global Geopark, based on the analysis of slope, surface shape (convexity), and surface
 357 roughness (fractal dimension) derived from a high-resolution DEM.

358 In the Mixteca Alta UNESCO Global Geopark, 70.35% of the terrain is mountainous in terms of altitude (>2200
 359 m a.s.l.) and 54.98% in terms of slope (>9°); therefore, morphological analysis is essential for the study of
 360 geodiversity and biodiversity.

361 5.1 Sensitivity to cell size and scale effects

The sensitivity of morphometric parameters to cell size was evaluated using four range values ($R = 22, 31, 38$, and 44), corresponding to cell sizes between 5 and 20 hectares. Results show a systematic increase in diversity values as cell size increases, due to the higher probability of incorporating multiple morphometric classes within each cell.

For the slope subindex, the relative proportion of steep and very steep classes increases with cell size, while gentle and moderate slopes decrease. This reflects a scale effect in which larger cells integrate heterogeneous terrain conditions, enhancing the representation of extreme values. Despite this variation, the overall spatial pattern remains consistent, indicating robustness in the identification of major morphologic units.

Convexity exhibits a clearer scale dependency. As cell size increases, flat surfaces decrease significantly, while convex areas increase, suggesting that larger observation windows tend to emphasize watershed structures over local concavities. This behavior highlights the influence of spatial aggregation on surface shape representation.

In contrast, the roughness variable shows only partial sensitivity to scale. Although minor variations are observed, the spatial distribution of roughness remains relatively stable. This suggests that roughness, as measured through local fractal dimension is less dependent on observation scale compared to slope and convexity.

Overall, these results confirm that scale influences the magnitude of morphometric descriptors, but do not fundamentally alter their spatial patterns. Based on both statistical behavior and visual interpretability, a range value of $R = 38$ (≈ 15 ha) was selected as the most appropriate compromise between spatial detail and representativeness.

5.2 Subindex behavior

The three subindices—slope, convexity, and roughness—exhibit distinct behaviors, reflecting their complementary roles in describing terrain morphology.

The slope subindex shows a strong sensitivity to topographic gradients and clearly differentiates mountainous areas from low-relief zones. Its distribution is consistent across scales, making it a reliable indicator of relief intensity. However, its dominance in steep terrains may lead to an overrepresentation of high-diversity values when considered independently.

Convexity provides information on surface shape and geomorphological structure, distinguishing between concave areas (valleys), flat surfaces, and convex features (watershed boundaries). Its behavior is more scale-dependent and introduces variability in the results, particularly when weighted more heavily. This subindex is especially useful for detecting transitional zones and subtle morphological variations.

The roughness subindex, derived from the local fractal dimension, captures more detailed topographic variability independently of elevation range. Its relative stability across scales makes it a robust descriptor of

surface irregularity. Additionally, it shows a strong correspondence with lithological boundaries, reinforcing its geomorphological relevance.

The comparative analysis indicates that slope and roughness tend to homogenize the morphodiversity pattern, while convexity introduces greater spatial differentiation. This suggests that convexity plays a key role in enhancing spatial contrast, whereas slope and roughness provide structural consistency.

5.3 Morphodiversity index

The morphodiversity index integrates the three subindices by summing their contributions and applying a normalization procedure. The resulting values were classified into five categories, ranging from very low to very high morphodiversity.

The spatial distribution of the index reveals three main morphological domains within the study area. First, the southern sector is characterized by low morphodiversity, corresponding to alluvial plains with minimal topographic variation. These areas form homogeneous zones dominated by flat surfaces.

Second, regions composed of polygenic conglomerates and volcanic covers exhibit high to very high morphodiversity. These areas are characterized by strong topographic contrasts and abrupt variations in convexity, reflecting complex geomorphological processes.

Third, the limestone regions located in the eastern and western sectors display intermediate morphodiversity values, associated with smoother surfaces and the presence of intermontane valleys.

The analysis of different weighting schemes shows that the relative importance of each subindex significantly influences the result. When convexity is dominant, the index exhibits greater spatial dispersion, whereas slope and roughness tend to produce more homogeneous patterns. This confirms that morphodiversity is not only a function of terrain complexity, but also of the relative contribution of its defining components.

Overall, the morphodiversity index provides an integrated and spatially coherent representation of terrain heterogeneity, revealing patterns that are not evident when analyzing individual morphometric variables.

6. Discussion

The morphodiversity assessment presented in this study provides a set of spatially explicit outputs that can directly support geopark management. By identifying areas of contrasting morphodiversity, the results contribute to the definition of management priorities, zoning strategies, and the planning of geotourism activities within the Mixteca Alta UNESCO Global Geopark.

