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Application of GIS in plant conservation programmes in Portugal

David Draper[a,*], Antonia Rosselló-Graell[a], César Garcia[a,b],
Cristina Tauleigne Gomes[a], Cecília Sérgio[a,b]

[a]*Museu e Jardim Botânico (Museu Nacional de História Natural) da Universidade de Lisboa, R. da Escola Politécnica, 58, 1250 Lisboa, Portugal*
[b]*Centro de Ecologia e Biologia Vegetal, Facultade de Ciências, Universidade de Lisboa, Portugal*

Abstract

A plant conservation programme is a complex process that requires several sets of studies. The relationships between plant location and its environment play an important role. Nowadays, the use of a GIS constitutes an essential complement for these studies that allows the incorporation of space and the analysis of these ecological interactions. GIS is being used at the Lisbon University Botanical Garden as a tool for conservation programmes on several plant groups and situations. Four case studies are presented in this work: (1) comparing ecological patterns between local and regional scale for the endangered bryophyte *Bruchia vogesiaca* Schwaegr.; (2) selecting protected areas according to habitat suitability—the case of endangered Portuguese bryophytes; (3) analysing the impact of the alien *Carpobrotus edulis* (L.) N. E. Br. on endemic plant species at the Berlengas Natural Reserve; and (4) ecogeographical survey for selection of sites for seed collection in order to guarantee a representative sample of the existing genetic diversity. Finally, this work discusses how the implementation of a GIS can help to optimise results and fieldwork effort.

Keywords: Threatened species; Spatial patterns; Bryophytes; Alien species; Germplasm Bank

1. Introduction

The main factors determining the geographical distribution of organisms are climate, availability of suitable habitat, edaphic factors, influence of herbivores and animal or plant competitors, and historical factors (Brown and Gibson, 1983; Antúnez and Mendoza, 1992; Spellerberg and Sawyer, 1999).

The distribution of a species along an environmental gradient follows a Gaussian distribution with an optimum point in the centre of the distribution and two marginal limits of performance of the species for the variable (Putman and Wraten, 1984). Under these conditions, if there are strong relationships between the presence of the organism and the environmental variable we may predict its distribution (Johnston, 1993).

Geographical Information Systems (GIS) are one of the tools that allow the integration and analysis of large amounts of data sets. GIS are used in the study of the geographical distribution of species in space and time (Johnston, 1998). Conservation species programmes involve a long and varied list of features such as particular aspects of the species or the habitat or the land use (Sperduto and Congalton, 1996). The interaction of these features must be carefully analysed in order to meet the objectives of the conservation programme. The integration of GIS in conservation programmes can help increase the input data information to be used and the output relationships that can be established among the data. The use of GIS to model plant distribution in conservation actions has increased and diversified in recent years. However, the characteristics of each particular case make each approach unique. The impact of human constructions on the environment is greater than ever as is their complexity, so GIS can play and important role in development planning. Some examples of GIS applications are the evaluation of the impact of a highway construction on a rare plant population (Wu and Smeins, 2000) or the translocation of an endangered plant population because of the construction of a dam (Draper et al., 2001). The important role that GIS can play in the conservation of wild crop relatives has been discussed by Hijmans and Spooner (2001).

In this paper some of the applications of GIS in plant conservation will be discussed, in order to show how they can help optimise efforts in species and areas management. The case studies have been developed at Lisbon University Botanical Garden during recent years to

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* Corresponding author. Tel.: +351-213-921882; fax: +351-213-970882.
E-mail address: ddraper@fc.ul.pt (D. Draper).

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answer some of the research needs of several teams of the institution. These case studies can be summarised as: (a) comparing ecological patterns between local and regional scale; (b) selecting protected areas according to habitat suitability for endangered bryophytes in Portugal; (c) analysing the impact of alien species on endemic flora; (d) ecogeographical studies for selection of sites for seed collection in order to guarantee a representative sample of the existing genetic diversity.

2. Case studies

2.1. *Comparing ecological patterns between local and regional scales. The example of an endangered bryophyte,* Bruchia vogesiaca *Schwaegr.*

2.1.1. *Purpose of study*

In this case study, we wanted to show the effect of scale and resolution (Dale, 1999) in order to define limitations in conservation strategies. Bryophyte species are ecologically an important group in view of their potential significance as indicators of bioclimatic conditions, air quality, etc. Being sensitive to natural fluctuations in humidity they can be used as ecological indicators (Hallingbäck and Hodgetts, 2000). In addition, they have also been considered suitable as biodiversity indicators (Sérgio et al., 2000). The subject of this study was the threatened bryophyte *B. vogesiaca* Schwaegr.

