EARTH SCIENCES
RESEARCH JOURNAL
Earth Sci. Res. J. Vol. 28, No. 3 (September, 2024): 305 - 323

UNIVERSIDAD NACIONAL DE COLOMBIA

Morphological characterization of karst geodiversity in Municipality of Archidona (Ecuador), Napo Sumaco Aspiring UNESCO Global Geopark

José Luis Sánchez-Cortez[1, 2] *, Kathleen Vélez-Macías[2,4], Marco Simbaña-Tasiguano[2,3], Mariela Rodríguez-Calvopiña[2,3], Oswaldo Fuentes-Campuzano[4], Carolina Freire-Guerrero[2]
1. Institute of Geography, National Autonomous University of Mexico. Scientific Research Circuit, University City. Coyoacán, México, D. F.
2. Napo Sumaco Geopark Foundation, Tena, Ecuador
3. Yachay Tech University, Hacienda San José, Urcuquí, Ecuador
4. University of Guayaquil, Natural Sciences Faculty. Juan Tanca Marengo Avenue and Raul Gomez Lince Avenue. Guayaquil, Ecuador
* Corresponding autor: jsanchez@geografia.unam.mx

ABSTRACT

Karst morphology is a complex and highly systems and beneficial resource, it plays a fundamental role in geosystemic services and providing landscapes, water, energy and economic resources through tourism. Karst geodiversity is one of the main geomorphological components of the Napo Sumaco Aspiring UNESCO Global Geopark (NSAUGG), through which education and conservation strategies are directed locally. The present study focuses on deepening the knowledge of the morphologies of karst origin in the geopark, specifically in the municipality of Archidona (Ecuador), with the characterization of the types of structures at the micro (between 1 and 100 cm) and mesoscale (between 1 and 1000 m), in five sites located within the municipality. The abundance of microscale geoforms are related to a limited evolution of karst morphologies that can be observe in the local Amazonian karst system. Furthermore, an inverse relationship is established between the relative values of intrinsic geodiversity (IG) and karst disturbance (KDI) levels, being that the sites with lower levels of impact or disturbance show a greater diversity of karst morphologies. In this socio-environmental dynamic, the role played by the Napo Sumaco Aspiring UNESCO Global Geopark is fundamental, contributing to the strengthening of local capacities and the promotion of geoeducational and informative processes focused on the conservation of the karst region and its geodiversity in the municipality of Archidona.

Keywords: Geoconservation; Geodiversity; Intrinsic geodiversity; Karst; Napo Sumaco Geopark

Caracterización morfológica de la geodiversidad kárstica en el Municipio de Archidona (Ecuador), Geoparque Aspirante UNESCO Napo Sumaco

RESUMEN

La morfología kárstica es un recurso complejo, altamente sistémico y beneficioso, desempeña un papel fundamental en los servicios geosistémicos y proporciona paisajes, agua, energía y recursos económicos a través del turismo. La geodiversidad kárstica es uno de los principales componentes geomorfológicos del Geoparque Aspirante UNESCO Napo Sumaco (NSAUGG), a través del cual se dirigen estrategias de educación y conservación a nivel local. El presente estudio se centra en profundizar en el conocimiento de las morfologías de origen kárstico en el geoparque, concretamente en el municipio de Archidona (Ecuador), con la caracterización de los tipos de estructuras a microescala (entre 1 y 100 cm) y mesoescala (entre 1 y 1000 m), en cinco sitios localizados dentro del municipio. La abundancia de geoformas a microescala se relaciona con una limitada evolución de las morfologías kársticas que se observan en los sistemas kársticos amazónicos locales. Además, se establece una relación inversa entre los valores relativos de la geodiversidad intrínseca (IG) y los niveles de perturbación kárstica (KDI), siendo que los sitios con menores niveles de impacto o perturbación son los que presentan una mayor diversidad de morfologías kársticas. En esta dinámica socio-ambiental, el papel desempeñado por el Geoparque Aspirante UNESCO Napo Sumaco es fundamental, contribuyendo al fortalecimiento de las capacidades locales y a la promoción de procesos geoeducativos y divulgativos centrados en la conservación de la región kárstica y su geodiversidad en el municipio de Archidona.

Palabras clave: Geoconservación; Geodiversidad; Geodiversidad Intrínseca; Karst; Geoparque Napo Sumaco;

Record
Manuscript received: 14/04/2024
Accepted for publication: 01/10/2024

How to cite item:
Sanchez Cortez, J. L., Velez-Macias, K., Simbaña-Tasiguano, M., Rodriguez-Calvopiña, M., Fuentes-Campuzano, O., & Freire-Guerrero, C. (2024). Morphological characterization of karst geodiversity in Municipality of Archidona (Ecuador), Napo Sumaco Aspiring UNESCO Global Geopark. *Earth Sciences Research Journal, 28*(3), 305-323. https://doi.org/10.15446/esrj.v28n3.113933

ISSN 1794-6190 e-ISSN 2339-3459
https://doi.org/10.15446/esrj.v28n3.113933

1. Introduction

Karst landscapes are made up of a series of morphologies, due to a combination of chemical and physical processes, which cause the rock dissolution and chemical precipitation of carbonate (Lewin and Woodward, 2009; De Waele, 2017; Ford and Williams, 2007; Robledo et al., 2020), whose development is influenced by water regimes, lithological and structural characteristics, among other factors (Andreychouk, 2016). Karst provides a series of environmental and ecosystem assets, from water provision, thermal regulation, generation of habitats and unique ecological niches, to the provision of landscapes for recreational purposes (Langer, 2020). Cave and show caves is one of the main aspects linked to the use of karst; its social and economic implications generate a great community impact (Cigna and Burri, 2000; Cigna and Forti, 2013). However, given the anthropic pressures suffered by the resources associated with karst, the study of the conservation and threats of these systems is a widely developed topic at a global level (Christman et al., 2005; Sánchez-Cortez et al., 2022b).

Karst systems represent very complex and sensitive natural systems (Bahtijarevic, 1996; North, 2009; Robledo et al., 2020), resulting from epigenetic processes that involve, in addition to the physicochemical conditions of the rocks, factors such as vegetation, thickness of overburden materials, and temperature of water and atmosphere (White, 1970). The set of karst morphologies can be divided by their location environment, being of subaerial (exokarst) and underground (endokarst) origin, which facilitates their classification and description in accordance with their scale (Robledo et al., 2020). However, it is quite common for there to be polygenic morphologies that can complicate classifications (Ford and Williams, 2007; Andreu et al., 2016).

Various morphologies at different scales are part of karst landscapes, and according to traditional geomorphology, they can be classifiable by their spatial and temporal scale (Rivases, 2007). Thus the sites defined at the microscale and mesoscale will be related to the quantity of time that the environment uses for the formation of a morphology (de Boer, 1992; Carvajal Perico, 2012). However, beyond the scale used, the entire set of these landscape elements is part of the karst geodiversity of a territory. It is necessary to consider that the analysis of geological diversity consists of determining the varieties, frequency and distribution of geological elements within a territory (Gray, 2004; Gray, 2013), with intrinsic geodiversity as one of its main values (Brilha, 2016; Nieto, 2023).

In this sense, was implemented a model to analyze the karst morphology diversity in carbonatics units in the area that includes the municipality of Archidona, located in the province of Napo, Ecuador, within the Napo Sumaco Aspiring UNESCO Global Geopark (NSAUGG) (Napo Sumaco Aspiring Geopark, 2019), in order to expose and describe the intrinsic geodiversity at micro and mesoscale present in this area of geological and geomorphological importance (Sánchez-Cortez et al., 2023). The general hypothesis maintains that sites with greater karst morphology diversity are associated with a better state of conservation and lower anthropic pressure, according to the correlation of the data obtained by Sánchez-Cortez et al. (2022b). These assessments show heterogeneous diversity values in each of the sites analyzed, and it is considered that the characterization of the karst elements within the NSAUGG will serve as a potential tool for geotourism practices, geoeducation and the promotion of geoconservation of the karst landscape.

2. Materials and Methods

Selection and description of the study area

In the geological context of Ecuador, geological formations that contain carbonate rocks are mainly concentrated in the Amazon region (Constantine et al., 2018), towards the east of the country, associated with the presence of a back-arc sedimentary basin, which develops as a result of transpressive stresses present from the terminal Cretaceous and subsequent tectonic inversion (Baby et al., 2014). These geodynamic conditions allowed the outcropping of carbonate rocks on the surface. The present study focuses on the municipality of Archidona, province of Napo, which houses a significant density of karst elements (Besson et al., 1982). This municipality extends from the Eastern Andes mountain range towards the Andean foothills or sub-Andean zone (also known in Ecuador as the Upper Amazon) (GAD Municipal de Archidona, 2011). Archidona has a total surface area of 3029 km^2, of which 14.92% (452 km^2) is defined as a karst area (Sánchez-Cortez et al., 2022b) (Fig. 1).