Areas classified as having high and very high morphodiversity correspond to zones of greater geomorphological complexity and interest, where variations in slope, convexity, and surface roughness are more pronounced.

These areas are likely to concentrate significant geomorphological features and landscape diversity, making them suitable candidates for geoconservation priorities and for the designation or reinforcement of geosites. Additionally, such areas may represent zones of high scenic and educational value, supporting the development of geotourism routes and interpretative activities.

In contrast, areas characterized by low morphodiversity tend to exhibit more homogeneous terrain conditions, such as alluvial plains and gently sloping surfaces. These zones may be more appropriate for the development of infrastructure, visitor facilities, or access routes, as they potentially involve lower environmental impact compared to more complex and sensitive areas. This differentiation can support the implementation of zoning schemes that balance conservation and use within the geopark.

Intermediate morphodiversity classes represent transition zones that may play a key role in connecting areas of high geoconservation value with zones of human use. These areas could be considered for controlled tourism or educational activities, where accessibility and landscape diversity can be combined without compromising sensitive geomorphological features.

Furthermore, the sensitivity of the morphodiversity index to the weighting of subindices highlights the adaptability of the method to different management objectives. For instance, emphasizing convexity may enhance the identification of geomorphological discontinuities, while slope and roughness may better capture terrain complexity relevant for hazard assessment or accessibility. This flexibility allows decision-makers to tailor the analysis according to specific planning needs.

Overall, the proposed morphodiversity approach represents a transferable and reproducible tool that can complement existing geodiversity assessments, particularly in regions where detailed thematic data are limited. Its integration into geopark management frameworks can support spatial zoning, conservation prioritization, and the sustainable development of geotourism.

7. Conclusions

Although the geodiversity of Mexico has been assessed at the national level, there are several limitations due to the lack of detailed cartography when the basic data are derived from large-scale cartographic documents, as in the study of the Mixteca Alta UNESCO Global Geopark. Here, the lack of detail regarding geology, geomorphology and edaphology (variables generally used to calculate geodiversity), precludes their use to detect diversity. For instance, the subindex calculated from the geological map of figure 2 does not provide information regarding diversity because it only identifies the boundaries between the four different formations (Fig. 14).

The use of a DEM of 5 m spatial resolution addresses this issue, because it can consider the continuous nature of the given information to calculate, directly from the tridimensional DEM surface, the value of various objective attributes such as slope, convexity or different types of roughness.

Bartuś and Mastej (2023) used altitude and topographic attributes (slope, aspect, curvature) to realize a morpho-structural analysis that they considered as morphodiversity. Adopting that concept, we have presented here a treatment of this type to characterize the morphological features of the Mixteca Alta UNESCO Global Geopark, using the continuous variables slope, surface shape (convexity), and roughness (tridimensional fractal dimension). Whatever the variable and partly whatever the weight of this variable, these results show a convergence between mountainous regions and morphologic zones that present high diversity; hence, measurement of morphodiversity is an objective instrument in geoconservation, to promote diverse aspects of the natural heritage, to create geoparks, to manage tourism and to conserve biodiversity.

The morphodiversity assessment of the Mixteca Alta UNESCO Global Geopark demonstrates that DEM-derived variables provide an effective and objective alternative for spatial characterization in areas lacking detailed thematic cartography. Beyond its methodological contribution, this approach offers direct applications for geopark management.

First, areas with high and very high morphodiversity can be considered priority zones for geoconservation, as they concentrate geomorphological complexity and landscape heterogeneity. Second, the spatial distribution of morphodiversity classes can support the planning of geotourism routes by identifying zones of high visual and educational interest. Third, the method allows the identification of homogeneous areas with low morphodiversity, which may be more suitable for infrastructure development or visitor services, reducing pressure on more sensitive zones.

Additionally, the sensitivity of the results to the weighting of subindices —particularly convexity— highlights the importance of adapting the method to specific management objectives. This flexibility makes morphodiversity a valuable tool not only for scientific analysis but also for decision-making processes within geoparks.

Therefore, morphodiversity mapping should be integrated into geopark management strategies as a complementary tool for zoning, conservation prioritization, and sustainable territorial planning.

