APPLYING ECOLOGICAL DIVERSITY INDICES WITH ECOSYSTEM APPROACH AT ECOREGIONAL LEVEL AND PRIORITIZING THE DECREE OF NEW PROTECTED NATURAL AREAS

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SUMMARY

One of the main challenges of the new Protected Natural Area prioritization is using the appropriate tools to determine which of the areas are more representative at the ecoregional level. In this work, we used ecological diversity indices (EDIs) with an ecosystem approach as a tool to compare the differences in ecosystem diversity among different ecoregions. After comparing five EDI at coastal and marine ecoregions on Northwestern Mexico, it is concluded that out of the five indices analyzed for ecosystem diversity, the Simpson's Inverse and Hill indices were the most sensitive ones, considering the trends of their charts, variations, and the distance between their range values, which describe ecosystem diversity more accurately among different ecoregions. However, in order to describe the richness and heterogeneity of the analyzed ecoregions, the Simpson's Inverse index was the most useful to define which of the regions have greater diversity of ecosystems in comparative studies among them, and therefore the priority to be enacted as a new Protected Natural Area.

Ecological diversity indices (EDIs) are indicators employed to describe the most important and inherent biological characteristics of an ecosystem (Izsák and Papp, 2000). EDIs are also directly used for ecosystem management and conservation, and some are used as health, structure, and performance indicators (Butturi-Gomes *et al*., 2014). They usually consider species richness and abundance, including some further considerations of the relationship between biotic and abiotic components (Jizhong *et al.*, 1991; Soininen *et al*., 2012; Lyashevska and Farnsworth, 2014).

EDIs such as the Shannon-Weaver index (Shannon and Weaver, 1949) and the Simpson index (Simpson, 1949) are commonly used; but other indices used in evenness analysis are those of Gleason (1922), Brillouin (1962), Menhinick (1964), Margalef (1968), and Pielou (1969), whose variations are due to differences in the weight given to species richness and their evenness, as well as a differential sensitivity to sample size. Also, in order to compare

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the similarity in species diversity among sites, a variety of indexes are used, such as those of Jaccard (1908), of Sorensen (1948) and the Bray-Curtis index (Bray and Curtis, 1957).

The EDI used at landscape level is the Shannon-Weaver index, because of its wide application to determine entropy and categorization of landscape patches (Yoshida and Tanaka, 2005; Dušek and Popelková, 2012). It has also been used to determine landscape structure, including area, shape, density and proportions to guarantee their conservation (Kuchma *et al*., 2013), and it has been applied at ecosystem level as an entropy index that identifies the number of components in an ecosystem and the interactions among them. On the other hand, the Simpson index has been used jointly with economic variables to determine life satisfaction in a specific area (Ambrey and Fleming, 2014).

No previous records were found on the use of EDI applied, not only to know the biodiversity within an ecosystem but also to determine the diversity of different coastal ecosystems within a given ecoregion. The nearest similar application of the EDI was performed by Lapin and Barnes (1995), who analyzed the landscape on the basis of species and ecosystems diversity to generate a map and a classification of the area under study, indicating the richness and heterogeneity of ecosystems. In our study, EDIs were applied to determine the variability of different ecosystems that occur in the coastal and marine ecoregions of the State of Baja California Sur, Mexico.

Taking into account that diversity has two components: species richness and evenness, in this study we considered species richness as the number of ecosystems present, and evenness as the coverage of each ecosystem in each study site along the coastal zone.

The EDIs that emphasize on diversity are those of Shannon-Weaver (1949), Simpson (1949), Simpson's Inverse (Williams and Lambert, 1959) and Hill (1973). They can help to obtain a profile of ecosystem diversity on a coastal area, for environmental monitoring and decision making for conservation and management (Spellerberg, 1991), and they can also be applied to monitor the possible effects of environmental disturbances (Moreno, 2001).

