The historical biogeography and conservation value of taxonomic distinctness: The case of ferns flora of the Gibraltar Arc

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Abstract. The pteridofloras of nine locations in the Gibraltar Arc were analyzed using a taxonomic distinctness index. We found that the index could be a proxy of historical biogeography of the pteridofloras from this area. Moreover, the value of the taxonomic distinctness index of the different locations showed relevant relationships with certain geographic variables. Finally, we hypothesize about the value of the information derived from taxonomic distinctness index for conservation of the pteridoflora in the Gibraltar Arc.

Keywords: Pteridophytes, Western Mediterranean, Historical biogeography, Conservation

Introduction

The fern flora of the Gibraltar Arc, i.e., the geological region corresponding to an arcuate orogen surrounding the Alboran Sea, extending from the Iberian Peninsula to Africa, has been extensively studied recently by Salvo Tierra et al. (2020). These authors suggested that the factors influencing diversity in fern floras of nine different mountain areas is so relevant that they should be included in the management of the territory. They concluded that the altitudinal gradient and the amplitude of the dry period have determined the distribution of pteridophytes in the Gibraltar Arc, a distribution in which the longitudinal gradient predominates over the latitudinal gradient. In particular, the oldest fern floras (with greater diversity) are located at the western ends of the arc on both continents. Five pterido-geographic units were detected, two of them spanning S Europe and N Africa, and eleven chorotypes. Finally, considering the diversity, age, singularity, and degree of threat to its pteridoflora, it was proposed that the Gibraltar Arc could be considered as a ‘Sanctuary for ferns’, an increasingly widespread conservation concept.

Taxonomic structure (based on the number of taxa included in higher levels of the taxonomic hierarchy) has been widely used in ecology to measure impacts on the diversity of ecosystems (for example, Clarke & Warwick 1998, 1999, 2001, Tucker et al. 2017, Pérez Hernández 2019). Taxonomic structure shows a latitudinal gradient and is maximum at the Equator (Krug et al. 2008). Among taxonomic richness estimators, taxonomic distinctness (TD; Pérez Hernández 2019, and references therein) is particularly significant because it appears to be less influenced by sample size than are species richness or Shannon species diversity. Moreover, TD may be a more sensitive univariate index of community perturbation than spe-
cies diversity (Pérez Hernández 2019, and references therein). Furthermore, the statistical significance of the TD index can be tested (Clarke & Warwick 2001, Pérez Hernández 2019). Clarke & Warwick (1998) proposed the $\Delta^+$ index (i.e., Delta-plus) to estimate taxonomic distinctness. This index measures the overall mean taxonomic path length between any two randomly chosen taxa. Because the index has no dependence on sampling effort, the $\Delta^+$ figures computed from different sources of data can be compared across studies with differing and uncontrolled degrees of sampling effort.

The main aim of the current note is to analyze the TD of fern floras from the Gibraltar Arc. The goal is to assess the differences in biogeographical composition on opposite shores of the Alboran Sea.

**Material and Methods**

**Data origin**

The determination of the OGUs (operative geographical units) was carried out according to criteria of geophysical homogeneity and in correspondence with the biogeographical units, according to Salvo Tierra et al. (2020). Nine mountain areas located in the Gibraltar Arc were selected, one for each biogeographical sector; the areas include the entire range of thermo- and ombrotypes found in these regions (Rivas Martínez 2008): Gata, Nevada, Tejeda, Ronda, Aljibe, Tingitania, Chaouen, Gurugú and Tlemcen (Fig. 1). The basic matrix of data is showed in the supplementary data (metadata available in Salvo Tierra et al., 2020).

**Data Analysis**

The $\Delta^+$ index is computed according to the equation:

$$\Delta^+ = \left( \sum_{i<j} \frac{w_{ij}}{s(s-1)/2} \right)$$

where $s$ is the number of species observed, and $w_{ij}$ is the weight or distinctiveness value given to each taxonomic branch of the hierarchical classification, from species $i$ to the first node in common with species $j$. Thus, $w_{ij} = 0$ if $i$ and $j$ are the same genus, $w_{ij} = 1$ if they are the same family.

