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GEODIVERSITY IN THE LAGUNA SANTA ROSA, NEVADO DE TRES CRUCES NATIONAL PARK, ATACAMA REGION, CHILE

GEODIVERSIDAD EN LA LAGUNA SANTA ROSA, PARQUE NACIONAL NEVADO DE TRES CRUCES, REGIÓN DE ATACAMA, CHILE

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ABSTRACT

The Nevado de Tres Cruces National Park is divided into two sectors associated with high-altitude lagoons. This study focuses on the North Sector, called “Laguna Santa Rosa”, which has an extension of 46,944 ha. Despite its large extent and the various abiotic components recorded for the area (geology, paleontology, pedology, geomorphology, hydrology, and minerals), there are few studies that mention the geodiversity found in the study area. Given the vast territorial extent of the Laguna Santa Rosa sector, GIS-based methodologies were utilized and compared to characterize the park's landscape. This process involved partitioning the area into16 km² quadrants based on the UTM coordinate system (WGS84), each assigned a quantitative index value. By assessing geological formations, fossils, geomorphology, soils, and mineral occurrences, the study identified areas of high geodiversity, which were subsequently verified through fieldwork. This first cartographic approach to the park's geological diversity provides a spatial appraisal, achieving greater efficiency to measure the relationship between geodiversity and the current biodiversity, helping to define conservation and recovery areas.

Keywords: Geoheritage enhancement, Conservation, Geographic information system, Copiapó.

RESUMEN

El Parque Nacional Nevado de Tres Cruces, se encuentra dividido en dos sectores asociados a lagunas altiplánicas. Este estudio se enfoca en el Sector Norte, denominado “Laguna Santa Rosa” que posee una extensión de 46.944 ha. A pesar de su gran extensión, y los diversos componentes abióticos registrados para el área (geología, paleontología, pedología, geomorfología, hidrología y minerales) existen pocos estudios que mencionen la geodiversidad del área de estudio. Producto de la extensión territorial del sector Laguna Santa Rosa, es que se utilizaron metodologías basadas en SIG que permiten caracterizar grandes extensiones territoriales como este parque generando cuadrantes divididos de 16 km^2 usando coordenadas UTM (WGS84), y caracterizándolos con un valor cuantitativo para cada uno de ellos, evaluando a la vez las formaciones geológicas, fósiles, geomorfología, suelos más ocurrencias minerales. Esto permitió identificar zonas con altos valores de geodiversidad que fueron verificadas en terreno. Este primer acercamiento cartográfico para definir la diversidad geológica del parque permite tener una visión espacial, logrando una mayor eficiencia a la hora de implementar índices más sofisticados que permitan proponer geositios posteriormente, evaluando a la vez la relación entre la geodiversidad con la biodiversidad presente, definiendo así áreas de conservación y recuperación.

Palabras clave: Puesta en valor del patrimonio geológico, Conservación, Sistema de información geográfica, Copiapó.

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1. INTRODUCTION

Geodiversity can be defined as the abiotic counterpart of biodiversity, encompassing the natural variability of geological components such as rocks, minerals, fossils, geomorphological structures, soils, and hydrological features (Gray, 2008; 2011). Historically, the term “geodiversity” emerged from research conducted in Germany and Australia in the early 1990s and subsequently gained widespread acceptance within the geoscientific community over the following decades (Wiedenbein, 1993; Sharples, 1993; Dixon, 1996; Kozłowski, 2004; Gray, 2004, 2005, 2008, 2011, 2012, 2018; García & Fernandez, 2005; Serrano and Flaño, 2007; Ruban, 2010; Gordon et al., 2012; Hjort et al., 2015; Brilha et al., 2018). Over time, geodiversity has evolved into a multi-scalar concept, referring to the number and variety of structures; including sedimentary, tectonic, and other geological features, that form the substrate of a region. These abiotic elements interact with biotic and anthropogenic factors within a balanced geosystem matrix, influencing ecosystem functioning and resilience (Rojas, 2005).

Quantitative approaches to assess geodiversity were subsequently developed, often employing territorial quadrants to analyze and sectorize the distribution and richness of abiotic elements (Serrano & Flaño, 2007; Pereira et al., 2013). Geodiversity provides a critical framework for evaluating abiotic contributions to ecosystem regulation, including landscape heterogeneity, soil fertility, hydrological processes, and habitat diversity (Gray, 2008; 2011). Despite its importance, geodiversity is frequently overlooked in biodiversity studies, even though it can play a crucial role in territorial planning, ecosystem management, and conservation prioritization (Serrano & Flaño, 2007).

In essence, geodiversity encompasses the natural range of geological elements, such as rocks, minerals, and fossils, as well as geomorphological features like landforms, topography, and physical processes. Additionally, it includes soil and hydrological characteristics, contributing to landscape complexity and ecological potential (Gray et al., 2013; Hjort et al., 2015; Brilha et al., 2018). The recognition of geodiversity is increasingly important for developing integrated conservation strategies, particularly in regions with high ecological and geological variability.

Chilean national parks exhibit highly variable geodiversity characteristics that have yet to be systematically analyzed, particularly in high-altitude Andean wetlands. This study focuses on the Santa Rosa Lagoon, located at the southern end of the Maricunga Salt Flat within the northern sector of Nevado de Tres Cruces National Park in the Atacama region. The park encompasses a total area of 59,981 ha (Figure 1; CONAF, 1997), where the Santa Rosa section spreads over 78% (46,944ha) of the protected area characterized by high Andean wetlands situated on a high plateau at 3,767 meters above sea level. This endorheic basin collects groundwater and subsurface flows, forming a network of water bodies; including lagoons and channels, whose salinity increases inward of the salt flat and ultimately evaporating leaving a solid salt deposit (Risacher et al., 1999; Vicencio, 2020; Vicencio Campos et al., 2022).

The edges of Laguna Santa Rosa are covered with high Andean wetland vegetation, providing habitat for a diverse assemblage of vertebrate fauna, including larger mammals such as vicuñas, guanacos, foxes, and pumas, iconic birds such as three species of flamingos, and some small lizzards (Niemeyer, 1968; CONAF, 1997; Risacher et al., 1999; Moreno et al., 2000; Troncoso-Palacios & Marambio, 2011; Troncoso-Palacios, 2014; Vicencio, 2020; Cerda & Medina, 2022).

The lagoon has been subject to hydrological monitoring and zoning for ecological recovery, as declines in water levels and vegetation reduction have been recorded since 2014 (Sepúlveda & Alam, 2018; Alam & Sepúlveda, 2022). From a geodiversity perspective, Laguna Santa Rosa contains geological formations ranging from the Devonian-Carboniferous to the Pleistocene (382.7 Ma–0.0117 Ma), with associated fossil records (Cornejo et al., 1998; Mpodozis et al., 2012; Clavero et al., 2012; Naranjo et al., 2019). Two geomorphological units and two soil types (Xerosols and Lithosols) have been identified (Novoa et al., 2008; Ulloa & Ortiz de Zárate, 1989; Abad et al., 2022).