The theoretical foundation of this study is the use of ecosystem richness as the basic criteria to be applied in the analysis and the recognition of priority areas for conservation. Our goal is to apply the Ecological Diversity Indices (EDIs) to determine the heterogeneity of ecosystems at ecoregional level in the coastal zone of Baja California Sur, and to determine which of them expresses the best results.

Material and Methods

Study area

The coastal zone of Baja California Sur (BCS), Mexico, has a length of 2,131km (Figure 1). An outstanding feature of BCS is the diversity of coastal and marine ecosystem due to the influence of the Pacific Ocean and the Gulf of California, both of them with particular geological and oceanographic features (De la Lanza-Espino *et al*., 2013). The Pacific coast is characterized by a wider continental shelf, sandy coast, alluvial fans, floodplains (Wilkinson *et al*., 2009) with the exception of the Cape Region, which is characterized by a mountainous system segmented into smaller blocks, a complex of crystalline igneous and metamorphic rocks, mainly granite (López-Blanco and Villers-Ruiz, 1995; Martínez and Díaz, 2011); while the Gulf showed a narrower continental shelf, abundant islands, rocky coastal cliffs, and small alluvial delta fans (Wilkinson *et al*., 2009).

The coastal zone of BCS includes 10 ecoregions (González-Abraham *et al*., 2010; Wilkinson *et al*., 2009): Gulf Coast (Gc), La Giganta Ranges (Gr), Sarcocaulescent Shrubland