2.1.2. *Material and methods*

The study areas were the Iberian Peninsula at a regional scale and Serra da Estrela Natural Park (Portugal) at a local scale (Fig. 1). *B. vogesiaca* is considered a very rare species of the western part of Europe (Sérgio et al., 1998) and is only known from about 20 localities, occupying an area from Austria, East Germany and France, to Portugal. Only 17 grid cells of 50×50 km are recorded in Europe (Sérgio et al., 1998). It has been classified as "Vulnerable" in the Iberian Peninsula according to IUCN categories (Sérgio et al., 1994). Due to its particular ecology and climatic requirements, *B. vogesiaca* is an endangered species in Europe and is included in Appendix I of the Bern Convention (Anon., 1979) and in Annex II of the European Community Habitat and Species Directive (Anon., 1992). The plant localities resolution was UTM (Universal Transversal Mercator) 10×10 km grid cells at regional scale and UTM 1×1 km grid cells at local scale.

Fig. 1. Study areas considered in this work: (a) the Serra da Estrela Natural Park; (b) the Berlengas Natural Reserve and (c) the Alqueva dam. The Iberian Peninsula is shown for comparison of the scale and resolution effect.

In order to elaborate the environmental model of *B. vogesiaca*, several data sets were included: Altitude (m), Aspect (°), Inclination (°), Latitude (°), Longitude (°), Annual mean rainfall (mm), Maximum temperature (°C), Minimum temperature (°C), Mean temperature (°C), Thermic amplitude (°C), Emberger index (Emberger, 1932), Gorezynshy index (Gorezynsky, 1920), Gams index (Gams, 1931), Dantin–Revenga index (Dantin and Revenga, 1940), De Martonne index (De Martonne, 1927), Lang index (Lang, 1915). Details about each index are presented in the Appendix. No soil layer was used due to the differences in legends and scales between Spanish and Portuguese soil maps.

Data sources were the climatic models proposed by Sánchez-Palomares et al. (1999) for Spain and official data from National Meteorological Institute of Portugal.

The digital terrain model (DTM) used for the Iberian Peninsula was the GTOPO30 (http://www1.gsi-mc.go.jp) with a pixel resolution of 500 m. The same resolution was used for the other variables used at a regional scale (Draper et al., 2001). The pixel resolution of Serra da Estrela Natural Park was 25×25 m obtained from the official altimetry (original scale 1:25,000). The same variables were used at local scale but they were created directly at 25 m resolution; the only difference was the addition of the distance (m) to the nearest water variable at local scale.

A multiple linear regression (MLR) was applied at both levels as environmental modelling method (Johnston, 1998) using only the resulting significant variables:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + \ldots + a_nx_n$$

where y is the occurrence of species, a_0 is the intercept value, $a_1\ldots$, a_n are the regression coefficients and $x_1\ldots$, x_n are the independent variables.

Following Hill and Domínguez (1994), the probability (P) of *B. vogesiaca* was calculated by:

$$P = \exp^y/(\exp^y + 1)$$

IDRISI (V.2) and MapInfo (V.4.0) were used as GIS software in all the cases in this work.

2.1.3. Results and discussion

The MLR for *B. vogesiaca* considering only the significant variables for the Iberian Peninsula was: *B. vogesiaca* = 0.091355 + 0.405141 *dantin* − 0.053008 *martonne* + 0.036929 *annual rainfall* − 0.025301 *thermic amplitude*.

The adjusted R^2 obtained was 0.6046 with $P < 0.0001$ (Fig. 2). Note the location of the dots mainly in the northwestern part of the area even though the highest values of occurrence probability do not overlap with them.

In the case of Serra da Estrela (Fig. 2): *B. vogesiaca* = −0.013869 + 0.000015 *altitude* − 0.000004 *aspect* − 0.000021 *inclination* − 0.000003 *water distance* + 0.000006 *annual rainfall* − 0.000503 *thermic amplitude* + 0.008074 *dantin*. The adjusted R^2 was 0.5682 and the significance $P < 0.0001$. This species should be more frequent at the upper part of the park than in valleys or rivers.