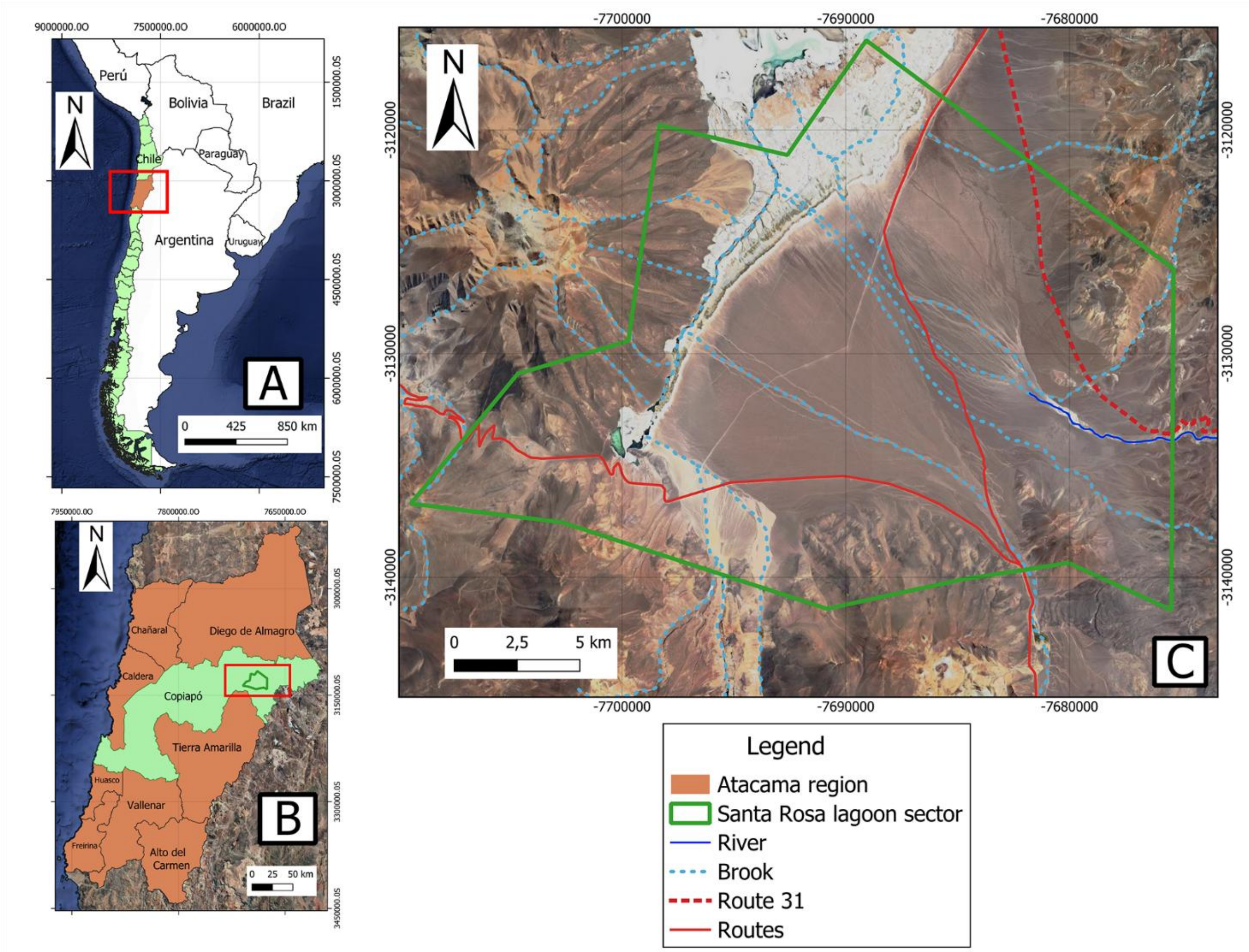

Figure 1. General location map of Atacama, Chile (a). Detail of the Atacama region (b). Location of Laguna Santa Rosa in the Copiapó Municipal district (c). Source: Own work.

This research aims to evaluate the geodiversity of Laguna Santa Rosa using established quantitative methodologies (Serrano & Flaño, 2007; Pereira et al., 2013), identify areas of high geodiversity, and assess their correlation with regions of ecological significance. This approach supports the development of integrated conservation strategies that consider both abiotic and biotic factors, reinforcing the management of the Nevado de Tres Cruces National Park as a high-altitude conservation priority.

2. MATERIALS AND METHODS

2.1. Study Approach.

As previously stated, several quantitative approaches to assess geodiversity have been proposed in the last two decades (García & Fernández, 2005; Brilha, 2016; Brilha, 2018). Almost all of them use accessibility defined as distance to humane settlements and roads as a criteria to be measured with a high weighted score. Most required detailed maps in larger scales. Now, in order to assess geodiversity in a large national park such as Tres Cruces National Park with no local resident population and only three roads, the maps would need a smaller scale. In such a case, the methodologies proposed by Serrano & Flaño (2007) and Pereira et al. (2013) would fit better because they use a mappable grid pattern methodology more suitable for its assessment and whose results are relevant for geoconservation planning Therefore, both methods were applied to measure the number of abiotic elements per predefined grid. Using GIS geoprocessing tools, specifically ArcMap 10.8, partial diversity indices were defined for each quadrant. Data collection and processing started using field data obtained from a professional field practice technical report and new mapping later published (Vicencio, 2016; Vicencio 2020). Further data collection, preparation, and development of geospatial data has enabled the creation of geological (lithological), paleontological, pedological, geomorphological, and hydrological maps (Cornejo et al., 1998; Mpodozis et al., 2012; Clavero et al., 2012; Naranjo et al., 2019; CMN, 2016; Ulloa & Ortiz de Zárate, 1989; BCN, 2024) at a scale of 1:170,000. The formula proposed by Serrano & Flaño (2007) and Pereira et al. (2013) was used to assess geodiversity, and the results were analyzed and interpreted.

2.2. Grid.

A grid was developed with each quadrant measuring 4 x 4 km each (16 km²). Overlaying the grid on several map pages, needed to better characterize the units and occurrences. Then, the Santa Rosa Park area (46,944 ha) was spread on a 40-quadrant grid, either fully or partially, allowing differentiation between the maximum range (highest values) and minimum range (lowest values) in the Geodiversity Index.

2.3. Serrano & Flaño (2007).

The methodology developed by Serrano & Flaño (2007) uses quantitative geodiversity assessment. This method is based on relating physical elements to the rugosity of a determined surface. The equation is as follows:

$$Gd = \frac{EgR}{\ln S}$$

Equation 1: Geodiversity equation where Gd is the geodiversity index; Eg is the number of physical elements (lithological, paleontological, pedological, geomorphological, hydrological, minerals) found in each quadrant; R is the rugosity coefficient according to terrain slope; and S is the quadrant's surface area (km²). Eg is obtained by summing the physical elements recorded in each quadrant. /Source: Serrano & Flaño (2007)

2.4. Pereira et al. (2013)

The methodology suggested by Pereira et al. (2013) is based on the results obtained in each quadrant for on the required indices within the study area (Equation 2). The total geodiversity index is the sum of five specific indices: lithology, paleontology, pedology, geomorphology, hydrology, and mineral occurrence.

$$\text{Geodiversity index} = \text{Lithological index} + \text{Paleontological index} + \text{Pedological index} + \text{Geomorphological index} + \text{Hydrology index} + \text{Mineral occurrence index.}$$

Equation 2: Geodiversity equation showing each corresponding index. /Modified from Pereira et al., 2013
Occurrences were determined based on the number of occurrences in each of the 40 quadrants directly matching the park area. The results for each index underwent a normalization process (Araujo & Pereira, 2017; Fernández et al., 2020), creating five categories: very low (1), low (2), medium (3), high (4), and very high (5); with minimum (5) and maximum (22) values obtained: very low (<8), low (8-10), medium (11-13), high (14-16), and very high (>16).

2.5. General Description of Each Component Used for Both Methodologies.

2.5.1. Geological and Paleontological Index.

For the calculation of the geological and paleontological index, geological maps by Cornejo et al. (1998), Mpodozis et al. (2012), Clavero et al. (2012), Naranjo et al. (2019) and the scientific note from the Chinches Formation (Bell, 1985) were used, counting the different geological formations/ Geological unit (lithology, L; Table 1) that coincide in each quadrant (Figure 2). For the paleontological index (Pa), the methodology presented by CMN (2016) was modified, assigning values of 2 to fossiliferous formations, 1 to susceptible formations, and 0 to barren units (Figure 3) counted inside each quadrant.

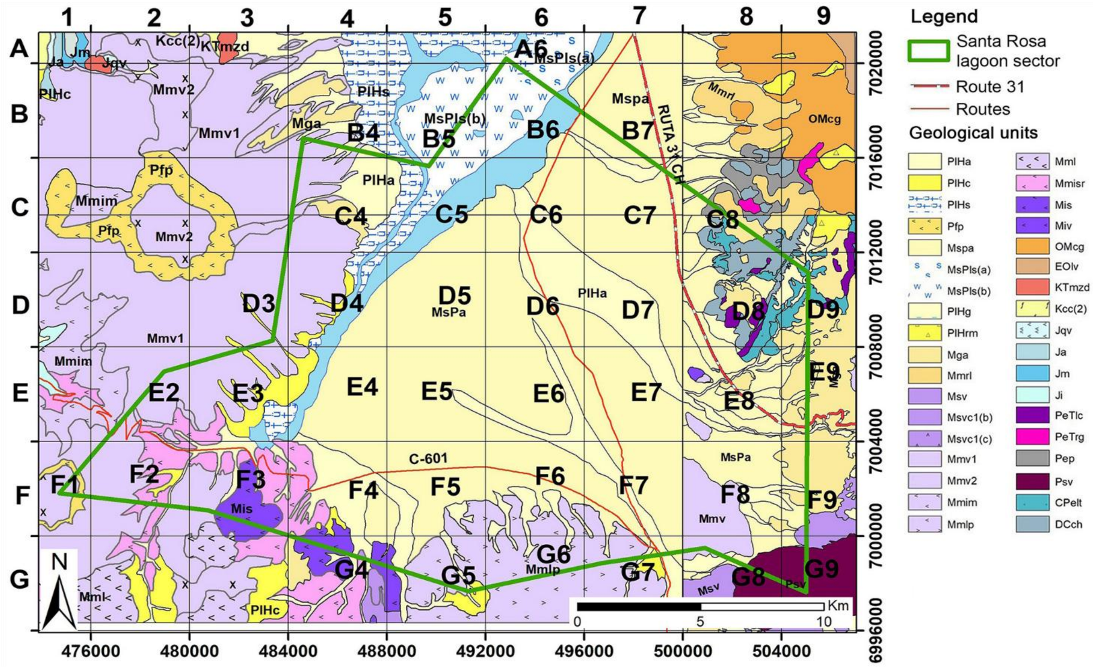

Figure 2. Geological map of the Laguna Santa Rosa area. Source: Modified from Cornejo et al. (1998), Mpodozis et al. (2012), Clavero et al., 2012, Vicencio 2016, 2020 and Naranjo et al. (2019)