References

- Bartuś T, Mastej W (2023) Morphodiversity as a Tool in Geoconservation: A Case Study in a Mountain Area (Pieniny Mts, Poland). *Sustainability*, 15(14), 11357.
- Bétard F, Peulvast JP (2019) Geodiversity Hotspots: Concept, method, and cartographic application for geoconservation purposes at a regional scale. *Environmental Management*, 63(6): 15 p., DOI 10.1007/s00267-019-01168-5
- Douglas I (1977) Humid landforms. An introduction to systematic Geomorphology. Vol.1, Australian National University Press, 288 p.
- Evans IS (1984) Correlation structures and factor analysis in the investigation of data dimensionality: Statistical properties of the Wessex land surface, England. *International Symposium on Spatial Data Handling*, Zurich, 1, 98-116.
- Ferrusquía I (1970) Geología del área Tamazulapan-Teposcolula-Yanhuitlán, Mixteca Alta, Estado de Oaxaca. In: Segura, L. and Rodríguez, R (eds). *Libro guía de la excursión geológica México-Oaxaca*. Ciudad de México: Boletín de la Sociedad Geológica Mexicana, 97-119.
- Ferrusquía I (1976) Estudios geológico-paleontológicos en la región de la Mixteca, Parte 1: Geología del área Tamazulapan-Teposcolula-Yanhuitlán, Mixteca Alta, Estado de Oaxaca, México. *Boletín del Instituto de Geología*, 97, 160.
- Haneberg WC, Creighton AL, Medley EW, Jonas DA (2005) Use of LiDAR to assess slope hazards at the Lihir gold mine, Papua New Guinea. In: *Proceedings, International Conference on Landslide Risk Management*, Vancouver, British Columbia.
- Hobson RD (1972) Surface roughness in topography: A quantitative approach. In: Chorley R.J. (ed) *Spatial Analysis in Geomorphology*, London, UK, Harper and Row, 221-245.
- Instituto Nacional de Estadística y Geografía (INEGI) (1984) Conjunto de datos geológicos vectoriales, Serie I, Oaxaca, E1409, escala 1:250,000.
- Instituto Nacional de Estadística y Geografía (INEGI) (2013) Conjunto de datos vectoriales de información topográfica E14D25, Villa de Tamazulápam del Progreso, escala 1:50 000, serie III.
- Kozłowski S (2004) Geodiversity. The concept and scope of geodiversity. *Przegląd Geologiczny*, 52(8/2), 833-837.
- Lausch A, Schaepman ME, Skidmore AK, Catana E, Bannehr L, Bastian O, Borg E, Bumberger J, Dietrich P, Glässer C, Hacker JM, Höfer R, Jagdhuber T, Jany S, Jung A, Karnieli A, Klenke R, Kirsten T, Ködel U, Kresse W, Mallast U, Montzka C, Möller M, Mollenhauer H, Pause M, Rahman M, Schrod F, Schmullius C, Schütze C, Selsam P, Syrbe RU, Truckenbrodt S, Vohland M, Volk M, Wellmann T, Zacharias S, Baatz R (2022) Remote Sensing of Geomorphodiversity Linked to Biodiversity—Part III: Traits, Processes and Remote Sensing Characteristics. *Remote Sens.*, 14, 2279.
- Lopes C, Teixeira Z, Pereira DI, Pereira P (2023) Identifying optimal cell size for geodiversity quantitative assessment with richness, diversity and evenness indices. *Resources*, 12(6), 65.
- Martiny B, Martínez R, Morán D, Macías C, Ayuso R (2000) Stratigraphy, geochemistry and tectonic significance of the Oligocene magmatic rocks of western Oaxaca, southern Mexico. *Tectonophysics*, 318, 71-98.

Montes de Oca-Villatoro A (2021) Actualización cartográfica geológico- estructural de la porción Noroeste del Geoparque Mundial UNESCO Mixteca Alta. Tesis de licenciatura. Universidad Autónoma del Carmen, Campeche.

Olaya V (2009) Chapter 6. Basic Land Surface Parameters. In: Hengl T and Reuter HI (eds), *Geomorphometry: Concepts, Software, Application*. Vol. 33 of *Developments in Soil Science*, 141-169, Elsevier, Amsterdam.

Orozco-Ramírez Q, Bocco G (2021) Agricultural landscapes diversity in the Global Geopark UNESCO Mixteca Alta, Oaxaca, Mexico.

Ortiz-Pérez MA, Hernández-Santana JR, Figueroa-Mah-Eng JN (2004). Reconocimiento fisiográfico y geomorfológico. In: García-Mendoza AJ, Díaz MDJO, Briones-Salas M (eds.) *Biodiversidad de Oaxaca*. Instituto de Biología, UNAM, Fondo Oaxaqueño para la Conservación de la Naturaleza, World Wildlife Foundation, 43-54.

Parrot JF (2007) Tri-dimensional parameterisation: an automated treatment to study the evolution of volcanic cones. *Géomorphologie* 3, 37-47. doi.org/10.4000/ geomorphologie. 2723

Parrot JF (2011) Software Pins_V2. Número de certificado INDA (Instituto Nacional de Derecho de Autor): 03-2011-120112060000-01.