We calculated the $\Delta^+$ index for each region (i.e., Tingitania, Chaouen, Gurugú, Tlemcen, Aljibe, Ronda, Tejeda, Nevada, and Gata) using the free PAST software (Hammer et al. 2001). Confidence intervals were calculated from 1000 random replicates taken from the pooled data set (Hammer 2020).

In addition, in a second step, linkage cluster analysis of the $\Delta^+$ index per locality was performed using a multivariate agglomerative method. Thus, we used the Bray-Curtis distance to generate the similarity matrix, using the free PAST version 4.02 software (Hammer et al. 2001). We chose Bray-Curtis distance to generate the similarity matrix, because it is especially recommended for standardized data (Yoshio 2008) (Fig. 2).

For each OGU, the values of latitude, longitude, maximum altitude, TD and TD range values (the difference between the upper and lower limits), specific richness, index m/t (Ito 1972, 1978) and degree of ploidy, as well as the percentages of the presence of each of the generalized tracks detected in the study area, were included in the analysis (Salvo Tierra et al. 2020).

**Results and Discussion**

The $\Delta^+$ index for each region (i.e., Tingitania, Chaouen, Gurugú, Tlemcen, Aljibe, Ronda, Tejeda, Nevada, and Gata) was estimated. We did not observe significant differences according to the criteria of the index. However, we observed three different and coherent similar groups according their $\Delta^+$ values (Fig. 1). Because the significance of the index was developed under other criteria (in relation to the number of sampling stations, and the number of species) (Clarke & Warwick 1998, 1999, 2001), we consider that they may not be useful here.

From Table 1 we conclude: 1) There is a strong inverse correlation between the value of TD and the maximum altitude (the lower the altitude, the greater the distinctness), as well as with the geographical longitude (decreasing from west to east) and with the index m/t. 2) From this last analysis, it can be inferred that there is a correspondence between higher values of TD and the older pteridofloras (the proportion of taxa with trilete spores = primitive character, is high compared to those with monolete spores = advanced character). 3) This same observation is corroborated on the one hand by analysing the correspondence between TD and the degree of ploidy (the lowest values of the degree of ploidy correspond to the most primitive pteridofloras), and on the other by observing that the lowest values of TD are correlated with those pteridofloras in which the generalized tracks of wider distributions (heterochoric and circumboreal) have a greater weight. 4) Consequently, the highest values of TD correspond to the most relict pteridofloras, although they arose from different historical events, and are scarcely ‘contaminated’ by species with wider geographical ranges that were incorporated into the territory during subsequent events. 5) Finally, TD has a complementary significance in the definition of priority conservation areas. In this sense, the lower values in the range of the upper and lower limits of TD for Aljibe and Nevada indicate a more ancestral
and consolidated flora, which would support a high priority as regions for the conservation of pteridophytes. This is confirmed when applying the Vane-Wright et al. (1993) these two units are defined in the first cycle on the application method.

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Figure 1.- Location of the study area and the operating geographic units (OGU) The $\Delta^+$ index plotted for each locality, ordered from lowest to highest according to their range of distinction (difference between the upper and lower limit) and identification according to the Pteridogeographic Units of Salvo Tierra et al. (2020).
Figure 2.- Dendrogram of the OGUs in the Alboran Arc carried out with UPGMA based on the similarity calculated with the similarity index of Bray & Curtis (Correlation coefficient 88.8%; Phenon line at 88%) (PU1: Aljibica Unit, PU 2: Tingitania Unit, PU 3: Chauen-Ronda Unit, PU 4. Tejeda-Nevada Unit, PU 5. Gurugú-Gata-Tlemcen Unit)
Table 1.- Values for each of the analyzed OGUs: TD, geographical references, pteridofloristic index (‘ploidy: ploidy grade; m/t: index monolete/trilete) and tracks generalized (CIR: Circumboreal; ENMED: Mediterranean endemisms; HET: Heterochoric; LAT: Latimediterranean; MROP: Mediterranean and neighboring eastern regions; REPAME: Paleomediterranean relicts; SUBMED: Submediterranean; SUBTROP: Subtropical)