In this sector, outcrops of the Napo formation (Upper Cretaceous) appear (Fig. 2), which comprises limestone, sandstone and calcareous shale (Baby et al., 2014). These materials correspond to the rocks where the main karst elements are generated in the study area. These limestones are associated with a shallow-marine deposit environment of a back-arc basin, and exhibit notable paleontological characteristics, highlighting the presence of fossils of ammonites, foraminifera and ostracods (Sánchez-Cortez et al., 2022a). The karst area of the Municipality of Archidona is part of the territory defined as Napo Sumaco Aspiring UNESCO Global Geopark (NSAUGG), whose extension is 1780 km^2 (Fig. 3). The NSAUGG is considered a geodiversity hotspot in the Amazon River basin (Alsbach et al., 2024). Its main geological and geomorphological interests are related to the karst reliefs and morphologies, as well as to the volcanic elements and processes inherent to the Sumaco Volcano (Sánchez-Cortez et al., 2023; Vera et al., 2023).

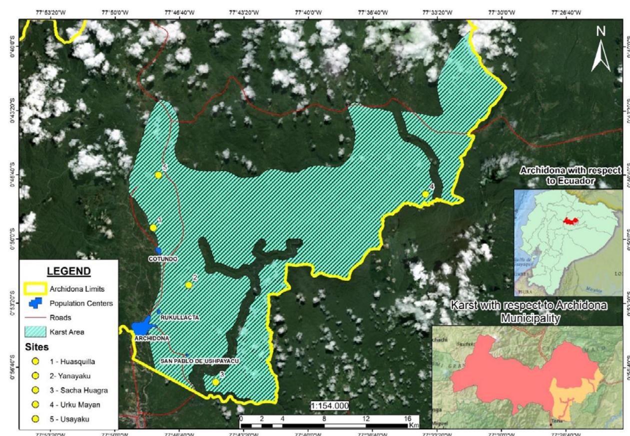


Figure 1. Municipality of Archidona. Sánchez-Cortez et al. (2022b) previously defined the karst area.

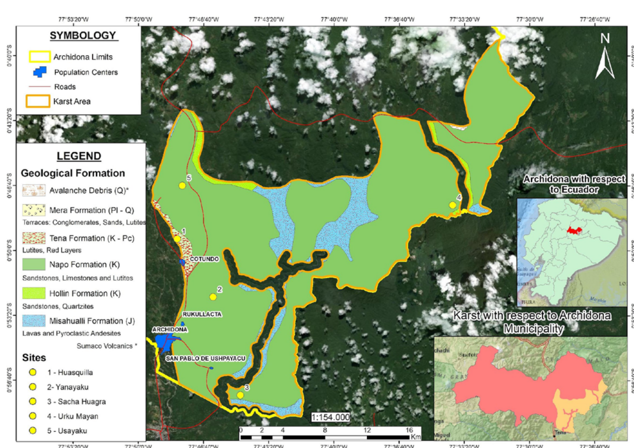


Figure 2. Geological map of the study area, which highlights the distribution of the Napo formation (Upper Cretaceous), consisting of limestone, sandstone and calcareous shale.

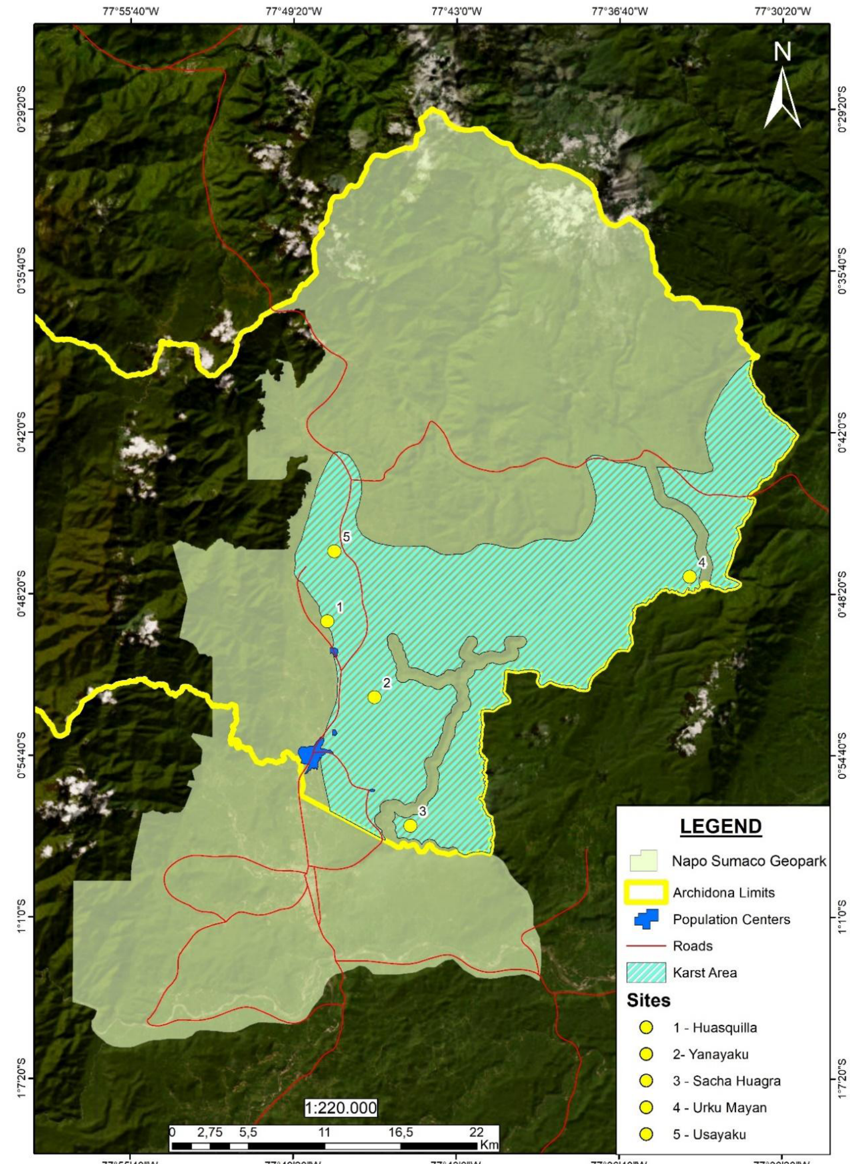


Figure 3. Karst area in Archidona and the reference of the Napo Sumaco Aspiring UNESCO Global Geopark

Methodology for the definition and description of karst morphologies in the study area

Once the work area was delimited within the municipal jurisdiction of Archidona and the Napo Sumaco Aspiring UNESCO Global Geopark, five sites were established to carry out specific observations of the karst geoforms: 1) Huasquila, 2) Yanayaku, 3) Sacha Huagra, 4) Urku Mayan and 5) Usayaku (Table 1, Fig. 1). A selective geomorphological survey or geomorphological mapping was applied, using a direct observation of the features of the karst morphologies (Lahe, 1985; Lugo Hubp, 1988), and a cross-sectional geological mapping method (Coe et al., 2010), along interpretive trails used within the NSAUGG. Each identified structure was described according to its conditions and specific characteristics.

For the definition and description of karst morphologies, two spatial scales were considered, in accordance with those established by Rivases (2017): geomorphological mesoscale and microscale, considering that this proposed spatial hierarchy is related to temporal scales. Time in the geomorphological mesoscale is related to intercalated processes of tectonic and climatic origin, while time in the geomorphological microscale is defined by short processes with climatic and environmental origins (Fernández, 2007; Carvajal Perico, 2012, Pardo-Igúzquiza et al., 2013). In addition to the genetic process that originated karst morphologies, microscale structures were standardized as centimetric (between 1 and 100 cm) and mesoscale structures as metric (between 1 and 1000 m); the scales fulfill the exclusive function of dimensioning the size of the inventoried morphologies.

Finally, for each of the five studied sites, an evaluation of intrinsic geodiversity was generated, which is established as the number of entities defined in a territory, or the number of morphologies observed within a specific area (1) (Carcavilla, 2006; Carcavilla et al., 2007). It has been considered that the greater the number of karst morphologies observed in a surface unit, the more diverse the area will be (Kubalíková et al., 2023; Najwer et al., 2023;

Nieto, 2023). The assessment of intrinsic geodiversity was carried out to establish areas with greater geodiversity, which were correlated with the state of conservation and the uses of each site.

$$IG = M / A \quad 1)$$

Being: IG, intrinsic geodiversity; M, number of morphologies; and A, area.