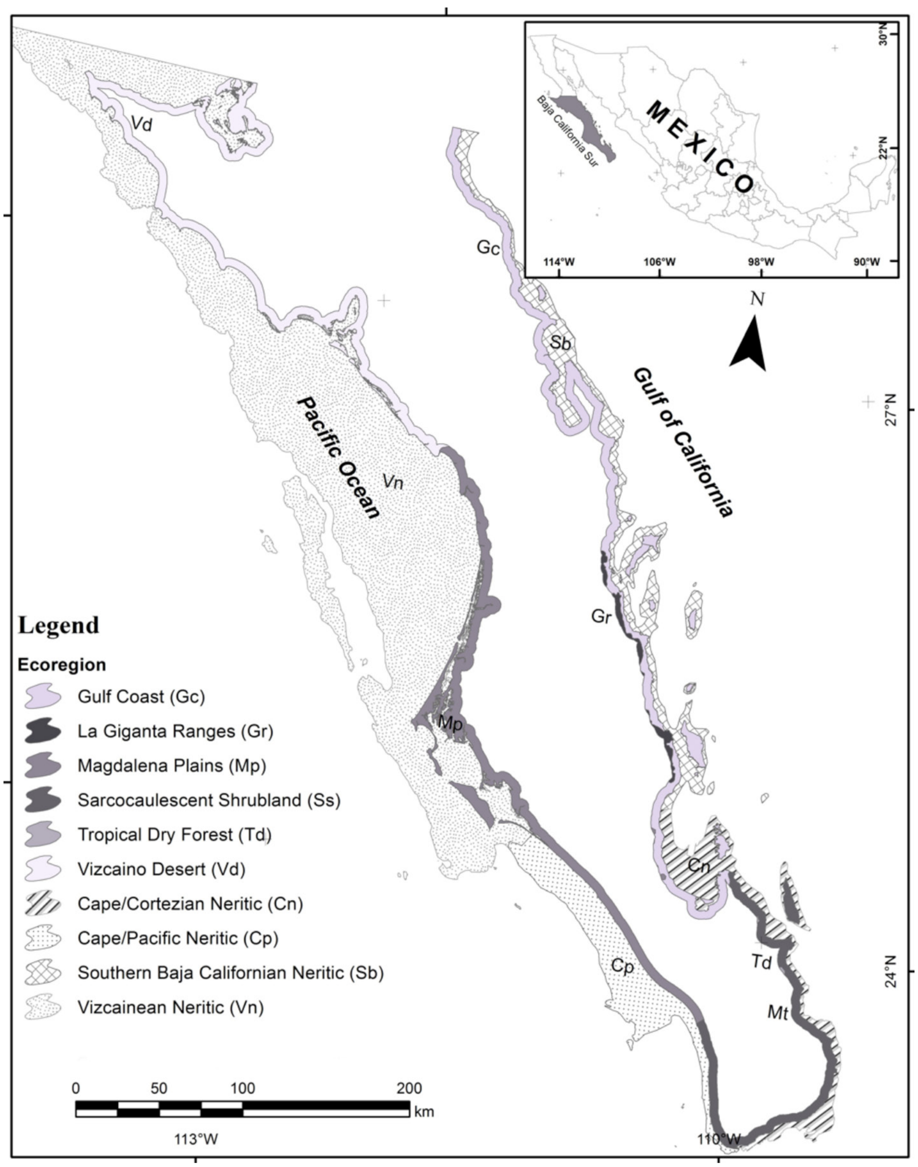

Figure 1. Study area indicating the ecoregions of Baja California Sur, Mexico. Adapted from González Abraham *et al*. (2010) and Wilkinson *et al*. (2009).

(Ss), Tropical Dry Forest (Td), Southern Baja California Neritic (Sb), Cape Cortezian Neritic (Cn), Magdalena Plains (Mp), Vizcaino Desert (Vd), Cape Pacific Neritic (Cp), and Vizcainean Neritic (Vn). As a variable we use the surface area (km^2) analyzing 11 categories: bare soil, beach, coastal water body, mangrove, riparian, salt flat, salt marsh, scrub, reef, seagrass, and other vegetation types. To test differences the following statistical analysis were applied: cluster analysis (similarity measure: Bray-Curtis) and EDI.

The ecoregion and ecosystem areas were estimated through the exploration method of satellite imagery with the IDRISI Taiga© software (Eastman, 2009), by performing a vector transformation of the shapes and expressing the results in hectares; 1,200 pixels of Landsat 5TM raster images were selected at random to determine the ecosystem type. The surface of each ecosystem was measured for each ecoregion. To validate their classification, type 973 checkpoints were chosen at simple random sampling to cover the coastal zone of BCS.

Ecosystems in ecoregions were classified hierarchically for cluster analysis, choosing the correlation coefficient as a measure of association (Sokal and Rohlf, 1962) and the unweighted pair group method using arithmetic averages (Sokal and Michener, 1958) as aggregation algorithm. The distortion of the relationships was measured by the cophenetic correlation coefficient (Cunningham and Ogilvie, 1972).

In addition to a multivariate analysis, nonmetric multidimensional scaling (nMDS, multidimensional scaling of nonparametric transformed data, fourth root), was applied and standardized to determine similarities among ecoregions. For this analysis we used Primer v.6 Software (Clarke and Gorley, 2006).

The surface values obtained were analyzed with PRIMER v.6 Software (Clarke and Gorley, 2006) using the similarity method (Bray and Curtis, 1957), obtaining the fourth root for each datum, and thus assessing each ecoregion, expressed on a dendogram that defined the relations among the BCS ecoregions.

We employed the following EDIs in this work: Margalef (1968), Simpson (1949), Simpson's Inverse (Williams and Lambert, 1959), Shannon-Weaver (1949) and Hill (1973). The mathematical expressions of each index are as follows

Margalef index

$$D = {}^{S-1}/_{\ln(N)}$$

where D: ecosystem richness, S> total number of ecosystem, and N: the sum of ecosystem i.

Simpson index

$$\lambda = \sum_{i=1}^{s} pi^2$$

where λ: dominance index, p_i: proportional abundance of ecosystem i, i.e. the total surface of ecosystem i divided by the total surface sum: $pi = {}^{ni}/_{N}$

Simpson's Inverse index

$$IS = 1/\lambda$$

Shannon-Weaver index

$$H' = -\sum pi \ln pi$$

where H': diversity and p_i: surface proportion in ecosystem i.