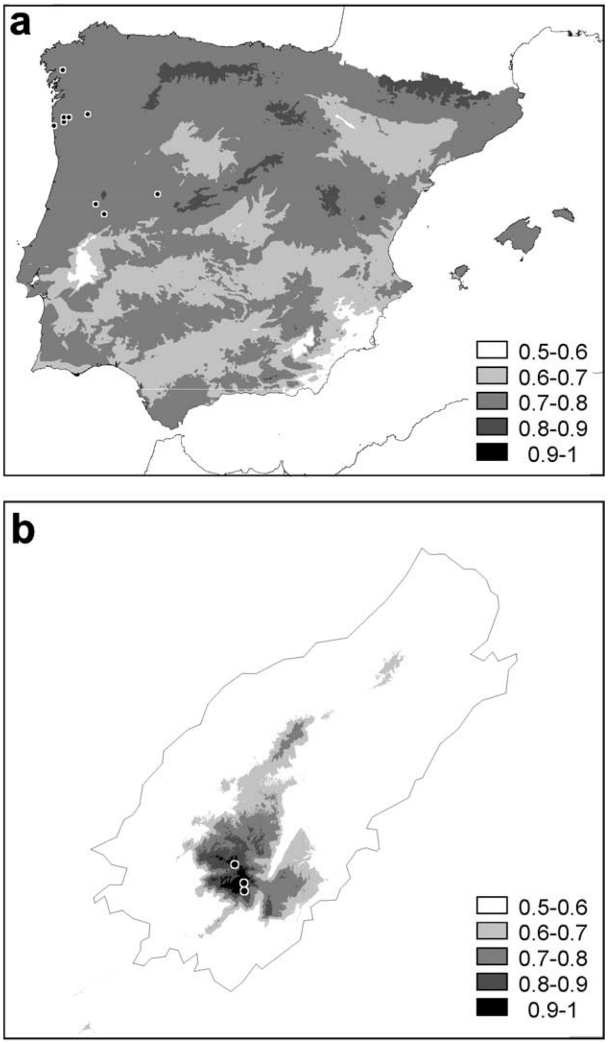

Fig. 2. (a) Predicted distribution of *B. vogesiaca* in the Iberian Peninsula. Dots are the input data used to calculate the model; (b) predicted distribution of *B. vogesiaca* in the Serra da Estrela Natural Park. Squares correspond to the actual known distribution of this species. The legend shows the intervals of probability according to the model.

When we compare the significant variables used in the two models, only three of them (annual mean rainfall, thermic amplitude, Dantin index) are shared. Results show a positive relationship between altitude, annual rainfall and Dantin index and *B. vogesiaca* distribution. This was expected (Tuhkanen, 1980) due to the rainfall increment in the mountain ranges in the north of the Iberian Peninsula. However, this relation is corrected by the thermal amplitude; *B. vogesiaca* does not tolerate a wide range of thermal oscillation so the continental areas are not be optimal for this species. *B. vogesiaca* seems to follow the same pattern in the Iberian Peninsula and in Serra da Estrela, but this cannot always be expected (Gaston and Lawton, 1990). Considering these variables, the relationships between the distribution of *B. vogesiaca* and the variables are similar both at the local and regional scale. Instead of accepting that the models are satisfactory in both cases one must consider that the relation between the spatial distribution of the input data and the area used to explain its distribution may not always be appropriate (Burrough, 1986). The importance of this comparison is to point out the environmental trends of the species and to show that the values of the coefficients are very sensitive to any alteration of any layer or the addition of a new plant locality.

In addition to conservation purposes, these trends can be used for some other objectives. In the case of bryophytes of the Iberian Peninsula the lack of knowledge about their distribution can be a limitation for this kind of survey. However, they can be used to select target areas to be prospected for particular species in order to increase the efficiency of prospecting (Draper and Sérgio, 1999).

2.2. Selecting protected areas according to habitat suitability. The case of endangered bryophytes in Portugal

2.2.1. Purpose of study

The dimension of a protected area is strongly dependent on the subject or subjects that it is meant to protect. In Portugal, as well as in Spain, most protected areas have been selected according to their animal heritage. These areas can also be useful to preserve some plant species but they are not always appropriate for the management of particular microhabitats that these species occupy. The ecological relationships established between bryophytes and other small organisms such as arthropods or earthworms allow bryophytes to be used as structural organisms at the microhabitat level. Pharo et al. (2000) used vascular plants to select reserves of bryophytes and lichens. However, a survey of methods and criteria to select micro-areas was started by Garcia et al. (2000) in order to ensure conservation and management efficiency of these small but important habitats. The concept of these micro-areas for conservation is similar to the micro-reserve areas network proposed by Laguna (1997, 1998) in the Valencian Community (Spain). The main difference is the application of the habitat suitability of the organism as an area descriptor so an ecological or statistical modelling (Johnston, 1998) study is developed in each case for the target species.