Both micro and mesoscale geomorphological sites were considered to define the assessment of intrinsic geodiversity (IG) or abundance of karst morphologies. To evaluate the state of conservation, the study carried out by Sánchez-Cortez et al (2022) was used, in which the areas of greater or lesser affectation of the karst in the municipality of Archidona are established using the Karst Disturbance Index (KDI). Finally, a simple relationship is created between the KDI values of each site, divided by the individual values of IG obtained.

Results and discussion

Inventory and description of karst morphologies

The area of karst rocks located in the Municipality of Archidona, province of Napo, Ecuador, presents an important diversity of morphologies of karstic origin, and has an antecedent of many sites being used for the development of speleotourism (Robledo and Durán, 2011; Cruz Ramírez, 2014, Sánchez -Cortez et al., 2017, 2022a). The five sites used for data collection and observation, are places where tourist services are provided through interpretive trails and observation points, as part of the Karstic Relief geosite of Napo Sumaco Aspiring UNESCO Global Geopark (NSAUGG).

In this sense, it is necessary to point out that the observations were made in the transects, trails and observation points that are normally used by the local guides of NSAUGG, therefore is a high probability that the variety and diversity of karst morphologies will be very greater than that determined in this work, considering that a large part of the total areas of each site was not intervened. However, it is known that georoutes are established in the sectors where the most representative examples of the geodiversity and geoheritage of a territory exist (Drapela, 2023).

Below, the morphologies observed at the sites Huasquila (Table 2), Yanayaku (Table 3), Sacha Huagra (Table 4), Urku Mayan (Table 5), and Usayaku (Table 6) are detailed. A total of 35 types of morphologies were observed during the information gathering, without making any distinction between their scale, corresponding to 11.11% of morphologies present in Huasquila, 13.89% in Yanayaku, 8.33% in Sacha Huagra, and finally 33.33% for Urku Mayan and Usayaku. It is worth pointing out that the types of morphologies could be repeated from one site to another (For example, stalactites and stalagmites were observed in three of the five sites) and is not counted the number of elements belonging to the same type (For example, if ten stalactites were observed, it is only considered as a single type).

Table 1. The main characteristics of the observation sites established for the present study.

Sites	Area (Km^2)	Average altitude (m.a.s.l.)	Average precipitation (mm)	Geological formation	Lithology (strata type)	Temperature (°C)	Main activities developed in the area
Huasquila	1.10	825	3800	Napo Formation (K)	Calcareous Sandstones, Limestones and Shales.	26	Tourism and family farming.
Yanayaku	3.20	728	3800	Napo Formation (K)	Calcareous Sandstones, Limestones and Shales.	28	Tourism, animal husbandry and farming.
Sacha Huagra	2.00	743	3800	Napo Formation (K)	Calcareous Sandstones, Limestones and Shales.	26	Tourism, animal husbandry and intensive farming.
Urku Mayan	3.50	990	4500	Napo Formation (K)	Calcareous Sandstones, Limestones and Shales.	23	Tourism, family farming, sale of wood and forest resources
Usayaku	1.20	950	3800	Napo Formation (K)	Calcareous Sandstones, Limestones and Shales.	24	Tourism and family farming.

Table 2. Main karst morphologies defined in Huasquila site

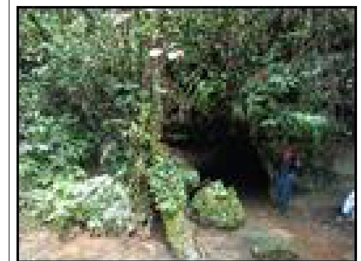
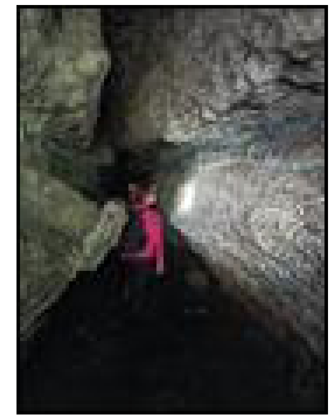
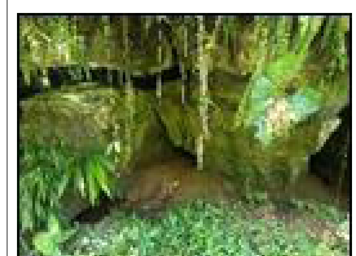
Karst Morphology	Scale	Description	Figure
Caves	Mesoscale	Cavities generated by dissolution as a result of active hydrological flows. It has a length close to 250 m and 2 m wide in average.	
Mommilk	Mesoscale	Whitish substance found inside the cave, which when hardened covers the walls of the cave and becomes aggregates of fine carbonate crystals.	
Rillenkarren	Microscale	Dissolution fissures like grooves, generated by the flow of water over the rock, following the gravity gradient.	
Subsoil Cups	Microscale	Small figures with very smooth slopes, they can be circular or semi-circular, and have a diameter no larger than 5 cm. Its formation is related to granular calcareous rocks.	

Table 3. Main karst morphologies defined in Yanayaku site.

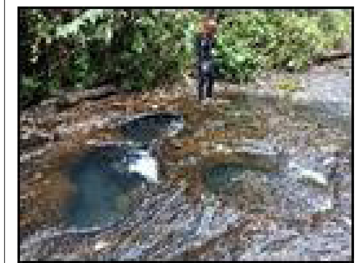
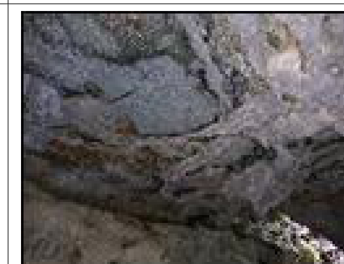
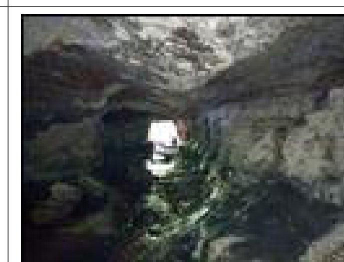
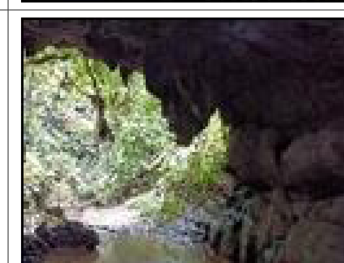
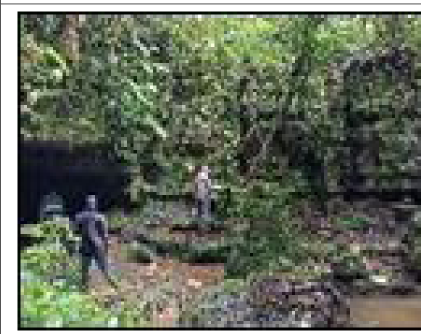
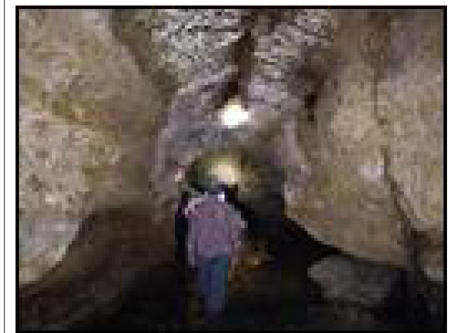
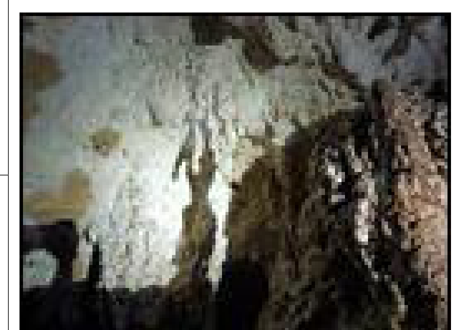
Karst Morphology	Scale	Description	Figure
Kamenitza	Microscale and Mesoscale	Small or large pot-shaped cavities, characterized by their closed shapes, which are developed by a mixture of dissolution and friction processes.	
Caves	Mesoscale	Cavity generated by dissolution as a consequence of active hydrological flows. This cavity is located in calcareous sandstone rocks, it is 100 m long and 7 m wide on average.	
Boxwork	Mesoscale	It is formed on the top of the cave and is generated by the crystallization of calcite within the joints, like a reticle. Boxwork appears when the limestone is eroded before the calcite of the joints.	
Mommilk	Mesoscale	Whitish substance found inside the cave, which when hardened covers the walls of the cave and becomes aggregates of fine carbonate crystals.	
Stalactites	Microscale	Karst morphology with shape of an irregular cone, its peak is oriented downwards. They form from the top of caves, and their growth is due to the slow filtration of water and calcareous materials.	