Hill index

$$N1 = e^{H'}$$

where N1: diversity of ecosystems, the natural logarithm (log to base e), and H': Shannon-Wiener diversity.

The numerical values of the EDIs were normalized and grouped according to similar patterns in charts, so as to make comparisons among them.

Results

The ecoregions with high surface values (>1000ha) were the Gulf Coast, Magdalena Plains, Vizcaino Desert and Sarcocaulescent Shrubland; with medium surface values (500-1000ha) was Cape Cortezian Neritic; and those with low surface values (<500ha) were Southern Baja California Neritic, La Giganta Ranges, Tropical Dry Forest, and Vizcainean Neritic (Table I).

Differences between N values were observed, highlighting two groups of interrelated ecosystem (Figure 2) and differentiating the coastal and marine parts. The groups of ecoregions with higher association by their similarity were 1) Sarcocaulescent Shrubland, Gulf Coast, Magdalena Plains, Vizcaino Desert; La Giganta Ranges, and Tropical Dry Forest; and 2) Cape Pacific Neritic, Cape Cortezian Neritic, Southern Baja California Neritic, and Vizcainean Neritic.

This was consistent with nMDS analysis, which indicated that in the coastal group Sarcocaulescent Shrubland, Gulf Coast, Magdalena Plains, Vizcaino Desert, and La Giganta Ranges had higher similarity, while in the marine group Cape Pacific Neritic, Cape Cortezian Neritic, and Southern Baja California Neritic had more similarity (Figure 3).

The behavior of the five indices proposed for this ecosystem diversity analysis showed three well defined patterns: 1) similar variation of Simpson´s Inverse and Hill indices (Figure 4a); 2) similar variation between Simpson and

TABLE I
ECOSYSTEM SURFACE (km^2) IN TEN ECOREGIONS
OF THE COASTAL ZONE OF BAJA CALIFORNIA SUR, MEXICO

Ecoregion	Ecosystem											
	Scrub	Coastal water body	Riparian	Bare soil	Other vegetation types	Beach	Salt flat	Mangrove	Salt marsh	Reef	Seagrass	N*
Gulf Coast	843	0	1276	176	268	18	18	1	3	0	0	2603
La Giganta Ranges	78	0	124	1	12	0	0	0	0	0	0	215
Sarcocaulescent Shrubland	976	0	139	23	234	2	3	1	2	0	0	1380
Tropical Dry Forest	12	0	3	0	1	0	0	0	0	0	0	16
Southern Baja California Neritic	0	358	0	0	0	0	0	1	0	0	1	360
Cape/Cortezian Neritic	0	946	0	0	0	0	0	1	1	4	0	952
Magdalena Plains	1923	0	55	85	146	198	51	99	1	0	0	2558
Vizcain Desert	163	0	31	1058	77	341	245	15	40	0	0	1970
Cape/Pacific Neritic	0	2018	0	0	0	0	0	28	22	0	0	2068
Vizcainean Neritic	0	5	0	0	0	0	0	1	0	0	0	6
Total area of ecosystem (km²)	3995	3327	1628	1343	738	559	317	147	69	4	1	

* N: total area of the ecoregion (km^2).