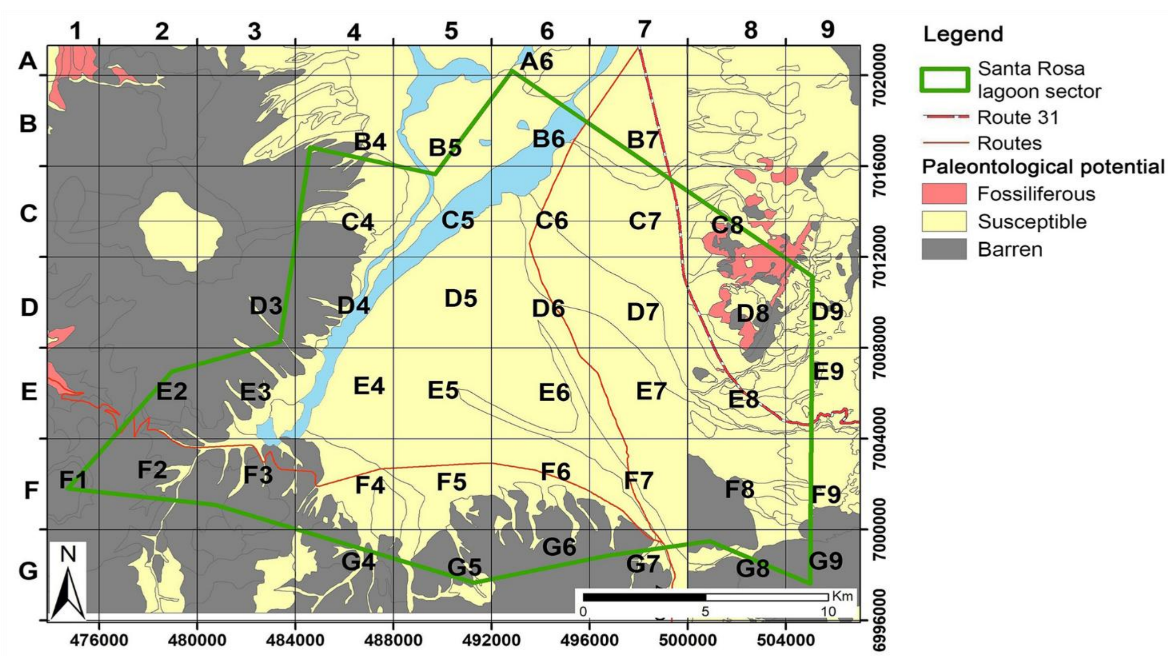

Figure 3. Potential paleontological map of the Laguna Santa Rosa area. Source: Modified from CMN, 2016.

Table 1. The geological units (Lithology) and paleontological potential present in the study area are indicated. Source: Own work based on Cornejo et al., 1998; Mpodozis et al., 2012; Clavero et al., 2012; CMN, 2016; Vicencio 2016, 2020 and Naranjo et al., 2019.

Code	Formation	Age	Rock type	Paleontological potential
PlHa	Alluvial deposits	Pleistocene-Holocene	Sedimentary sequence	Susceptible
PlHc	Colluvial deposits	Pleistocene-Holocene	Sedimentary sequence	Susceptible
PlHs	Saline deposits	Pleistocene-Holocene	Sedimentary sequence	Susceptible
PlHg	Glacial deposits	Pleistocene-Holocene	Sedimentary sequence	Susceptible
PlHrm	Mass wasting deposits	Pleistocene-Holocene	Sedimentary sequence	Susceptible
Psv	Volcanic sequences	Upper Pliocene	Volcanic sequence	Barren
Pfp	Pyroclastic flows	Pliocene	Volcanic sequence	Barren
MsPa	Ancient alluvial deposits	Upper Miocene-Lower Pliocene	Sedimentary sequence	Susceptible
MsPls	Ancient saline deposits from the Maricunga Salt Flat	Upper Miocene-Pliocene	Sedimentary sequence	Susceptible
Msv	Block and ash deposits	Miocene-Pliocene	Volcanic sequence	Barren
Mga	Atacama gravels	Middle Miocene	Sedimentary sequence	Susceptible
Mmrl	Lamas river gravel	Middle Miocene	Sedimentary sequence	Susceptible
Msvc	Domes and pyroclastic flows from Copiapó Volcano	Middle Miocene	Volcanic sequence	Barren
Mmv	Central volcanic edifices	Middle Miocene	Volcanic sequence	Barren
Mmim	Maricunga ignimbrite	Middle Miocene	Volcanic sequence	Barren
Mmlp	Lavas from Pastillos volcano	Middle Miocene	Volcanic sequence	Barren
Mml	Andesitic and dacitic-Andesitic lavas	Middle Miocene	Volcanic sequence	Barren
Mmisr	Santa Rosa ignimbrite	Middle Miocene	Volcanic sequence	Barren
Mis	Lavas from the Soledad Prospect	Lower Miocene	Volcanic sequence	Barren
Miv	Volcanic edifices	Lower Miocene	Volcanic sequence	Barren
OMcg	Claudio Gay strata	Upper Oligocene - Lower Miocene	Volcanic sequence	Susceptible
EOlv	Vertiente strata	Eocene-Oligocene	Volcanic sequence	Barren
KTmzd	Monzodiorite and pyroxene monzodioritic porphyries	Upper Cretaceous-Lower Paleocene	Volcanic sequence	Barren
Kcc	Cerro los Carneros strata	Upper Cretaceous	Volcanic sequence	Barren
Jqv	Quebrada Vicuñita strata	Upper Jurassic	Volcanic sequence	Barren
Ja	Asientos Formation	Middle Jurassic	Sedimentary sequence	Fossiliferous

Code	Formation	Age	Rock type	Paleontological potential
Jm	Montandón Formation	Middle Jurassic	Sedimentary sequence	Fossiliferous
Jl	Lautaro Formation	Middle Jurassic	Sedimentary sequence	Fossiliferous
PeTlc	Los Colorados granite	Upper Permian-Lower Triassic	Plutonic Unit	Barren
PeTrg	Granitoids	Upper Permian-Lower Triassic	Plutonic Unit	Barren
Pep	Pantanoso Formation	Permian	Volcanic sequence	Barren
CPelt	La Tabla Formation	Carboniferous-Permian	Plutonic Unit	Barren
DCch	Los Chinches Formation	Devonic-Carboniferous	Sedimentary sequence	Fossiliferous

2.5.2.Pedological Index.

To calculate the Pedological Index (Pe), the regional soil map by Ulloa & Ortiz de Zárate (1989) was used, counting the represented soil orders. The map contains information on the distribution of two (2) soil orders, where calcic xerosols and lithosols are recognized (Figure 4).