Table 4. Main karst morphologies defined in Sacha Huagra site.

Karst Morphology	Scale	Description	Figure
Scallops	Microscale	Also known as ripple, they are wave-like shapes that are sculpted into the walls of soluble rocks. They have a very variable length, from 1 to 30 cm. The space between wave and wave is much deeper as the wave is wider.	
Grikes and Clints	Mesoscale	Deep dissolution fissures in the form of grooves penetrate even impermeable strata. The grikes penetrate beyond 10 m. On top, impermeable and flat strata (slabs).	
Rundkarren	Microscale and Mesoscale	Solution runnels formed under soil layers. Its edges are rounded, and its channels are usually wider and shallower than rillenkarren.	

Table 5. Main karst morphologies defined in Urku Mayan site.

Karst Morphology	Scale	Description	Figure
Canyons and narrow valleys	Mesoscale	Narrow valleys with vertical walls and steep slopes. Low or non-existent hydraulic gradient. Presence of impermeable rocks beds.	
Grikes and Clints	Microscale and Mesoscale	Deep dissolution fissures in the form of grooves penetrate even impermeable strata. On top, impermeable and flat strata (slabs).	
Rillenkarren	Microscale	Dissolution fissures like grooves, generated by the flow of water over the rock, following the gravity gradient.	
Collapse Doline	Mesoscale	Sinking structure generated by the presence of the cavity, generated from the bottom up. The loss of collapse material has caused an increase in its lateral slopes.	

Karst Morphology	Scale	Description	Figure
Caves	Mesoscale	Cavities generated by dissolution as a result of active hydrological flows. It has a length rectilinear close to 300 m and between 4 and 5 m wide.	
Drip Holes	Microscale	Tiny cavities formed in places where dripping occurs or due to the presence and concentration of organic matter.	
Stalactites	Microscale	Karst morphology with shape of an irregular cone, its peak is oriented downwards. They form from the top of caves, and their growth is due to the slow filtration of water and calcareous materials.	
Stalagmites	Microscale	Karst morphology with shape of an irregular cone, its peak is oriented upwards. They form on the floor of caves, and their slow growth is related to the dripping that receive from the top of cave from a stalactite.	

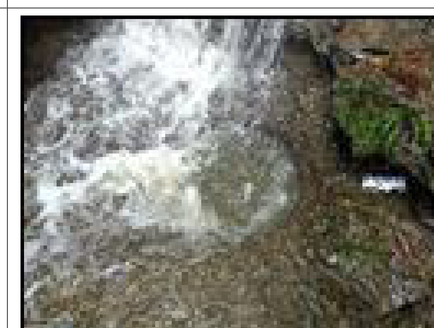
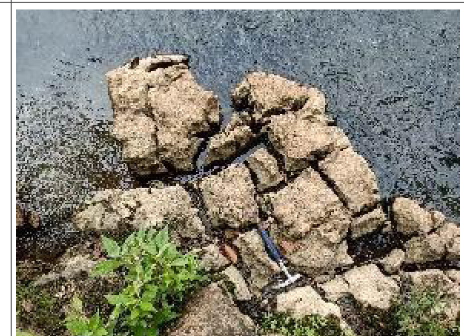
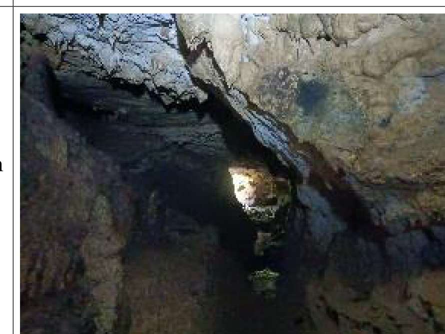
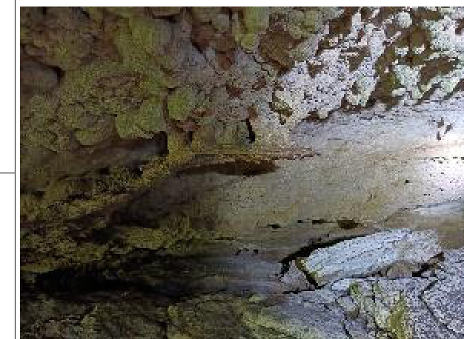
Karst Morphology	Scale	Description	Figure
Drapery	Microscale	Are thin wavy sheets of calcite hanging downward. Its drip can be vertical or oblique, following the shape of the contour of the caves.	
Soda Straw	Microscale	Consist of very thin but long stalactites that have a cylindrical shape, unlike the conical shapes of stalactites.	
Kamenitza	Microscale	They are small or large pot-shaped cavities, characterized by their closed shapes, which are developed by a mixture of dissolution and friction processes.	

Table 6. Main karst morphologies defined in Usayaku site.

Karst Morphology	Scale	Description	Figure
Fissure Caves	*Microscale*	Small dissolution cavities (approximately 30 cm), developed on fissures in calcareous rocks. These fissures have been widened by the river current, as the river level rises.	
Grikes and Clints	*Mesoscale*	Deep dissolution fissures forming grooves widened by the action of the river flow. In the upper part, flat slabs are formed as platforms (limestone pavement).	
Caves	*Mesoscale*	Cavities generated by dissolution as a result of active hydrological flows. It has a length close to 500 m and 5 m wide in average.	

Karst Morphology	Scale	Description	Figure
Trays	*Microscale*	Flat structures, generated by erosion processes within the cavities. There may be other speleothems crystallized on its surface.	
Mammilary	*Microscale*	In the caves, calcite crusts formed on the top and on the hanging walls. They form at low water levels and by condensation.	
Gour Terrace	*Microscale*	Carbonate concretion with shape of small dikes or dams. They have very gentle slopes and fluctuating water flows.	
Drapery	*Microscale*	Thin wavy sheets of calcite hanging downward. Its drip can be vertical or oblique, following the shape of the contour of the caves.	
Stalactites	*Microscale*	Karst morphology with shape of an irregular cone, its peak is oriented downwards. They form from the top of caves, and their growth is due to the slow filtration of water and calcareous materials.	
Stalagmites	*Microscale*	Karst morphology with shape of an irregular cone, its peak is oriented upwards. They form on the floor of caves, and their slow growth is related to the dripping that receive from the top of cave from a stalactite.	

Karst Morphology	Scale	Description	Figure
Stalagnate (Column)	*Microscale and Mesoscale*	Structure created by a mineral precipitation, from the contact between a stalactite and stalagmite. They are tendentiously circular and can grow horizontally.	
Phytokarst	*Microscale*	Type of karstic structures generated by biological erosion.	
Kamenitza	*Microscale*	Small or large pot-shaped cavities, characterized by their closed shapes, which are developed by a mixture of dissolution and friction processes.	

Some of the particularities evidenced during the observation of morphologies consisted of establishing complex conditions for observing particular features of the karst, for example in sites such as Sacha Huagra, Urku Mayan and Usayaku, aspects such as buried caves and *terra rossa* deposits were denoted, which it is also conditions typical of karst territories (Palmer, 2012). However, are complex to locate their specific size or scale, or were also associated with other secondary morphologies, such as the case of burial marks (subsoil channels and subsoil dissection). The morphologies that are generated below the soil tend to be much more active in dissolution, considering that in addition to the action of acidic water, soil particles also work in the same or greater acidity condition (Ginés et al., 2009). Bioturbations are other elements present in these karst sites, whose biological nature makes their interpretation diffuse and confusing (Fig. 4).

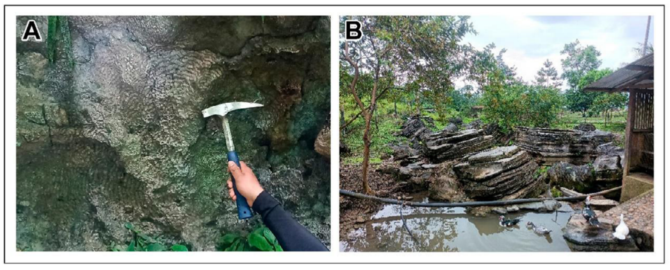


Figure 4. A) Image of bioturbation in limestone rocks, Urku Mayan site. B) Pinnacles buried by mass movements, Sacha Huagra site.