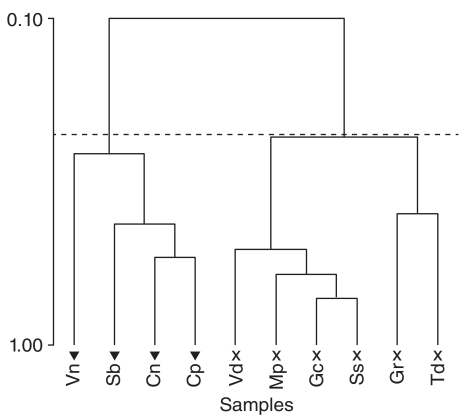

Figure 2. Classification of ecoregions according to cluster analysis. Ordinate shows coefficient of correlation. Cophenetic correlation coefficient: 0.94. Ecoregions: Gulf Coast (Gc), La Giganta Ranges(Gr), Sarcocaulescent Shrubland (Ss), Tropical Dry Forest (Td), Southern Baja California Neritic (Sb), Cape Cortezian Neritic (Cn), Magdalena Plains (Mp), Vizcaino Desert (Vd), Cape Pacific Neritic (Cp) y Vizcainean Neritic (Vn).

Finding the right method to describe the ecosystem diversity is a challenge, because all indices have different purposes and each one of them has several advantages and disadvantages. Therefore, in this work three fundamental advantages led us to detect and recommend the Simpson's Inverse and Hill indices as the most appropriate to determine differences among ecosystem diversity in ecoregions: 1) the theoretical foundations of both indices, 2) the minimum

Shannon-Weaver indices (Figure 4b); 3) a different pattern was shown by the Margalef index (Figure 4c). In the four cases of Figures 4a and b, the highest value (1.0) was observed in the Vd ecoregion, and the lowest values in Sb and Cn ecoregions. Both minimum and maximum value of the Margalef index (Figure 4c) corresponded to different ecoregions.

According to the EDIs applied, the results indicated that the areas with higher diversity were distributed in the coastal zone and those with lower diversity were located in the marine part. For the coastal zone the EDIs showed that Gc was the most diverse ecoregion at the Gulf of California. In the Pacific Ocean, however, Vd and Mp were the ecoregions representing the areas with the greatest diversity.

The Hill index had lower values with a mean difference between range values of 0.18, but it agreed with the Simpson's inverse index in the Vd ecoregion, both with a value of 1.0 (Figure 4a). The Simpson and Shannon-Weaver indices showed differences in the mean range of 0.07 between the values for each ecoregion but agreed in the highest values in Mp and Vd, as well as in the lowest value in Cp (Figure 4b). The Margalef index had a distinct pattern with variations between 0.27 in Cp to 1 in Ss (Figure 4c).

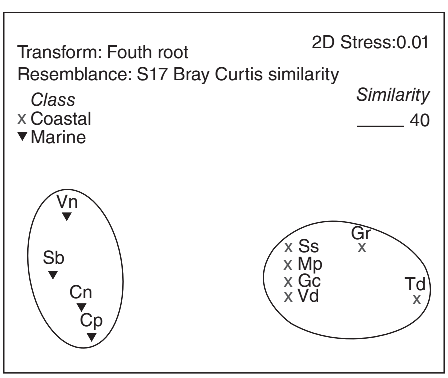

Figure 3. nMDS ordination of the ecoregions of the coastal zone of Baja California Sur: Gulf Coast (Gc), La Giganta Ranges(Gr), Sarcocaulescent Shrubland (Ss), Tropical Dry Forest (Td), Southern Baja California Neritic (Sb), Cape Cortezian Neritic (Cn), Magdalena Plains (Mp), Vizcaino Desert (Vd), Cape Pacific Neritic (Cp) y Vizcainean Neritic (Vn).

Discussion

The diversity index applied to the ecosystems in ecoregions suggest a useful approach, as there is a diversification of environments in the coastal zone of Baja California Sur that contributes to area heterogeneity mainly in two strands, the Gulf of California and the Pacific Ocean, where distinct patterns of ecosystems are identified according to Lapin and Barnes (1995) and González-Abraham *et al*. (2010). We consider that such patterns are associated to climate, physiography, topography and geology of the zone, and reflect the complexity of the geomorphological and geological processes that form this landscape and in turn the ecosystem.