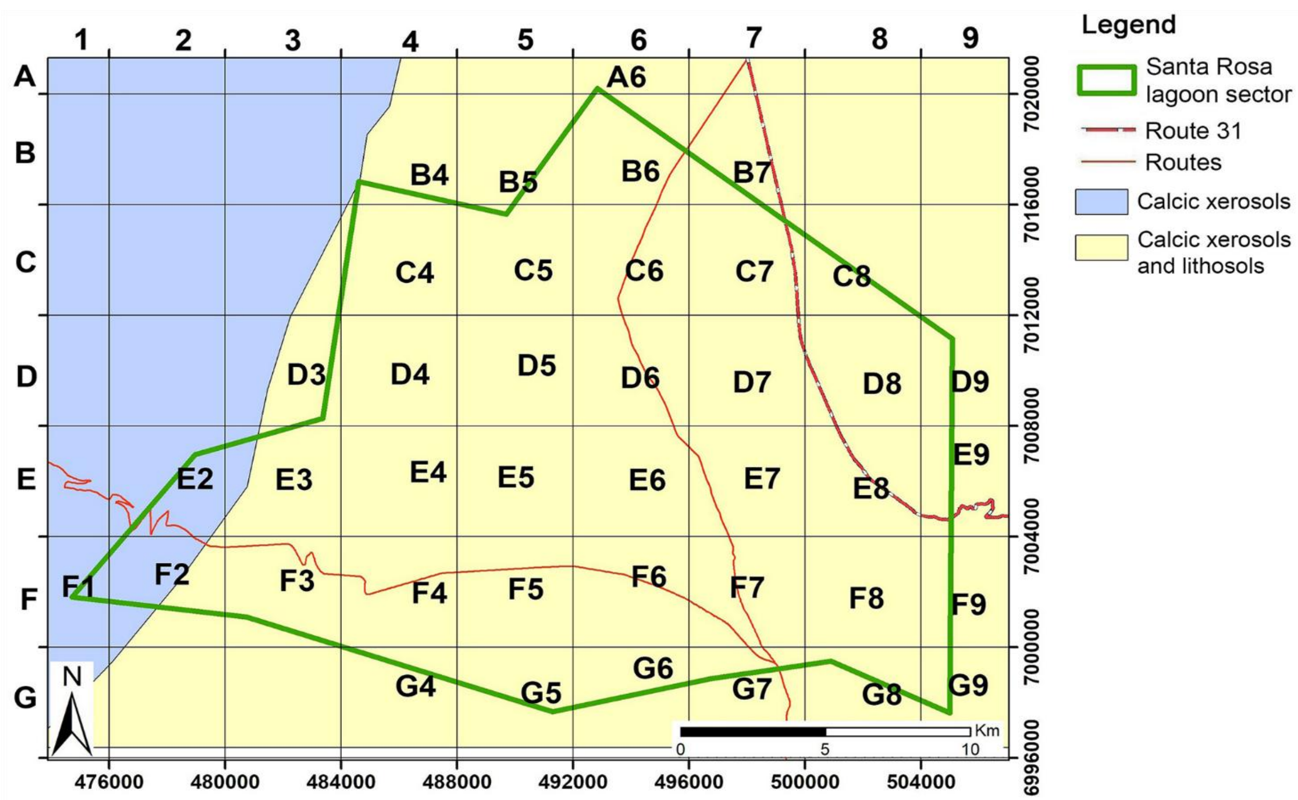

Figure 4. Pedological map of the Laguna Santa Rosa area. Source: Modified from Ulloa & Ortiz de Zárate, 1989.

2.5.3.Geomorphological Index.

For the calculation associated with the geomorphological index, the sum of the geomorphological units (G) present in each 4 × 4 km² quadrant was used. The map by Ulloa & Ortiz de Zárate (1989) was modified to a scale of 1:170,000 (Figure 5), quantifying the number of units present in each 16 km² quadrant.

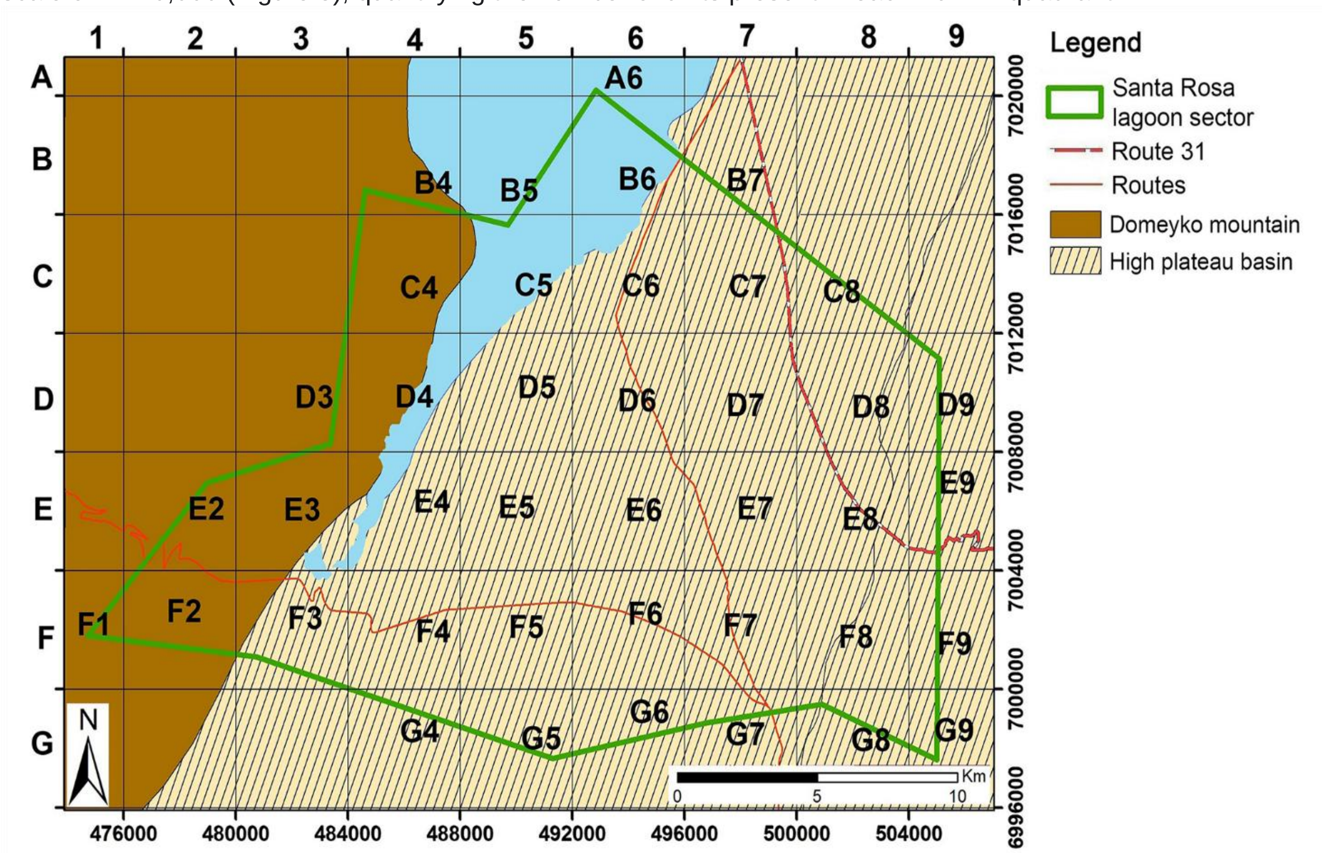

Figure 5. Geomorphological map of the Laguna Santa Rosa area. Source: Modified from Ulloa & Ortiz de Zárate, 1989.

2.5.4.Hydrological Index.

To calculate the hydrological index, a hydrological database from the National Congress of Chile Library website (www.bcn.cl) was used and modified to a scale of 1:170,000 (Figure 6). The sum of the hydrological units (H) present in each 4 × 4 km² quadrant was calculated. A value of three (3) was assigned to squares containing lagoons (Laguna Santa Rosa and water bodies in the Maricunga Salt Flat), a value of two (2) to squares containing rivers (Río Lamas), and one (1) to those squares with intermittent streams (Brooks). Finally, a value of 0 was assigned to squares without hydrological elements.

2.5.5.Mineral Index.

The Mineral Index was calculated based on a set of maps by Cornejo et al. (1998), Mpodozis et al. (2012), Clavero et al. (2012), and Naranjo et al. (2019), which provide data on various mineral localities and known occurrences associated with geological formations. Any element classified as a mineral of interest was assigned one point for the scoring for each corresponding square in the grid (Pereira et al., 2013; Carrión-Mero et al., 2022).