|        | TD       | Geographical references | Pteridofloristic index | Tracks generalized |
|--------|----------|-------------------------|------------------------|--------------------|
|        | Value    | Range (DiFUI-LI) | Longitude | Latitude | Maximum elevation | Specific richness | 'ploidy | m/t | HET | CIR | SUBTROP | LAT | MROP | SUBMED | ENMED | REPAME |
| Aljibe  | 3.84     | 0.92                   | 5.29       | 36.11    | 1092             | 46                | 2.78     | 1.09 | 15.22 | 13.04 | 6.52    | 19.57| 6.52  | 19.57  | 4.35  | 13.04  |
| Chauen  | 3.62     | 0.96                   | 5.12       | 35.1    | 2159             | 41                | 3.07     | 1.28 | 19.51 | 17.07 | 2.44    | 17.07| 9.76  | 17.07  | 12.20 | 4.88   |
| Gata    | 3.79     | 1.37                   | 1.53       | 36.59    | 562              | 23                | 2.87     | 0.64 | 17.39 | 13.04 | 4.35    | 17.39| 8.70  | 30.43  | 4.35  | 4.35   |
| Gurugú  | 3.65     | 1.55                   | 2.57       | 35.16    | 890              | 22                | 3.09     | 1.00 | 31.82 | 9.09  | 0.00    | 13.64| 4.55  | 22.73  | 4.55  | 13.64  |
| Nevada  | 3.46     | 0.93                   | 3.26       | 37.9    | 3749             | 46                | 3.22     | 1.71 | 17.39 | 23.91 | 2.17    | 23.91| 6.52  | 17.39  | 4.35  | 2.17   |
| Ronda   | 3.53     | 0.98                   | 5.07       | 36.37    | 1919             | 40                | 3.05     | 1.22 | 20.00 | 15.00 | 2.50    | 22.50| 7.50  | 20.00  | 5.00  | 7.50   |
| Tejeda  | 3.38     | 1.13                   | 3.46       | 36.52    | 2066             | 33                | 3.21     | 1.75 | 21.21 | 21.21 | 3.03    | 24.24| 9.09  | 15.15  | 3.03  | 3.03   |
| Tingitania | 3.65   | 1.22                   | 5.28       | 35.47    | 1362             | 30                | 2.53     | 1.00 | 20.00 | 10.00 | 3.33    | 26.67| 6.67  | 13.33  | 10.00 | 10.00  |
| Tlemcen | 3.59     | 1.30                   | 1.26       | 34.45    | 1418             | 26                | 3.08     | 1.00 | 23.08 | 3.85  | 0.00    | 23.08| 7.69  | 26.92  | 7.69  | 7.69   |
SUPPLEMENTARY DATA - Checklist of pteridophytes from the Gibraltar Arch ordered according to the PGP1 (2016) systematics and presence (1), absence (0) for the OGUs studied.

| ORDER | FAMILY | GENUS | SPECIES (incl. subspecies recognized as species by some authors) | CODE |
|-------|--------|-------|---------------------------------------------------------------|------|
|       | Isoetales |      | Isoetes duriae Bory | ISO DUR |
|       |         |      | Isoetes gigantea Germ. | ISO GIG |
|       |         |      | Isoetes Velazquez A. Braun | ISO VEL |
|       | Selaginellales |          | Selaginella bohniaceae (A. Braun) | SEL BAL |
|       |         |      | Selaginella denticulata (L.) | SEL DEN |
|       | Equisetales |        | Equisetum arvense L. | EQU ARV |
|       |          |      | Equisetum ramosissimum | EQU RAM |
|       |          |      | Equisetum telmateia Ehr. | EQU TEL |
|       | Ophioglossales |      | Botrychium lunaria (L.) | BOT LUN |
|       |          |      | Ophioglossum vulgatum | OPH VUL |
|       |          |      | Ophioglossum vulgatum | OPH VUL |
|       |         |      | Ophioglossum vulgatum (L.) | OPH VUL |
|       | Psilotales |       | Psilotum | PSI NUD |
|       |         |      | Omocladus regalis L. | OSM REG |
|       | Hymenophyllales |       | Hymenophyllum speciosum (Willd.) | VAN SPE |
|       |          |      | Culcitaceae | CUL MAC |
|       | Cyathales |       | Cyathaceae | CYA |