The similarity analysis allowed us to observe three groups in the coastal and marine zones, with a clearly larger ecosystem diversification in the coastal than in the marine zone. These groups are: 1) Sarcocaulescent Shrubland, Gulf Coast, Magdalena Plains, and Vizcaino Desert; 2) La Giganta Ranges and Tropical Dry Forest; and 3) Cape Pacific Neritic, Cape Cortezian Neritic, Southern Baja California Neritic, and Vizcainean Neritic.

The analysis also indicated that not all the marine environmental conditions allow the presence of reefs and seagrass. Also, it indicated that the coastal ecosystems are strongly influenced by the marine zone, by topography, and by latitudinal species distribution.

In particular, the terrestrial ecosystems have a higher affinity and similarity among them, and the analysis showed that even having the same kind of vegetation, topography plays a major role. For instance, the differences between Gr and Td ecoregions are attributed to topography despite the fact that the dominant vegetation in both ecoregions is scrub (González-Abraham *et al.*, 2010). This was consistent when using nMDS analysis.

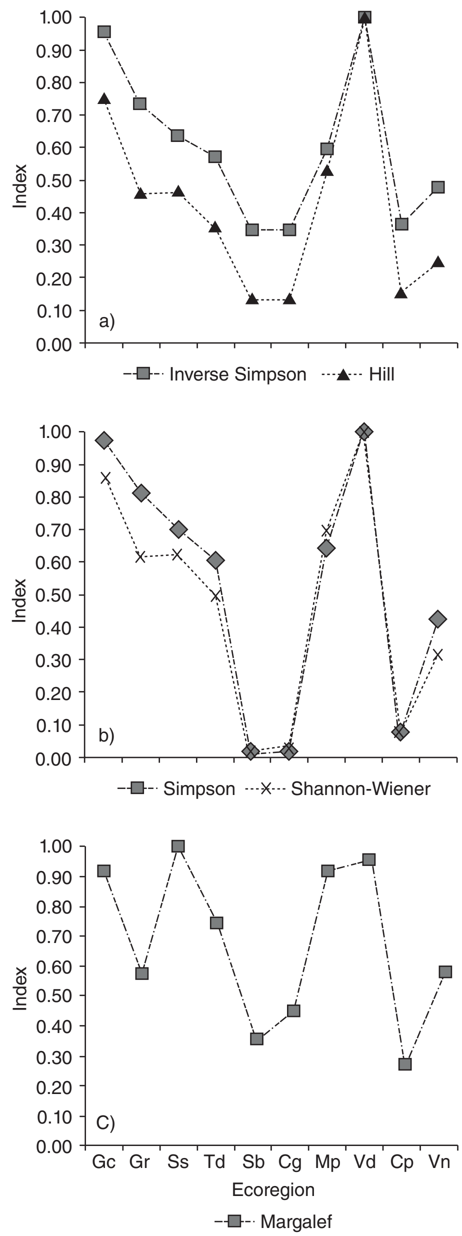

Figure 4. Variation of the diversity index normalized to ecoregions of the coastal zone of Baja California Sur: Bare soil (Bs), beach (Be), coastal water body (Cw), mangrove (Mg), riparian (Ri), salt flat (Sf), salt marsh (Sm), scrub (Sc) other vegetation types (Ot) reef (Rf) and seagrass (Sg).

variations found in the results, and 3) the distance between the ranges.

On the other hand, the Simpson and the Shannon-Weaver indices were less consistent considering that they showed a graphic pattern of similar behavior with no marked differences between them. Also, the results of these two indices showed small differences in ecosystem diversity among ecoregions.

The Margalef index showed the highest variation and highlighted variable richness between ecoregions. However, this index was not able to determine the importance of their components and stopped defining variations when exceeding 50ha of difference among the samples. This index attempts to balance the variation between ecosystems, distributing the differences between them.