The lack of knowledge of bryophytes from large areas in Portugal is obvious, especially from the interior, including Serra da Estrela. However, there are historical records from 1848 collected by Welwitsch in Serra da Estrela. From this protected area, there are some botanical studies mainly focused on vascular flora (Pinto da Silva and Teles, 1986). The bryoflora of Serra da Estrela is extremely rich, including about 65% of all Portuguese bryoflora and 45% of Iberian bryoflora (Garcia et al., 2000). This bryoflora is also important because it includes endemic species of the Iberian Peninsula, bryophyte communities of international interest, and species of phytogeographic (Sérgio and Draper, 2001) and conservation value (Anon., 1992). A survey on endangered bryophytes in Serra da Estrela Natural Park is presented to illustrate this situation.

2.2.2. Material and methods

The study area was the Serra da Estrela Natural Park (Fig. 1). Plant data were obtained from bibliographical records, recent field works and revision of the material in several herbaria (LISU, COI, PO, LISE, LISFA). The working floristic data units were 1×1 km UTM. Over 200 1×1 km squares were prospected and up to 7500 specimens were studied (Garcia et al., 2000). From the species list only endangered species (Sérgio et al., 1994) were used as descriptors in area selection.

The endangered species selected were: *Brachythecium dieckii* Roell, *Saccogyna viticulosa* (L.) Dum., *Frullania fragilifolia* (Tayl.) Gott., *B. vogesiaca* Schwaegr. and *Marsupella profunda* Lindb. The same geographical data as those in the previous study case of Serra da Estrela Natural Park were used.

The data analysis was MLR, the same as that in the previous case but with the difference that here we considered as a dependent variable the sum of threatened species per pixel. In this way, the resulting map represented the places where it was more probable to find the greatest number of threatened species. Then, an interval of probability was defined in order to select the suitable area to be protected.

2.2.3. Results and discussion

When the sum of threatened species per pixel was used as dependent variable the resulting MLR was: $-0.243081 + 0.000183\,\textit{altitude} - 0.000039\,\textit{aspect} - 0.000608\,\textit{inclination} - 0.000062\,\textit{water distance} + 0.000129\,\textit{annual rainfall} - 0.003901\,\textit{thermic amplitude} + 0.078488\,\textit{dantin index}$ (Fig. 3). The adjusted $R2$ was 0.5984 with $P < 0.0001$.

The weight of each variable was relatively small with the exception of the Dantin index. This index emphasizes the humid conditions of the highest points of the range in contrast with the depressions (Dantin and Revenga, 1940). This was also confirmed by the presence of peat mosses in the upper part of the park (Séneca, 1993).

Once the probability surface is calculated it is necessary to select the optimal area to protect as a long-term conservation strategy. Until now, only the suitability of the area for species richness of threatened bryophytes has been considered. At this point, it is necessary to know the needs and capabilities of the managers of the park. It is important to know what resources (human and financial) they can spend on small areas of bryophytes and translate these resources to number of hectares or other practical variables. Fig. 4 illustrates the area covered by each probability interval calculated from Fig. 3. This kind of survey could help determine the cut-off point interval to select areas to be protected. According to the numerical interval considered, the shape, the perimeter length or the number of patches could change considerably. Fig. 5 shows the areas selected considering probabilities higher than 0.95 and 0.98. The last step will be the selection of the best area for this objective considering all the limitations. In this part of the work other types of ecological modelling can also be considered (Johnston, 1998).

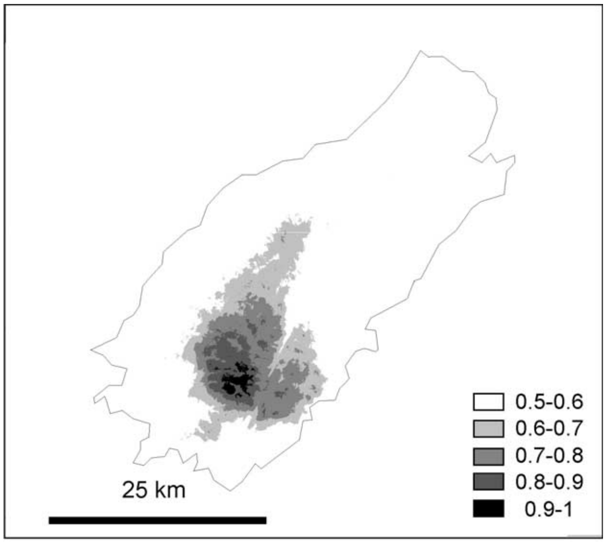

Fig. 3. Predicted distribution of sum of threatened bryophytes in the Serra da Estrela Natural Park. The most important bryophytic area in the park is located in upper part of the mountain range. The legend shows the intervals of probability according to the model.