On the other hand, establish segmentations or subdivision of karst morphologies by scale, beside to being a pragmatic form of classification, allows generating a better understanding of the geological, biological, environmental and climatic interactions (Fernández, 2007; Forrero-Ospino and Duarte-Delgado, 2019). If we analyze results tables 2 to 6, we observe that 62.6% of the morphologies correspond to microscale structures, while a range of 37.5% of morphologies are mesoscale, which may be related to the low evolutionary level of the systems karst shown in these study areas, as established by Sánchez-Cortez et al (2022b).

Following this same line, Fookes and Hawkings (1988) and Waltham and Fookes (2003) mention that karst systems evolve from juvenile systems to mature and senile systems. If is considered that spatial scales are linked to temporal periods, having more elements of microscale morphologies in this inventory ratifies the youthful and young state of these karst systems. In this sense, the scales of observation of morphologies are fundamental to define these evolutionary levels.

Intrinsic geodiversity of karst morphologies and their conservation status

Geodiversity is recognized as the variety of geological and geomorphological characteristics and processes, in addition to soil and even hydrological events (Gray, 2018), which entails some exceptional values such as tourist, educational and cultural use (Caetano and Ponciano, 2021), as well as the proportion of energy and nutrients (Parks and Mulligan, 2010). Geodiversity is a concept designed to support sustainable development, because knowledge of it encourages optimization of the use of natural resources (Kozlowski, 2004). All the elements to which geodiversity refers have existence values, or intrinsic values, starting from the philosophical vision that all things have value because they are useful to man, or provide services to society (Brilha, 2016; Nieto, 2023).

In this strict sense, karst systems and their different elements are components of geodiversity, as well as the processes and resources that are generated from them. For the study and evaluation of geodiversity, there are different applicable methodologies, which depend on the depth of the study, its spatial dimensions and the availability of information (Zwoliński et al., 2018). The assessment of intrinsic geodiversity (IG) or abundance of karst morphologies was established using the equation proposed by Carcavilla (2006) and Carcavilla et al (2007) (1), in which the quotient between the number of morphology types and the area is equal to the IG. The application of this formula allowed us to establish that the Usayaku site obtained the highest value of intrinsic geodiversity relative to the other sites investigated, in turn Sacha Huagra was the site with the least representative value (Table 7).

Table 7 details the intrinsic geodiversity values, along with the KDI assessments, as well as the state of disturbance of each site addressed in this work, highlighting that these data were previously collected in the research carried out by Sánchez-Cortez et al (2022b). The correlation of data highlights that those sites with the highest KDI correspond to the territories with the lowest intrinsic geological diversity in aspects related to karst morphologies (Fig. 5), regardless of activities developed in each area. In this sense, the tourist and agricultural activities developed in each geosite seem not to directly interfere with the diversity of karst morphologies, but not with the state of conservation of the karst. On the other hand, the proximity to the municipal head of Archidona is directly related to the decrease in the IG, as well as the increase in the KDI, considering that the anthropogenic pressure of cities is a natural enemy of geodiversity (Clivaz and Reynard, 2018) and karst systems (Zhao et al., 2021). The simple relationship between the KDI and the IG allowed us to obtain the disturbance coefficient of intrinsic geodiversity in karst morphologies (Table 5 and Fig. 6), with which it was possible to establish, through data extrapolation, the areas where the morphologies Karsts have a lower level of disturbance. The karst elements defined in this work do not really present a high degree of complexity; however, the relationship between karst morphological diversity and the state of conservation of the karst systems evaluated should be highlighted.

Table 7. Main characteristics of the karstic areas, in which can be observed the assessments of intrinsic geodiversity and their comparisons with the karst disturbance index. High intrinsic geodiversity is correlated with low disturbance values. finally shows the disturbance coefficient of intrinsic geodiversity in karst morphologies, this coefficient is obtained from a simple quotient between the KDI and the IG.

Sites	Types of morphologies (M)	Area in Km^2 (A)	Intrinsic Geodiversity (IG = M/A)	Karst Disturbance Index (KDI)*	Disturbance*	Main activities developed in the area *	Disturbance coefficient of intrinsic geodiversity in karst morphologies (KDI/IG)
Huasquila	4	1.1	**3.64**	20	Minor affectation	Tourism and family farming	**5.50**
Yanayaku	5	3.2	**1.56**	33.33	Minor affectation	Tourism, animal husbandry and farming	**21.33**
Sacha Huagra	3	2	1.5	40.58	Moderately affected	Tourism, animal husbandry and intensive farming	**27.05**
Urku Mayan	12	3.5	**3.43**	15.47	Pristine	Tourism, family farming, sale of wood and forest resources	**4.51**
Usayaku	12	1.2	10	20.51	Minor affectation	Tourism and family farming	**2.05**

* The data have been obtained from Sánchez-Cortez et al. (2022b)

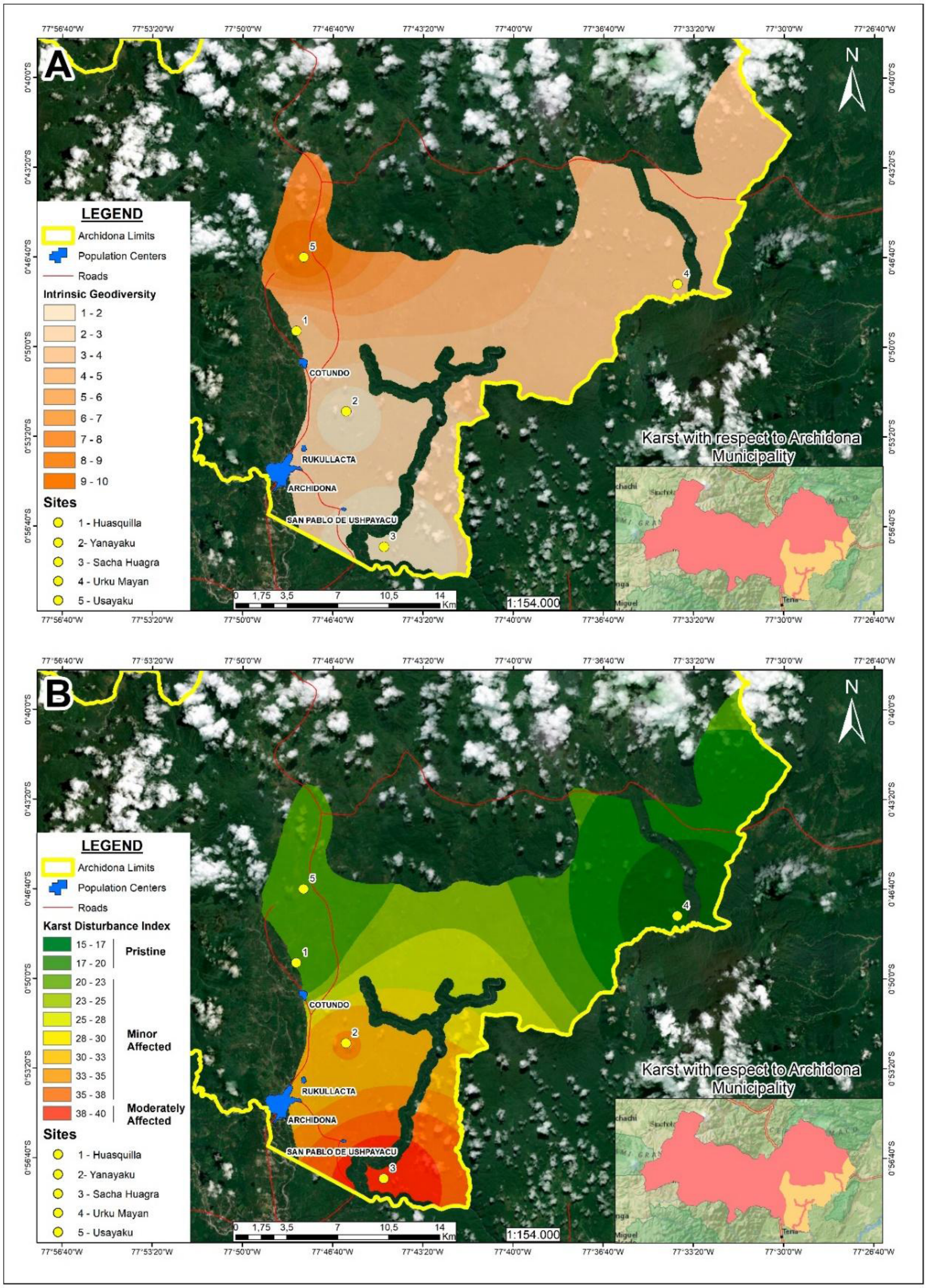


Figure 5. A) Map of the geodiversity distribution, based on values obtained by the Intrinsic Geodiversity of karst morphologies, extrapolated throughout the karst area. B) Map with the distributions of KDI assessments of each site. The data has been extrapolated throughout the karst area (Sánchez-Cortez et al., 2022b).