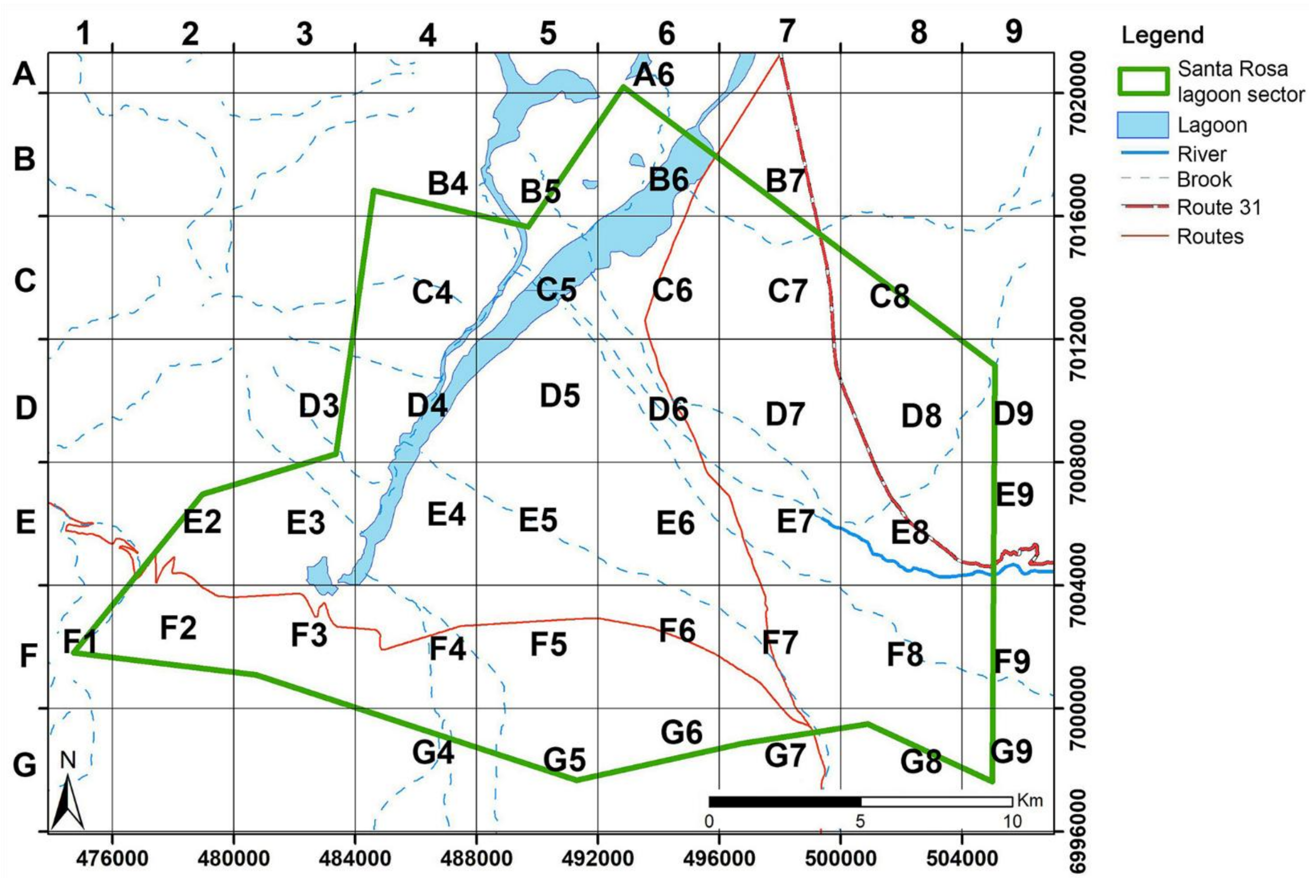

Figure 6. Hydrological map of the Laguna Santa Rosa area. Source: Modified from http://www.bcn.cl.

2.5.6.Rugosity Coefficient (Slopes).

The rugosity coefficient (R) contributes to the understanding of topographic characteristics. It is an integrative parameter of the system's abiotic elements. Its calculation was carried out using a contour map with the ArcGIS 10.8 program. The rugosity level is divided into four (4) intervals according to the dominant slope in each quadrant (Figure 7; Table 2). The area is marked by the size of the quadrant, so the surface data is constant in all cases: 16 km². For the final geodiversity value map, the method establishes predefined value intervals (Table 3).

Table 2. Rugosity values according to the slope. Source: Serrano & Flaño (2007).

Slope (°)	0-5	6-15	16-25	25-50	>50
Rugosity level	1	2	3	4	5

Table 3. Intervals of geodiversity categories. Source: Serrano y Flaño (2007).

Geodiversity	Very low	Low	Medium	High	Very high
Interval	<15	15-25	25-35	35-45	>45

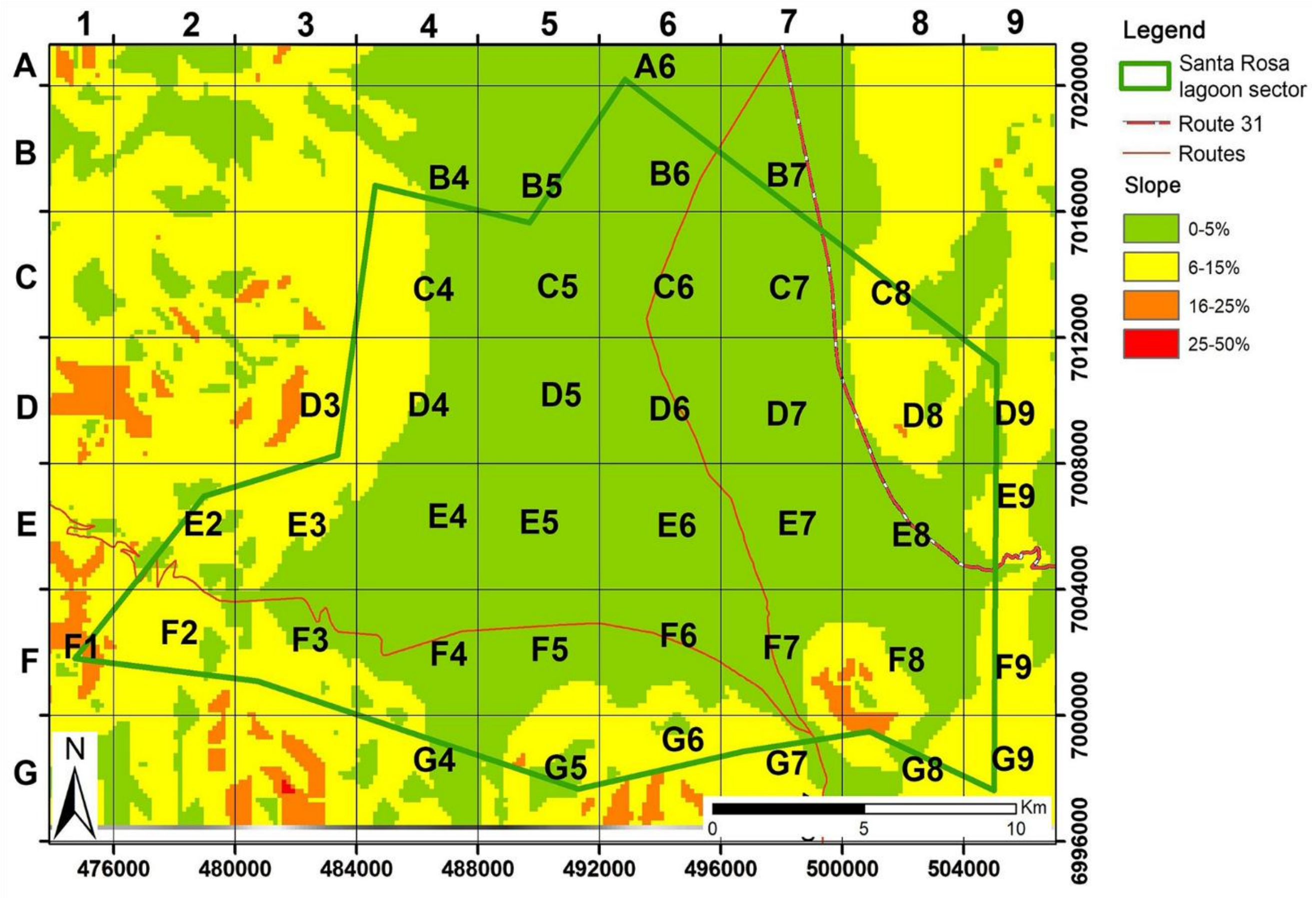

Figure 7. Rugosity map of the Laguna Santa Rosa area. Source: Own work, based on contour lines.

2.5.7.Geodiversity Index Map

Based on the proposals by Serrano & Flaño (2007); Pereira et al. (2013), and Carrión-Mero et al. (2022), the Geodiversity Index of each quadrant is directly related to the sum of all the previously characterized partial indices (Table 4). This allows for the creation of the Geodiversity Index map.