Parrot JF (2016) Generación de MDE a partir de datos vectoriales. Paquete de Módulos Ejecutables desarrollados en C++. Número de registro del certificado público de Derecho de Autor: 03-2016-103110072200-01.

Parrot JF (2023a) Programa Map Explor. Número de registro del certificado público de Derecho de Autor: 03-2023-091810372800-01.

Parrot JF (2023b) Programa Diversity Index. Número de registro del certificado público de Derecho de Autor: 03-2023-091810384900-01. 0257

Parrot JF (2025a) Programa Surface JFP Param V2. Número de registro del certificado público de Derecho de Autor: 03-2025-082911473100-01.

Parrot JF (2025b) Programa Surf 2D 3D JFP V2. Número de registro del certificado público de Derecho de Autor: 03-2025-082911143500-01.

Parrot JF, Lugo-Hubp JI, Ramírez-Núñez C, Zamorano-Orozco JJ (2025) Geomorfología tridimensional para el análisis del relieve mexicano. *Geografía Para el Siglo XXI*. ISBN:978-607-587-005-2.

Parrot JF, Ramírez-Núñez C (2021) Positive and negative roughness according to local differences between DEM surface and 3D reference planes. *ISPRS Ann. Photogramm. Remote Sens. Spatial Inf. Sci.*, V-3-2021, 159–165, <https://doi.org/10.5194/isprs-annals-V-3-2021-159-2021>

Parrot JF, Ramírez-Núñez C (2024) Índices morfométricos de los Geoparques de México. V Simposio Mexicano sobre Geopatrimonio y Geoparques. 4-7 de diciembre de 2024, Ciudad de México (Ponencia).

Parrot JF, Ramírez-Núñez C (2025) Programa Objective Window Size. Número de registro del certificado público de Derecho de Autor: 03-2025-082911365300-01.

Parrot JF, Ramírez-Núñez C, Palacio JL (2024) Geodiversity of Mexico. *Investigaciones Geográficas*, (115). <https://doi.org/10.14350/rig.60903>

- Pike RJ, Evans IS, Hengl T (2009) Geomorphometry: a brief guide. In: Hengl T., Reuter HI (eds). Geomorphometry: concepts, software, applications. Vol. 33 of Developments in Soil Science, 3-30, Elsevier, Amsterdam.
- Ramírez-Santiago R, Orozco-Ramírez Q, Clark Tapia R, Cruz Ramírez MÁ (2021) Woody Vegetation Types and floristic composition in the UNESCO|4567 Global Geopark Mixteca Alta, Oaxaca. *Madera y bosques*, 27(3).
- Ramírez Núñez, C., Parrot, J.-F., Siebe, C., Vázquez Selem, L. (2026) Semiautomated classification of units in volcanic terrain based on three morphometric attributes derived from a digital elevation model (DEM). *Earth Surface Processes and Landforms*, 51(5), e70299.
- Ruhe RV (1960) Elements of the soil landscape. *Transactions 7th Int. Congr. Soil Sci.*,4: 165-170.
- Salas G (1949) Bosquejo geológico de la cuenca sedimentaria de Oaxaca. *Boletín de la Asociación Mexicana de Geólogos Petroleros*, 1, 79–156.
- Sánchez-Cortez JL, López-Castañeda N, Orozco-Ramírez Q, Palacio-Prieto JL, Ramírez-Miguel X (2025) Updating the Inventory of Geosites in the Mixteca Alta UNESCO Global Geopark Through the Application of Participatory Strategies. *Geoheritage*, 17(2), 1-17.
- Serrano E, Ruiz-Flaño P (2007) Geodiversity: a theoretical and applied concept. *Geographica Helvetica*, 62(3), 140-147.
- Servicio Geológico Mexicano (SGM, 2000) Carta Geológico-Minera Oaxaca E14-9. Oaxaca y Puebla.
- Taud H, Parrot JF (2005) Measurement of DEM roughness using the local fractal dimension. *Géomorphologie*, 4: 327-338. doi.org/10.4000/geomorphologie.622
- Taud H, Parrot JF, Álvarez R (1999) DEM generation by contour line dilation. *Computers & Geosciences*. 25(7), 775-783. ISSN: 0098-3004.
- Wilson MF, O'Connell B, Brown C, Guinan JC, Grehan AJ (2007) Multiscale terrain analysis of multibeam bathymetry data for habitat mapping on the continental slope. *Marine Geodesy*, 30(1-2), 3-35.