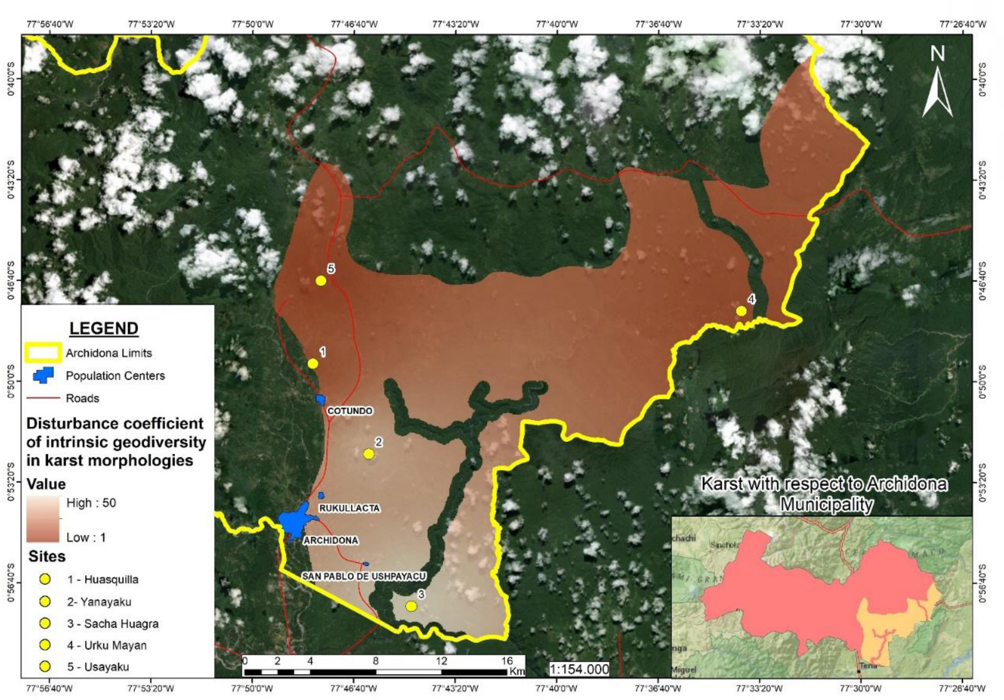


Figure 6. Distribution map of disturbance coefficient of intrinsic geodiversity in karst morphologies. This coefficient is obtained from a simple quotient between the KDI and the IG.

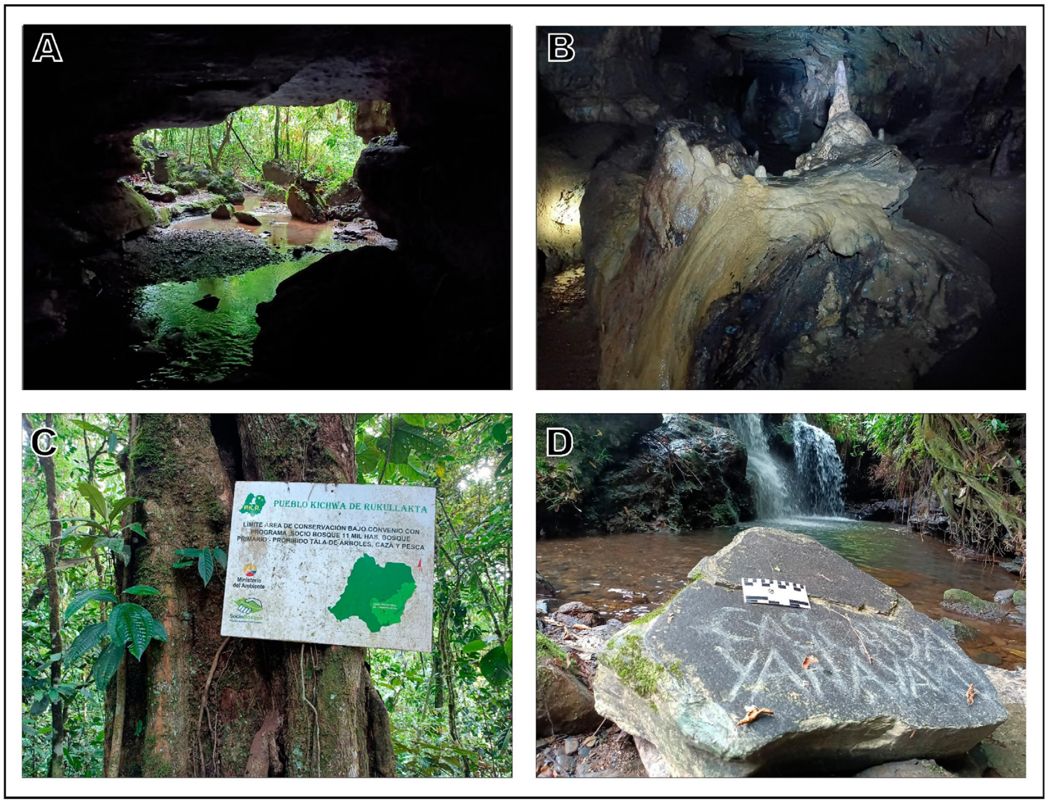


Figure 7. A) Main cave of the Urku Mayan site. B) Speleothems present at the Usayaku site, evidence of karst morphological diversity. C) Signage present in the Urku Mayan conservation area, within the Kichwa People of Rukullakta Reserve. D) Vandalization of carbonate rocks at the Yanayaku site.

The tourist use of these sites is a strong indicator of the potential that karst systems have as recreational elements, but also as an informative tool of the dynamics and geological and geographical evolution of the territory, as well as the effects as a result of global climate change (Xiao and Weng, 2007). The conservation policies of the sites studied are based on community systems, which are used as local tools to directly manage their territories, supported by the emotional and spiritual attachment to the land, and the sustainability of its resources, rooted in their indigenous worldview (Johnson, 1992; Rajasekaran, 1993; Díaz, 2004; Gómez Peralta, 2005).

Napo Sumaco Aspiring UNESCO Global Geopark territory has constituted a joint workspace that over nine years has served as an area for research, geoeducation and geoconservation, in accordance with the principles established by UNESCO (2015), prior to the declaration of a global geopark. Napo Sumaco has a participatory management structure that promotes the development of the conservation of karst resources, and in general geological and geomorphological resources, through teaching-learning processes (Fig. 7). To fulfill the role of geoheritage conservation, NSAUGG is oriented towards strengthening and improving local capacities and the holistic dissemination of the territory (Sánchez-Cortez et al., 2023).

Conclusions

In recent years, the concept of geodiversity has received special attention due to its close relationship with biodiversity and biogeography patterns (Alsbach et al., 2024), in addition the conservation of geodiversity has gained value and relevance, due to its nature irrecoverable (Gray, 2008, Micheo et al., 2022). The application of local geodiversity indices or evaluations can be a valuable and complementary input when making decisions for the protection and conservation of fragile ecosystems. Karst areas are sensitive and complex systems, however, in the case of the Municipality of Archidona, within Napo Sumaco Aspiring UNESCO Global Geopark, the karst areas analyzed maintain an optimal level of conservation, as well as a variety of morphologies whose characteristics fit to the Ecuadorian Amazon karst. The work of the local communities in conjunction with the NSAUGG has been fundamental in the process of conservation and preservation of the karst elements and other aspects, such as biodiversity and agrodiversity.

The karst relief is a valuable geological heritage and an important tourist resource, for example, Cigna and Burry (2000), mention that worldwide there is an average of between 25 and 150 million caving tourists per year. Furthermore, karst systems are recurring resources within geoparks, for example, in the case of geoparks in China, of a total of 41 UNESCO Global Geoparks, 10 have karst themes in their territory (Wu et al, 2024), which demonstrates the specific potential of karst towards tourism through the interpretation of geological and geomorphological processes. However, in the case of NSAUGG, caving tourism requires a major push that involves planning and in-depth local administrative processes.