Table 4. Table with the information used for the development of geodiversity indices. C=Quadrant; L=Lithology (Geological units); Pa=Paleontology; Pe=Pedology; G=Geomorphology; H=Hydrology; M=Minerals; R= Roughness; I= Index (*C5, Lithium in Mspls and PlHs; F3, Gold and Silver in Mmv and Gold in Mis; F1, Gold and Silver in Mmv and Gold and Silver in Pfp) / Source: Own work, based on: Ulloa & Ortiz de Zárate, 1989; Cornejo et al., 1998; Serrano & Flaño,2007; Mpodozis et al., 2012; Clavero et al., 2012; and Pereira et al., 2013; CMN, 2016; Naranjo et al., 2019; BCN, 2024.

C	L		Pa	Pe	G	H	M		I. Pereira et al., 2013	R	I. Serrano y Flaño
C5	4	Mspa; Mspls; PlHs; PlHa	4	1	1	9	2	Lithium	21	3	22,722
E3	6	Mmim; Mmv; Mmisr; PlHa; PlHs; PlHc	3	2	2	4	2	gold; silver	19	3	20,558

C	L		Pa	Pe	G	H	M		I. Pereira et al., 2013	R	I. Serrano y Flaño
C8	7	DCch; Cpelt; Pep; Mga; Mmlr; MsPa; PlHa	6	1	1	1	0		16	3	17,312
E4	6	Mmv; Mmisr; MsPa; PlHa; PlHs; PlHc	4	1	2	7	2	gold; silver	22	2	15,869
E8	8	DCch; Cpelt; PeTlc; Mga;Miv; Mmlp MsPa; PlHa	6	1	1	3	3	gold; silver; copper	22	2	15,869
D4	4	Mmv; Mspa; PlHs; PlHc	3	1	2	5	3	gold; silver; Lithium	18	2	12,984
C4	5	Mmv; Mga; Mspls; PlHa; PlHs	3	1	1	4	3	gold; silver; Lithium	17	2	12,262
F3	5	Mmv; Mis; Mml; Mmisr; PlHa	1	1	2	3	3	gold; silver	15	2	10,820
C6	3	Mspa; Mspls; PlHs	3	1	1	5	1	Lithium	14	2	10,098
D8	6	DCch; Cpelt; PeTlc; Mga; MsPa; PlHa	5	1	1	1	0		14	2	10,098
E2	4	Mmim; Mmv; Mmisr; PlHa	1	1	1	0	2	gold; silver	9	3	9,738
F1	2	Mmv; Pfp	0	1	1	1	4	gold; silver	9	3	9,738
B6	3	Mspa; Mspls; PlHa	3	1	1	4	1	Lithium	13	2	9,377
D5	2	Mmv; PlHs	1	1	1	4	2	gold; silver	11	2	7,934
D9	4	DCch; Cpelt; Mga; PlHa	4	1	1	1	0		11	2	7,934
E7	2	MsPa; PlHa	2	1	1	5	0		11	2	7,934
E9	3	Mga; MsPa; PlHa	3	1	1	2	0		10	2	7,213
D3	2	Mmv; PlHc	1	1	1	2	2	gold; silver	9	2	6,492
D6	2	Mspa; PlHa	2	1	1	3	0		9	2	6,492
B5	1	Mspls	1	1	1	1	1	Lithium	6	3	6,492
E6	2	MsPa; PlHa	2	1	1	2	0		8	2	5,770
A6	1	Mspls	1	1	1	0	1	Lithium	5	3	5,410
B4	2	Mmv; PlHa	1	1	1	0	2	gold; silver	7	2	5,049
C7	2	Mspa; PlHa	2	1	1	1	0		7	2	5,049
D7	2	Mspa; PlHa	2	1	1	1	0		7	2	5,049
E5	2	MsPa; PlHa	2	1	1	1	0		7	2	5,049

C	L		Pa	Pe	G	H	M		I. Pereira et al., 2013	R	I. Serrano y Flaño
F4	5	Mis; Mmisr; MsPa; PlHa; PlHc	3	1	1	2	1	gold	13	1	4,688
G5	4	Mmlp; MsPa; PlHa; PlHc	3	1	1	1	3	gold; silver; copper	13	1	4,688
G7	4	Mmlp; MsPa; PlHa; PlHc	3	1	1	1	3	gold; silver; copper	13	1	4,688
F2	4	Mmv; Mmisr; PlHa; PlHc	2	2	1	1	2	gold; silver	12	1	4,328
F8	4	Mmv; Mga; MsPa; PlHa	3	1	1	1	2	gold; silver	12	1	4,328
B7	2	Mspa; PlHa	2	1	1	0	0		6	2	4,328
F5	3	Mmlp; MsPa; PlHa	2	1	1	1	3	gold; silver; copper	11	1	3,967
F6	3	Mmlp; MsPa; PlHa	2	1	1	1	3	gold; silver; copper	11	1	3,967
F7	3	Mmlp; MsPa; PlHa	2	1	1	1	3	gold; silver; copper	11	1	3,967
F9	4	Msv; Mga; MsPa; PlHa	3	1	1	1	0		10	1	3,606
G4	4	Mis; Msvc; MsPa; PlHa	2	1	1	1	1	gold	10	1	3,606
G8	4	Psv; Mmv; MsPa; PlHa	2	1	1	0	2	gold; silver	10	1	3,606
G6	2	Mmlp; PlHa	1	1	1	0	3	gold; silver; copper	8	1	2,885
G9	3	Psv; Mmv; MsPa	1	1	1	0	0		6	1	2,164

3. RESULTS

3.1. Geology.

Based on the applied methodology, the resulting geodiversity index values varied considerably depending on the specific index assessed. In the case of the geological index, which evaluates the diversity of lithological formations within each quadrant, values ranged from 1 to 8 points across the Santa Rosa sector. This variation reflects the heterogeneous distribution of geological units throughout the park. Notably, the highest lithological diversity is concentrated along the edge of Laguna Santa Rosa and in the eastern part of the park, specifically within quadrants E8, C8, D8, E3, and E4. These areas are characterized by a complex assemblage of rock types, including both sedimentary and volcanic formations, which contribute to a richer geological record and greater potential for paleontological findings. In contrast, the broader high plateau basin, encompassing quadrants D5, D6, D7, E5, E6, and E7, exhibits lower geological diversity. This region is dominated by extensive, relatively homogeneous unconsolidated units, with limited variation in rock type, resulting in lower overall geological index values and a simpler lithological landscape.

3.2. Paleontology.

The Paleontological Index values for the Santa Rosa sector range from 0 to 6 points, reflecting significant variation in fossil potential across the study area. Higher index values are primarily associated with quadrants containing a substantial abundance of sedimentary rocks, which are more likely to preserve fossil evidence. A notable example is the Chinches Formation, which contains a variety of fossil ichnites and contributes significantly to the overall paleontological value of the corresponding quadrant. These higher values indicate areas where paleontological research and conservation efforts could be particularly productive, providing insight into past ecological and environmental conditions. In contrast, the lowest index value of 0 is attributed to rocks that are considered barren with regard to fossil content. These typically include high-energy volcanic units, where depositional conditions were unfavorable for fossil preservation. The resulting spatial distribution of paleontological index values highlights those areas of concentrated fossiliferous potential as opposed to regions with minimal or no expected paleontological resources, providing an essential tool for prioritizing geoconservation and research within the park.

3.3. Pedology.

The values obtained for the Pedological Index in the Santa Rosa sector range from 1 to 2 points, reflecting limited variability in soil types across the park. These values are primarily associated with the presence of calcic xerosols and lithosols. The highest Pedological Index values are found in the Laguna Santa Rosa area, where soils, though thin, are slightly more developed compared to the surrounding mountainous regions. Conversely, the lower index is associated with the high-altitude mountainous areas exhibiting impoverished soils of limited thickness, contributing minimally to the overall geodiversity of the park. Likewise, the Geomorphological Index values range from 1 to 2 points. Higher values are observed in those areas characterized by larger slopes, particularly along the Domeyko mountain range, which contrasts sharply with the flatter high plateau basin, highlighting the significant morphological variability within the study area and its contribution to geodiversity patterns.