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| Family         | Genus            | Species                                    | Code  | Out | In | 3  | 4  | 5  | 6  |
|----------------|------------------|--------------------------------------------|-------|-----|----|----|----|----|----|
| Polypodiales   | Asplenium        | *Asplenium adiantum-nigrum* L.             | ASP ADI | 1   | 1  | 0  | 1  | 1  | 1  |
|                |                  | *Asplenium ceterach* L.                    | CET OFF | 1   | 1  | 1  | 1  | 1  | 1  |
|                |                  | *Asplenium csikii* Kümmerle & András.      | ASP PAC | 0   | 1  | 0  | 0  | 0  | 1  |
|                |                  | *Asplenium fontanum* (L.) Bernh.           | ASP FON | 0   | 0  | 0  | 0  | 1  | 0  |
|                |                  | *Asplenium forezieniae Magnier*            | ASP FOR | 0   | 0  | 0  | 0  | 0  | 1  |
|                |                  | *Asplenium hemionitis* L.                  | ASP HEM | 1   | 0  | 1  | 1  | 0  | 0  |
|                |                  | *Asplenium hispanicum* (Coss.) Greuter & Burdet | PLE HIS | 0   | 1  | 0  | 1  | 1  | 1  |
|                |                  | *Asplenium marinum* L.                     | ASP MAR | 1   | 0  | 1  | 0  | 0  | 0  |
|                |                  | *Asplenium obovatum* Viv. subsp. obovatum  | ASP OBO | 1   | 1  | 0  | 0  | 0  | 0  |
|                |                  | *Asplenium obovatum* Viv. subsp. billotii (Schultz) Kerg. | ASP BIL | 1   | 1  | 1  | 1  | 1  | 1  |
|                |                  | *Asplenium onopteris* L.                   | ASP ONO | 1   | 1  | 1  | 1  | 1  | 1  |
|                |                  | *Asplenium petrarchae* (Guérin) DC.        | ASP PET | 0   | 1  | 1  | 0  | 1  | 1  |
|                |                  | *Asplenium ruta-muraria* L.                | ASP RUT | 0   | 1  | 0  | 0  | 1  | 1  |
|                |                  | *Asplenium sagitatum* (DC.) Bunge           | PHY SAG | 1   | 1  | 0  | 1  | 1  | 0  |
|                |                  | *Asplenium scolopendrium* L.               | PHY SCO | 1   | 1  | 0  | 1  | 1  | 1  |
|                |                  | *Asplenium septentrionale* (L.) Hoffm.     | ASP SEP | 0   | 1  | 0  | 0  | 0  | 1  |
|                |                  | *Asplenium viride* Hudson                  | ASP VIR | 0   | 0  | 0  | 0  | 0  | 1  |
| Athyriaceae    | Athyrium         | *Athyrium filix-femina* (L.) Roth          | ATH FIL | 1   | 0  | 0  | 0  | 1  | 1  |
|                | Diplazium        | *Diplazium caudatum* (Cav.) Jermy          | DIP CAU | 0   | 0  | 0  | 0  | 1  | 0  |
|                | Struthiopteris   | *Struthiopteris spicant* (L.) F.W. Weiss   | BLE SPI | 1   | 1  | 0  | 0  | 1  | 0  |
| Polypodiales               | Cystopteridaceae | Cystopteris | Cystopteris dickieana R. Sim | CYS DIC | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
|---------------------------|------------------|------------|------------------------------|---------|---|---|---|---|---|---|---|---|---|
|                           |                  | Cystopteris fragilis (L.) Bernh. | CYS FRA | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
|                           |                  | Cystopteris viridula (Desv.) Desv. | CYS VIR | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 |
|                           | Gymnocarpium     | Gymnocarpium robertianum (Hoffm.) Newman | GYM ROB | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
|                           | Davalliacae      | Davallia   | Davallia canariensis (L.) Sm. | DAV CAN | 1 | 1 | 1 | 0 | 1 | 1 | 0 | 0 | 0 |
|                           | Polypodiaceae    | Polypodium | Polyodium cambricum L.       | POL CAM | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
|                           |                  | Polypodium | Polyodium interjectum Shivas | POL INT | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 1 | 0 |
|                           |                  | Polyodium | Polyodium vulgare L.         | POL VUL | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
|                           | Thelypteridaceae | Thelypteris | Thelypteris palustris Schott | THE PAL | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