Through this research it was possible to confirm that the sites with the highest intrinsic geodiversity (IG) of karst morphologies coincide with the karst areas considered to be less intervened and with less disturbance. Furthermore, it was possible to corroborate in the study area that urban centers exert pressure on geodiversity resources, and that tourism is not an activity that directly influences the relative abundance of morphologies, and the levels of disturbance of the geoheritage, nevertheless, this affirmation still needs to be confirmed through the application of future research. Finally, the contribution of this study is to promote awareness about the geosystemic services of karst environments at the population level, as a strategy for their preservation, contributing to the scientific-divulgate work that strengthens the NSAUGG communities.

Fundings

This research received no external funding.

Declaration of Competing Interest

The authors declare no conflict of interest.

Acknowledgments

Thanks to the group of local guides *Yuyaiwa Pushak Runakuna*, especially Luis Chacha (Huasquila and Saccha Huagra), Jimmy Andy (Urku Mayan), Rider Alvarado (Usayaku) and Valerio Grefa (Yanayaku), who contributed their knowledge to the development of this research. Also, to the Napo Sumaco Aspiring UNESCO Global Geopark team for their contribution and support.

References

Alsbach, C.M.E., Seijmonsbergen, A.C. & Hoorn, C. (2024). Geodiversity in the Amazon drainage basin. *Philosophical Transaction Royal Society A*, 382: 20230065. https://doi.org/10.1098/rsta.2023.0065.

Andreychouk, V. (2016). The system nature of karst landscape and principles of cave protection resulting from it. *Zeitschrift für Geomorphologie, Supplementary Issues*, 60(2), 257-291. DOI:10.1127/zfg_suppl/2016/00300.

Andreu, J.M., Calaforra, J.M., Cañaveras, J.C., Cuezva, S., Durán, J.J., Garay, P., García del Cura, M.A., García-Cortés, A., Gázquez, F., Ordóñez, S., & Sánchez-Moral, S. (2016). Karst: un concepto muy diverso. *Enseñanzas de las Ciencias de la Tierra*, 24(1), 6-20.

Baby, P., Rivadeneira, M. & Barragán, R. 2014. *La cuenca oriente: geología y petróleo*. Convenio IFEA-IRD-PETROAMAZONAS EP. Quito. 414 pp.

Bahtijarevic, A. (1996). Karst Landforms in Florida: Geomorphological Analysis. Thesis, University of South Florida, United State.

Besson, J.P., Lera, O. & Valicourt, E. (1982). *Ecuador 82: Expédition spéléologique de la S.S.P.P.O. [du 1er juillet au 23 août 1982]: suivi d'un pré-inventaire spéléologique de l'équateur*. Société de spéléologie et de préhistoire des Pyrénées occidentales. Pau - France. 168 pp.

Brilha, J. (2016). Inventory and quantitative assessment of geosites and geodiversity sites: A review. *Geoheritage*, 8, 119-134. DOI: 10.1007/s12371-014-0139-3.

de Boer, D. H. (1992). Hierarchies and spatial scale in process geomorphology: a review. *Geomorphology,* 4(5), 303-318, https://doi.org/10.1016/0169-555X(92)90026-K.

Caetano, J.M.V., & Ponciano, L.C.M.D.O. (2021) Cultural geology, cultural biology, cultural taxonomy, and the intangible geoheritage as new strategies for geoconservation. *Geoheritage,* 13(79). https://doi.org/10.1007/s12371-021-00603-6.

Carcavilla L. (2006). Patrimonio geológico y geodiversidad: investigación, conservación, gestión y relación con los espacios naturales protegidos. PhD. Thesis, University of Madrid, España.

Carcavilla, L., López-Martínez, J. & Durán, J.J. (2007). *Patrimonio geológico y geodiversidad: Investigación, conservación, gestión y relación con los espacios naturales protegidos*. IGME, Madrid. 360 pp.

Carvajal Perico, J.H. (2012). *Propuesta de estandarización de la cartografía geomorfológica en Colombia.* Colección Guías y Manuales, Servicio Geológico Colombiano, Colombia. 83 pp.

Christman, M. C., Culver, D. C., Madden, M. K., & White, D. (2005). Patterns of endemism of the eastern North American cave fauna. *Journal of Biogeography*, 32(8), 1441–1452. https://doi.org/10.1111/j.1365-2699.2005.01263.x.

Cigna, A., & Burri, E. (2000). Development, management and economy of show caves. *International Journal of Speleology*, 29, 1–27. http://dx.doi.org/10.5038/1827-806X.29.1.1.

Cigna, A., & Forti, P. (2013). Caves: The most important geotouristic feature in the world. *Tourism and karst areas*, 6(1), 9-22.

Clivaz, M., & Reynard, E. (2018). How to integrate invisible geomorphosites in an inventory: a case study in the Rhone River valley (Switzerland). *Geoheritage*, 10, 527-541. https://doi.org/10.1007/s12371-017-0222-7.

Coe, A. L., Argles, T. W., Rothery, D. A., & Spicer, R. A. (2010). *Geological field techniques*. United Kingdom: John Wiley & Sons, Ltd. 339 pp.

Constantin, S., Toulkeridis, T., Moldovan, O. T., Villacís, M., & Addison, A. (2018). Caves and karst of Ecuador – State-of-the-art and research perspectives. *Physical Geography*, 40(1), 28–51. https://doi.org/10.1080/02723646.2018.1461496.

Cruz Ramírez, D.N. (2014). Las rutas turísticas y su incidencia en el turismo de aventura en el cantón Archidona, provincia de Napo. Degree Thesis, Universidad Técnica de Ambato, Tourism and Hospitality Career, Ambato, Ecuador.

Díaz, F. (2004). Comunidad y comunalidad. *Culturas Populares e Indígenas, Diálogos en la acción, segunda etapa*, 365-373.

Drápela, E. (2023). Using a Geotrail for Teaching Geography: An Example of the Virtual Educational Trail "The Story of Liberec Granite". *Land*, 12(4):828. https://doi.org/10.3390/land12040828.

Fernández, V.R. (2007). Algunas consideraciones acerca de la escala geográfica y en geomorfología. *Centro de Geociencias Aplicadas. Facultad de Ingeniería, UNNE*. 45-56.

Fookes, P.G., & Hawkins, A.B. (1988). Limestone weathering: Its engineering significance and a proposed classification scheme. *Quarterly Journal of Engineering Geology*, 21, 7–31. https://doi.org/10.1144/gsl.qjeg.1988.021.01.02.

Ford, D. C., & Williams, P. (2007). *Karst hydrogeology and geomorphology*. Chichester: John Wiley & Sons, Ltd. 562 pp.

Forero-Ospino, O.E. & Duarte-Delgado, W.F. (2019). Caracterización e identificación de la geomorfología (ambientes y unidades geomorfológicas) en la plancha 121 - Cerrito, Colombia, aplicado a movimientos en masa, escala 1:100.000. *Boletín de Geología*, *41*(2), 35-45. https://doi.org/10.18273/revbol.v41n2-2019002.

GAD Municipal de Archidona (2011). Plan de desarrollo y ordenamiento territorial [Development plan and territorial planning]. Archidona, Ecuador: Gobierno Autónomo Descentralizado Municipal de Archidona, 174 pp.

Ginés, A., Knez, M., Slabe, T. & Dreybrodt, W. (2009). *Karst rock features: Karren sculturing.* Zalozba ZRC/ZRC Publishing, Ljubljana. 561 pp.

Gómez Peralta, H. (2005). Los usos y costumbres en las comunidades indígenas de Los Altos de Chiapas como una estructura conservadora. *Estudios Políticos*, (5). https://doi.org/10.22201/fcpys.24484903e.2005.5.37657.

Gray, M. (2004). *Geodiversity: Valuing and Conserving Abiotic Nature*. Wiley, Chichester. 434 pp.

Gray, M. (2008). Geodiversity: developing the paradigm. *Proceedings of the Geological Association,* 119(3-4), 287-298. https://doi.org/10.1016/S0016-7878(08)80307-0.

Gray, M. (2013). *Geodiversity: Valuing and conserving abiotic nature.* 2nd ed. Wiley-Blackwell, Chichester. 512 pp.

Gray, M. (2018). Chapter 1 - Geodiversity: The Backbone of Geoheritage and Geoconservation. In: Reynard, E. & Brilha, J. (Editors). *Geoheritage, Assessment, Protection, and Management.* Elsevier, 13-25. https://doi.org/10.1016/B978-0-12-809531-7.00001-0.

Johnson, M. (1992). Lore: Capturing Traditional Environmental Knowledge. In: Ellen, R., Parkes, P. & Bicker, A. (Editors). *Indigenous environmental knowledge and its transformations: Critical anthropological perspectives*. Harwood Academic, Amsterdam, 319 –331.