3.4. Hydrology.

For the Hydrological Index, values range from 0 to 9 points, reflecting the variability in water presence across the Maricunga Salt Flat region. Higher values correspond to quadrants containing permanent water bodies or springs, while intermittent watercourses receive intermediate scores. Specifically, quadrants C5 and E4 contain springs and minor watercourses, contributing to their higher index values. The quadrant encompassing Laguna Santa Rosa (E3) is assigned to a medium value of 4 points, indicating moderate hydrological significance. This index emphasizes the spatial distribution of water resources and their influence on overall geodiversity.

3.5. Minerals.

Mineral outcrop occurrences across the study area show limited variation, with most quadrants presenting similar values. Exceptions occur in specific locations where higher concentrations of gold, silver, and copper are present. The highest index value of 4 points corresponds to volcanic units containing hydrothermal mineral deposits, highlighting areas of significant mineralogical interest.

3.6. Geodiversity (Serrano & Flaño, 2007).

Based on the applied methodology, the geodiversity index was calculated by summing the values obtained for each specific component, including geology, paleontology, pedology, geomorphology, hydrology, and mineral occurrences. Using the calculation proposed by Serrano & Flaño (2007), which incorporates both terrain rugosity and the spatial extent of each quadrant, the results indicate very low geodiversity values across nearly the entire park area. Only five quadrants; C5, C8, E3, E4, and E8, show relatively higher geodiversity, although still within the low to moderate range. These quadrants correspond closely to areas with higher lithological diversity and elevated hydrological index values, particularly near Laguna Santa Rosa and the Maricunga Salt Flat (Figure 8). This pattern demonstrates the influence of terrain complexity and water availability on overall geodiversity, highlighting specific zones where abiotic diversity is concentrated, adding key insights for prioritization of targeted geoconservation efforts.

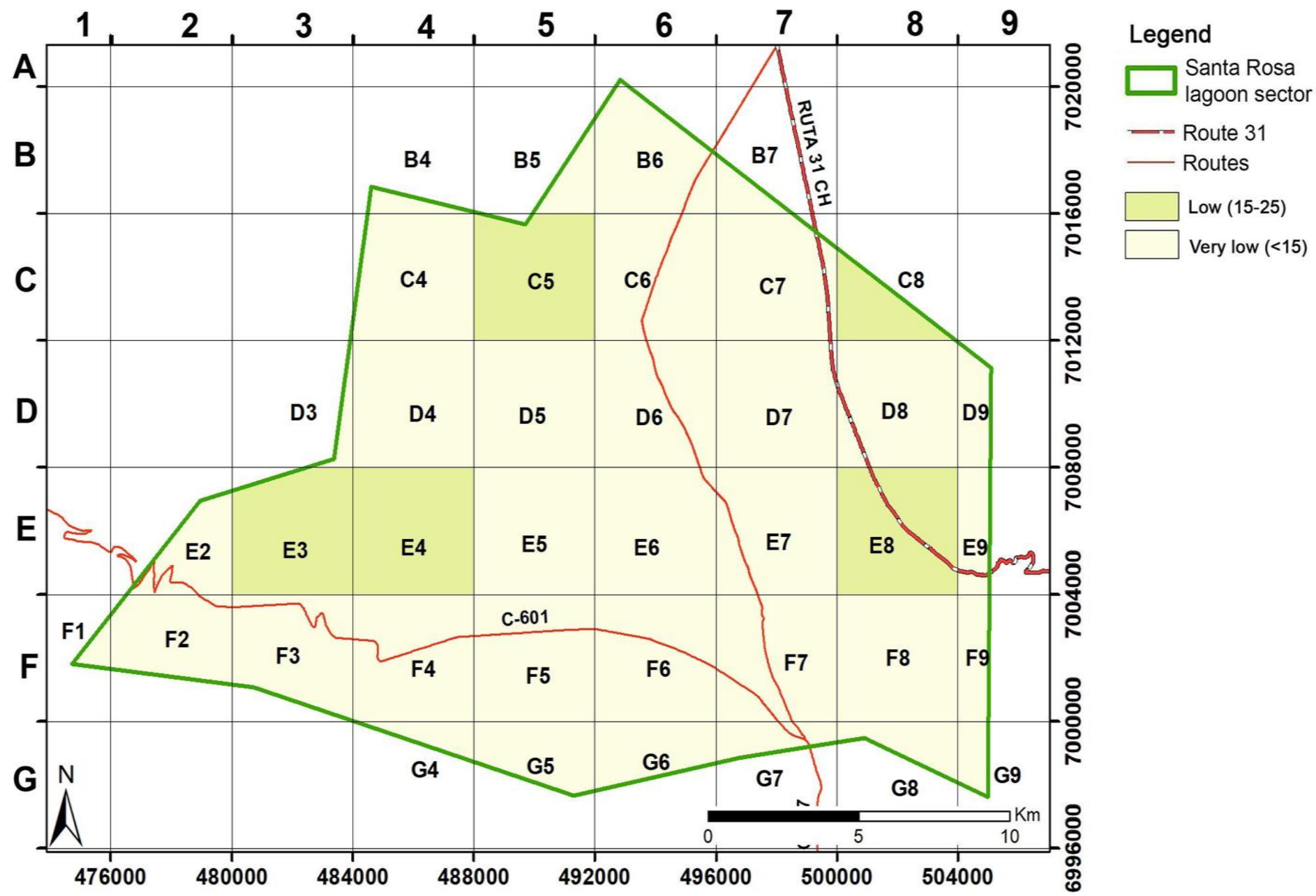

Figure 8. Geodiversity map of the Laguna Santa Rosa area, according to the methodology of Serrano & Flaño (2007). Source: Own work.

3.7. *Geodiversity Pereira et al. (2013).*

Using the methodology proposed by Pereira et al. (2013), the geodiversity index was calculated by summing the values obtained for each individual component, including geology, paleontology, pedology, geomorphology, hydrology, and mineral occurrences. Applying this approach to the Laguna Santa Rosa sector, the geodiversity index values range from 5 to 22 points (Figure 9), reflecting substantial variability in abiotic diversity across the park. Very low values, below 8 points, are primarily observed in areas characterized by limited lithological variability and the absence of significant water bodies, highlighting regions of minimal geological complexity. In contrast, high and very high geodiversity scores, ranging from 14 to 16 and exceeding 16 points, are concentrated in the park's eastern sector, where a greater number of geological formations with fossiliferous potential occur. The quadrants directly associated with Laguna Santa Rosa (E3 and E4) exhibit very high geodiversity, with numerous formations that not only enhance geological diversity but also present significant paleontological and mineral potential, including gold, silver, and other minerals associated with volcanic units, underscoring the area’s importance for both geoconservation and scientific research.