|                           |                  | Cyclosorus | Cyclosorus dentatus (Forssk.) Ching | CHR DEN | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
|                           | Dennstaedtiaceae | Pteridium | Pteridium aquilinum (L.) Kuhn | PTE AQU | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 0 |
| Polypodiales | Pteridaceae | Adiantum capillus-veneris L. | Oeosporangium pteridioides (Reichard) Fraser-Jenk. & Pariyar subsp. acrosticum (Balb.) Fraser-Jenk. & Pariyar | CHE ACR | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 1 |
| Polypodiales | Pteridaceae | Oeosporangium guanchicum (Bolle) Fraser-Jenk. & Pariyar | Oeosporangium guanchicum (Bolle) Fraser-Jenk. & Pariyar | CHE GUA | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Polypodiales | Pteridaceae | Oeosporangium hispanicum (Mett.) Fraser-Jenk. & Pariyar | Oeosporangium hispanicum (Mett.) Fraser-Jenk. & Pariyar | CHE HIS | 0 | 1 | 0 | 1 | 0 | 1 | 0 | 1 | 0 |
| Polypodiales | Pteridaceae | Oeosporangium pteridioides (Reichard) Fraser-Jenk. & Pariyar subsp. pteridioides | Oeosporangium pteridioides (Reichard) Fraser-Jenk. & Pariyar subsp. pteridioides | CHE MAD | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Polypodiales | Pteridaceae | Oeosporangium tinaei (Tod.) Fraser-Jenk. | Oeosporangium tinaei (Tod.) Fraser-Jenk. | CHE TIN | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 0 |
| Polypodiales | Pteridaceae | Anogramma leptophylla (L.) Link | Anogramma leptophylla (L.) Link | ANO LEP | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Polypodiales | Pteridaceae | Cosentinia vellea (Aiton) Tod. | Cosentinia vellea (Aiton) Tod. | COS VEL | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Polypodiales | Pteridaceae | Cryptogramma crispa (L.) R. Br. ex Hook. | Cryptogramma crispa (L.) R. Br. ex Hook. | CRY CRI | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Polypodiales | Pteridaceae | Paragymnopteris marantae (L.) K.H. Shing | Paragymnopteris marantae (L.) K.H. Shing | NOT MAR | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 0 |
| Polypodiales | Pteridaceae | Pteris incompleta Cav. | Pteris incompleta Cav. | PTE INC | 1 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Polypodiales | Pteridaceae | Pteris vitata L. | Pteris vitata L. | PTE VIT | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 | 1 |
| Family       | Genus          | Species                          | Abbreviation | Status  |
|--------------|----------------|----------------------------------|--------------|---------|
| Polypodiales | Dryopteris     | *Dryopteris affinis* (Lowe)      | DRY AFF      | 0 0 0 1 1 1 1 1 0 |
|              |                | Fraser-Jenkins                   |              |         |
|              |                | *Dryopteris borreri* (Newman)    | DRY BOR      | 0 0 0 0 0 1 1 1 0 |
|              |                | Oberh. & Tavel                   |              |         |
|              |                | *Dryopteris filix-mas* (L.)      | DRY FIL      | 0 1 0 1 1 1 1 0 |
|              |                | Schott                           |              |         |
|              |                | *Dryopteris guanchica* Gibby     | DRY GUA      | 0 0 0 1 0 0 0 0 0 |
|              |                | & Jenny                          |              |         |
|              |                | *Dryopteris mindshelken-sa* N.Pavl. | DRY SUB   | 0 0 0 0 0 1 1 1 0 |
|              |                |                                  |              |         |
|              |                | *Dryopteris tyrhena* Fraser-Jenkins & Reichst. | DRY THY | 0 0 0 0 0 0 0 1 0 |
|              |                |                                  |              |         |
| Polystichum  | *Polystichum aculeatum* (L.) Roth | POS ACU | 0 1 0 1 0 1 1 1 0 |
|              | *Polystichum lonchitis* (L.) Roth | POS LON | 0 0 0 0 0 0 0 1 0 |
|              | *Polystichum setiferum* (Forssk.) Woyn. | POS SET | 1 1 0 1 1 0 1 0 |
| Salviniales  | Marsilea        | *Marsilea strigosa* Willd.       | MAR STR      | 1 0 0 0 0 0 0 0 0 |
|              |                 |                                  |              |         |
|              | *Pilularia minuta* Durieu | PIL MIN | 1 0 0 0 0 0 0 0 0 |