Kozlowski, S. (2004). Geodiversity. The concept and scope of geodiversity. *Przeglad Geologiczny,* 52(8/2), 333-837.

Kubalíková, L., Coratza, P, Pál, M., Zwoliński, Z., Irapta, P.N. & van Wyk de Vries, B. (2023). Visages of geodiversity and geoheritage: a multidisciplinary approach to valuing, conserving and managing abiotic nature. In: Kubalíková, L., Coratza, P., Pál, M., Zwoliński, Z., Irapta, P. N. & van Wyk de Vries, B. (Editors). *Visages of Geodiversity and Geoheritage.* Geological Society, London, Special Publications, 1–12. https://doi.org/10.1144/SP530-2022-321

Lahee, F.H. (1985). *Geología Práctica.* Ed. Omega. Barcelona, España. 382 pp.

Langer, P. (2020). Groundwater mining in contemporary urban development for European spa towns. *Journal of Human, Earth and Future*, 1(1), 1–9. https://doi.org/10.28991/HEF-2020-01-01-01.

Lewin, J. & Woodward, J. (2009). Karst Geomorphology and Environmental Change. In: Woodward, J. (Editor), *The Physical Geography of the Mediterranean,* 1st Edition. Oxford University Press, England, 287-318. DOI:10.1093/oso/9780199268030.003.0022.

Lugo Hubp, J. (1988). *Elementos de geomorfología aplicada (métodos cartográficos).* Instituto de Geografía, Universidad Nacional Autónoma de México. México. 128 pp.

Micheo, F., Piña, J., Vicens, M., Robledo, P., Carles, R., Pi, E., Picart, J., & Cirés, J. (2022). Analysis of karst geodiversity in the Garraf massif (Catalonia). 10th International Conference on Geomorphology, Coimbra, Portugal, 130. https://doi.org/10.5194/icg2022-130.

Najwer, A., Reynard, E. & Zwoliński, Z. (2023). Geodiversity assessment for geomorphosites management: Derborence and Illgraben, Swiss Alps. In: Kubalíková, L., Coratza, P., Pál, M., Zwoliński, Z., Irapta, P. N. & van Wyk de Vries, B. (Editors). *Visages of Geodiversity and Geoheritage.* Geological Society, London, Special Publications, 89–106. https://doi.org/10.1144/SP530-2022-122.

Napo Sumaco Aspiring Geopark (2019). *Application Dossier for nomination to UNESCO Global Geopark.* Napo Sumaco Foundation. Tena, Ecuador. 50 pp.

Nieto, L.M. (2023). Geodiversity as a Tool for the Nature Conservation. Current Perspectives on Applied Geomorphology. *IntechOpen.* http://dx.doi.org/10.5772/intechopen.109010.

North, L. A. (2007). Application and refinement of the karst disturbance index in west central, Florida. University of South Florida, Master's thesis. Florida, United States.

Palmer, A. N. (2012). *Geología de Cuevas.* Dayton, Estados Unidos: Sociedad Espeleológica de Cuba, 502 pp.

Pardo-Igúzquiza, E., Durán, J.J., Dowd, P.A. (2013). Automatic detection and delineation of karst terrain depressions and its application in geomorphological mapping and morphometric analysis. *Acta Carsologica*, 42(1), 17-24. http:// dx.doi.org/10.3986/ac.v42i1.637.

Parks, K.E. & Mulligan, M. (2010). On the relationship between a resource based measure of geodiversity and broad scale biodiversity patterns. *Biodiversity and Conservation,* 19(9), 2751–2766. https://doi.org/10.1007/s10531-010-9876-z.

Rajasekaran, B. (1993). A Framework for Incorporating Indigenous Knowledge System into Agricultural Research and Extension Organizations for Sustainable Agricultural Development in India. Dissertation, Iowa State University, United State.

Rivases, J. (2017). Geomorfología kárstica en la cabecera del valle de Río Ésera, Benasque. Degree in Geologu, University of Zaragoza, Zaragoza, España.

Robledo, P.A. & Durán, J.J. (2011). Geoturismo y cavidades: perspectiva en las Islas Baleares, España. *ANAIS do 31º Congresso Brasileiro de Espeleologia. Sociedade Brasileira de Espeleologia*, 189-200.

Robledo, P.A., Durán, J.J., & Pardo, E. (2020). *Karst y Cuevas: la cuarta dimensión de la naturaleza*. Catarata. Madrid, España, 144 pp.

Sánchez-Cortez, J. L., Cárdenas-Pinto, V., Ocampos-Valarezo, D., Jaque-Bonilla, D., Quilumba-Dután, D., Ortiz-Barrionuevo, J., Quinteros-Cevallos, R.A., & Toledo-Rojas, N. (2017). Aplicación de Proceso Metodológico para el Inventario Geoturístico de Cavidades Naturales en la Provincia de Napo – Ecuador [Application of natural cave geological tourism survey method in Napo Province, Ecuador]. *Anuário do Instituto de Geociências,* 40(2), 61–73. https://doi.org/10.11137/2017_2_61_73.

Sánchez-Cortez, J. L., Jaque-Bonilla, D., Simbaña-Tasiguano, M., Astudillo-Bravo, D., & Cabascango-Chiliquinga, E. (2022a). Participatory strategies applied for the geoconservation of speleological heritage at the Napo Sumaco Geopark (Ecuador). *Episodes,* 45(4), 417-429. https://doi.org/10.18814/epiiugs/2022/022001.

Sánchez-Cortez, J.L., Fuentes-Campuzano, O., Rosero-Lozano, J. (2022b). Determination of disturbance levels in karstic areas with application of qualitative indicators: Case studies in municipalities of Archidona and Pedro Carbo (Ecuador). *International Journal of Geoheritage and Parks,* 10(3), 400-416. https://doi.org/10.1016/j.ijgeop.2022.08.005.

Sánchez-Cortez, J.L., Simbaña-Tasiguano, M., Vélez-Macías, K., Grefa-Shiguango, H., Jaque-Bonilla, D., Cabascango-Chiliquinga, S. (2023). Sumaco Volcano (Ecuador) Integral Approach to its Geotourism Potential. *Geoconservation Research,* 6(2), 271-290. https://doi.org/10.57647/j.gcr.2023.0602.18.

UNESCO (2015). Statutes of the International Geoscience and Geoparks Programme and Operational Guidelines for UNESCO Global Geoparks. UNESCO. https://unesdoc.unesco.org/ark:/48223/pf0000234539.

Vera, D., Simbaña-Tasiguano M., Guzmán O., Cabascango, E., Sánchez-Cortez, J.L., Campos C., Grefa, H. (2023). Quantitative assessment of geodiversity in Ecuadorian Amazon—case study: Napo Sumaco Aspiring UNESCO Geopark. *Geoheritage,* 15(28). https://doi.org/10.1007/s12371-023-00792-2.

Waltham, A.C., & Fookes, P.G. (2003). Engineering classification of karst ground conditions. *Quarterly Journal of Engineering Geology and Hydrogeology*, 3(2), 101–118. https://doi.org/10.1144/1470-9236/2002-33.

White, W.A. (1970). The Geomorphology of the Florida Peninsula. *Florida Bureau of Geology, Bulletin No. 51*., Tallahassee, United State, 164 pp.

Wu, L., Zhang, Y., Wang, P., Li, B., Ye, Q., Peng, W., Jiang, H., Jiang, J., Wei, H. & Li, F. (2024). Karst Geoheritage of the Red Stone Forest in the Xiangxi UNESCO Global Geopark: Chromogenic Factors, Microgeomorphology and Dissolution Behaviour. *Geoheritage,* 16(18). https://doi.org/10.1007/s12371-024-00917-1.

Xiao, H., & Weng, Q. (2007). The impact of land use and land cover changes on land surface temperature in a karst area of China. *Journal of Environmental Management,* 85(1), 245–257. https://doi.org/10.1016/j.jenvman.2006.07.016.

Zhao. Y., Han, R., Cui. N., Yang, J., & Guo, L. (2021). The Impact of Urbanization on Ecosystem Health in Typical Karst Areas: A Case Study of Liupanshui City, China. *International Journal of Environmental Research and Public Health*, 18(1):93. https://doi.org/10.3390/ijerph18010093.

Zwoliński, Z., Najwer. A., & Giardino, M. (2018). Chapter 2 – Methods for Assessing Geodiversity. In: Reynard, E. & Brilha, J. (Editors). *Geoheritage, Assessment, Protection, and Management.* Elsevier, 27-52. https://doi.org/10.1016/B978-0-12-809531-7.00002-2.