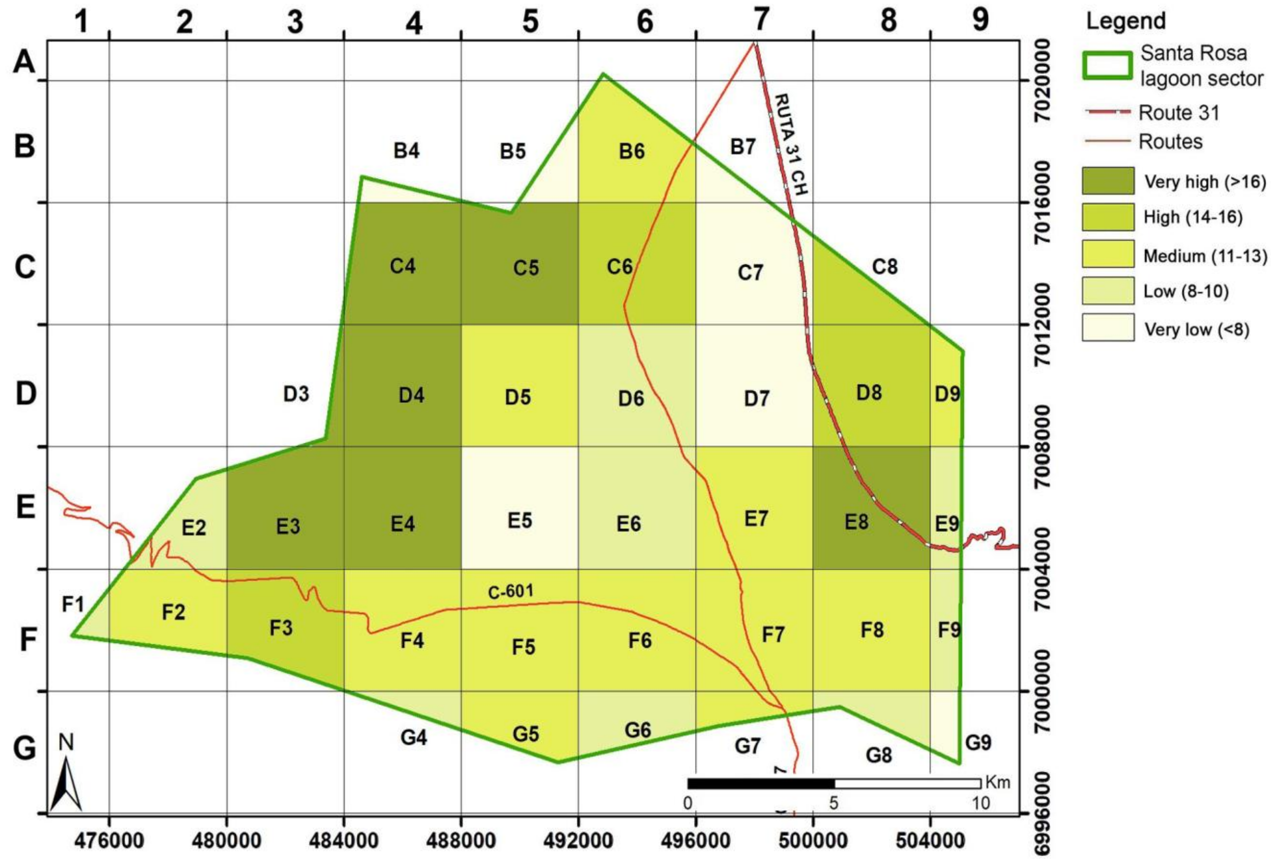

Figure 9. Geodiversity map of the Laguna Santa Rosa area, according to the methodology of Pereira et al. (2013). Source: Own work.

4. DISCUSSION

Several Geodiversity indices have been proposed and applied to study specific areas in different countries in the last 30 years, and more recently appraisals have been discussed and reviewed to compare their value to assess risk of degradation for geoheritage (Brilha, 2016, 2018). With that goal in mind, these methods focus on the identification of geosites using weighted scores that consider criteria and parameters such as accessibility, proximity to roads and urban areas, as well as population density, so not suitable to assess larger areas far from any road or population as is this national park, whereas other methods as those used in this work (Serrano & Flaño,2007) and Pereira et al. (2013) fit better because they are able to compile all the geological features that define a larger specific area providing a tool to highlight areas with high geodiversity such as those found in national parks, and whose results are summarized and shown as a map that is useful for land planning and geoconservation. Then, both methods produce a geodiversity index map comparable across a large area that fits better to the features of the Santa Rosa area of the Tres Cruces National Park studied here. The method accuracy improves as well because the results were checked including our own recent field data compilation (Vicencio, 2016; Vicencio, 2020) taken from campaigns done between 2016 to 2020, which were added to a larger database compiled from the geological, paleontological, pedological, geomorphological, hydrological, and mineralogical sources known for the area (Cornejo et al., 1998; Mpodozis et al., 2012; Clavero et al., 2012; Naranjo et al., 2019; CMN, 2016; Ulloa & Ortiz de Zárate, 1989; BCN, 2024). When comparing these results, the indices show minimal variation between the two methodologies applied (Serrano & Flaño, 2007; Pereira et al., 2013). However, notable differences emerge when considering the rugosity component. The methodology of Serrano & Flaño (2007), which integrates terrain slope as a factor in the calculation, produces significantly lower geodiversity values compared to Pereira et al. (2013), which aggregates the individual indices without weighting for slope. Using Serrano and Flaño's approach, approximately 90% of the park area is classified as having very low geodiversity, with the remaining 10% (Table 5; Figure 10) falling within the lower category. Notably, these higher-value quadrants correspond closely to areas exhibiting elevated vertebrate biodiversity within the park (Figure 10E), suggesting a spatial correlation between topographic complexity and habitat richness.

In contrast, the method proposed by Pereira et al. shows that very low geodiversity represents only 20% of the park, while 15% of the area reaches very high geodiversity levels. This discrepancy underscores how methodological decisions, particularly the inclusion of terrain complexity and slope can influence absolute index values while still identifying the same priority zones for conservation. Both approaches were applied using raster-based cartographic formats, which facilitate systematic counting of abiotic elements per quadrant and simplify the mathematical application of geodiversity indices. These indirect, GIS-based methods are particularly useful for evaluating large, remote, or difficult-to-access areas, as they allow consistent spatial analysis across challenging landscapes and help to concentrate efforts on areas that exhibit high geological diversity. In these identified quadrants defined by UTM coordinates (WGS84), other more detailed methodologies focused to assess geosites such as those proposed by Brilha (2016) can then be applied, starting with the higher scoring quadrants that are close enough to a road (*e.g.* E8).

Despite differences in absolute index values, both quadrant based methodologies applied here consistently highlight the region surrounding the Maricunga Salt Flat and Laguna Santa Rosa as exhibiting the highest geodiversity within the park. These findings are consistent with observed vertebrate biodiversity patterns, emphasizing the interdependence of abiotic complexity and biological richness. Overall, this analysis reinforces the importance of incorporating geodiversity assessments into conservation planning, as areas with high geological complexity also provide critical ecosystem services and habitat heterogeneity, serving as key targets for biodiversity protection and sustainable management (CONAF, 1997; Vicencio, 2020; Cerda & Medina, 2022; Vicencio-Campos et al., 2023).

Table 5. Comparison of the relative surface area occupied by each geodiversity assessment obtained using each assessment method applied. Source: Own work.

Geodiversity assessment					
Method	Very low	Low	Medium	High	Very high
Serrano and Flaño, 2007	90	10	-	-	-
Pereira et al., 2013	20	25	30	10	15

Figure 10. Landscape view inside Tres Cruces NP. A. Quadrant E2, Rocks corresponding to Central volcanic buildings (Mmv). B Quadrant D5, Ancient alluvial deposits (MsPa). C. Quadrant E7, Alluvial deposits (PlHa). D.Quadrant D8, los Colorados Granite (PeTlc) contact with Chinches Formation (DCch). E. Quadrant E3, view geological outcrop Santa Rosa ignimbrite (Mmisr). F. Quadrant E3, with high geodiversity index shows support

for biodiversity (high andean vegetation and camelid herd of *Lama guanicoe*). Source: Own elaboration.

5. CONCLUSIONS

In conclusion, the assessment of geological indices—including Geology, Paleontology, Pedology, Geomorphology, Hydrology, and Minerals—using the methodologies proposed by Serrano & Flaño (2007) and Pereira et al. (2013) demonstrates a complex interplay between geodiversity evaluation and its implications for biodiversity. Both methodologies produced comparable results for most individual indices, indicating that the distribution and richness of abiotic elements such as lithological formations, fossiliferous units, soil types, geomorphological structures, hydrological features, and mineral occurrences are consistently captured. However, notable differences emerge in the assessment of rugosity, with Serrano & Flaño's method yielding significantly lower geodiversity values compared to Pereira et al. This difference in slope integration results in a stark contrast in overall geodiversity assessment: Serrano & Flaño's method highlights a predominance of very low geodiversity across the majority of the park, whereas Pereira et al.'s approach identifies a more heterogeneous distribution, including areas of high and very high geodiversity, particularly in the eastern sector and around Laguna Santa Rosa.

From a methodological perspective, both approaches employed raster-based cartographic formats, which proved advantageous for analyzing large, remote, and difficult-to-access areas. This format allows for systematic counting of abiotic elements per quadrant and facilitates the application of geodiversity equations, ensuring consistency in large-scale spatial assessments. While each methodology has inherent strengths and limitations, their results converge in identifying critical regions of high geodiversity, notably around the Maricunga Salt Flat and Laguna Santa Rosa. These areas also correspond to zones of elevated vertebrate biodiversity, reinforcing the strong correlation between abiotic complexity and biological richness. At the same time, these higher geodiversity quadrants also cartographically identify the most suitable areas in a large park where as a following step geosite focused methodologies may be then applied.

Overall, the comparative analysis of these methodologies emphasizes the significance of methodological selection in geodiversity studies, as different approaches can produce varying absolute values but still reliably highlight priority areas for conservation. Integrating multiple methodologies in future research could enhance the precision of geodiversity mapping, providing a more nuanced understanding of abiotic and biotic interactions. Recognizing geodiversity as a fundamental component of ecosystem management is essential for developing comprehensive conservation strategies, protecting high-altitude wetlands, and ensuring the long-term maintenance of both geological and biological diversity within the Nevado de Tres Cruces National Park.

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