Without belittling the other indices used in this study, we strongly propose Simpson's Inverse and Hill indices as the most adequate methods for developing *a priori* diversity and heterogeneity ecosystem analyses. These indices allow determining accurately which ecoregions contain priority sites for conservation because its values showed a behavior pattern with greater sensitivity to describe the ecosystems diversity. Besides, both indices provide additional elements, such as habitat heterogeneity between ecosystems, as well as more information concerning the evenness observed in each ecoregion.

Moreover, these two indices are suitable to determine ecosystem diversity at ecoregion level because the average distance between the ranges of 0.18 is lower than those shown by the other indices. Comparing the Simpson's Inverse index with the Hill index, clues indicate that the Simpson's Inverse can be considered sensible to also measure ecosystem diversity including social and economic variables (Ambrey and Fleming, 2014), which were not considered in this study.

Conclusions

From our analysis, we suggest using the Inverse Simpson Index, more than other indexes, as it proved to be a suitable tool for detecting both the diversity of the ecosystems of an ecoregion as the subtle differences between ecoregions. Using this index can also be appropriate to determine sites of particular importance to bioconservation and for their promotion as Protected Areas.

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APLICACIÓN DE ÍNDICES DE DIVERSIDAD ECOLÓGICA CON ENFOQUE ECOSISTÉMICO A NIVEL ECOREGIONAL Y LA PRIORITIZACIÓN DEL DECRETO DE LAS NUEVAS ÁREAS PROTEGIDAS

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RESUMEN

Uno de los principales desafíos en la priorización de las nuevas Áreas Naturales Protegidas es utilizar las herramientas apropiadas para determinar cuáles de las áreas a nivel ecorregional son las más representativas. En este trabajo utilizamos índices de diversidad ecologica (IDEs) con un enfoque ecosistémico como una herramienta para comparar las diferencias en la diversidad de ecosistemas entre las diferentes ecorregiones. Después de comparar cinco IDE en las ecorregiones costeras y marinas en el Noroeste de México, se concluye que de los cinco indices analizados para la diversidad de ecosistemas, el índice Inverso de Simpson y el índice de Hill fueron los más sensibles, considerando las tendencias de sus gráficas, las variaciones y las distancias entre sus valores, que describen la diversidad de ecosistemas entre las ecoregiones más apropiadamente. Sin embargo, para describir la riqueza y la heterogeneidad de las regiones analizadas, el índice Inverso de Simpson fue el más útil a fin de definir cuál de estas tiene la mayor diversidad de ecosistemas en estudios comparativos entre ellas y por lo tanto su prioridad para ser decretadas como nuevas Áreas Naturales Protegidas.

APLICAÇÃO DE ÍNDICES DE DIVERSIDADE ECOLÓGICA COM ENFOQUE ECOSSISTÊMICO EM NÍVEL ECORREGIONAL E PRIORIZAÇÃO DO DECRETO DAS NOVAS ÁREAS NATURAIS PROTEGIDAS

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RESUMO

Um dos principais desafios da priorização de novas Áreas Naturais Protegidas é o uso de ferramentas apropriadas para determinar quais das áreas em nível ecorregional são mais representativas. Neste trabalho usamos índices de Diversidade Ecológica (IDE) de enfoque ecossistêmico como uma ferramenta para comparar as diferenças na diversidade de ecossistemas entre diferentes ecorregiões. Depois de comparar cinco EDI de ecorregiões costeiras e marinhas no noroeste do México, conclui-se que, dos cinco índices analisados para a diversidade de ecossistemas, os índices Inverso de Simpson e de Hill foram os mais sensíveis considerando as tendências de seus gráficos, variações e a distância entre seus valores, descrevendo assim a diversidade de ecossistemas entre as ecorregiões mais apropriadamente. Entretanto, a fim de descrever a riqueza e heterogeneidade das regiões analisadas, o índice Inverso de Simpson foi o mais útil para definir em estudos comparativos entre diferentes ecorregiões qual delas tem a maior diversidade de ecossistemas e, portanto, a prioridade para ser decretada como uma nova Área Natural Protegida.