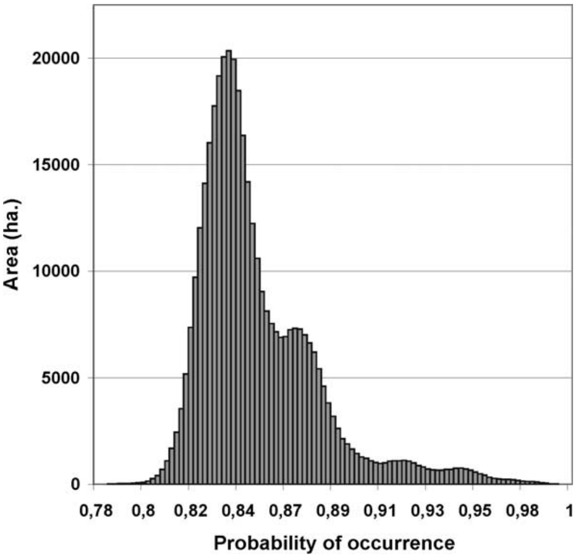

Fig. 4. Covered area in hectares of each interval of probability for the variable sum of threatened bryophytes in Serra da Estrela Natural Park.

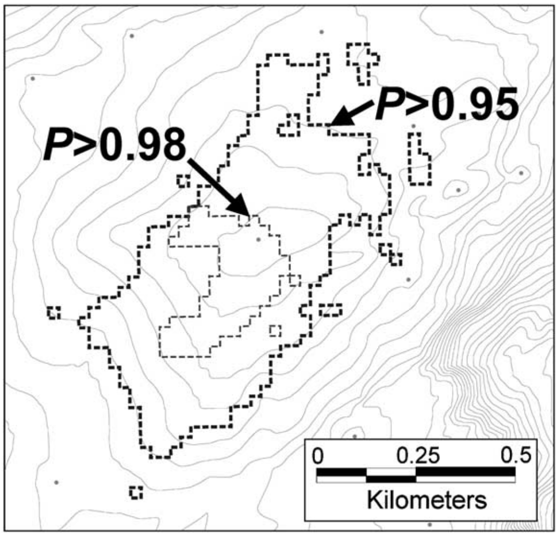

Fig. 5. Application of a cut-off point on the predicted distribution of the sum of threatened bryophytes in Serra da Estrela Natural Park. A lower interval of probability not only represents an increment of area but also a larger number of discrete areas.

2.3. Impact of an alien species, Carpobrotus edulis *(L.) N. E. Br., on endemic plant species at the Berlengas Natural Reserve*

2.3.1. Purpose of study

The archipelago of Berlengas Natural Reserve is an Atlantic Portuguese protected area (39° 24′ 49″ N and 9° 30′ 29″ W). This archipelago is formed by ca. 10 islands and several islets located 10–20 km from the mainland. Berlenga, the largest island, covers 79 ha and is 1.5 km long, 800 m wide and 92 m high (Fig. 1).

In the late 1950s, *C. edulis* was introduced in Berlengas Natural Reserve to reduce rock fall in recreation areas. Nowadays, *C. edulis* has spread out over the cliffs and hillsides of these islands. On Berlenga island, the presence of *C. edulis* produces a loss of floristic diversity. The ratio of floristic diversity is 2.89:1 when areas with natural vegetation are compared to those where *C. edulis* is present (Tauleigne Gomes et al., 1999). The impact of this species on other island endemic plants from several Mediterranean archipelagos has also been reported (Vidal et al., 1997) and it is the particular focus of the EPIDEMIE Project (http://www.ceh.ac.uk/EPIDEMIE/index.htm).

Three plant species (2.6% of the flora) are endemic to this archipelago: *Armeria berlengensis* Daveau, *Pulicaria microcephala* Lange and *Herniaria berlengiana* (Chaudhri) Franco following Tauleigne Gomes et al. (in press). *A. berlengensis* and *H. berlengiana* are included in Annex II of the European Community Habitat and Species Directive (Anon., 1992) and they are considered as "Vulnerable" species in Portugal (Walter and Gillett, 1998). Another interesting species is *Angelica pachycarpa* Lange, an Iberian endemic only reported from this archipelago in Portugal.

2.3.2. Material and methods

A global positioning system (GPS) was used to determine the area occupied and the position of *C. edulis* in 1999, as well as those of *A. berlengensis*, *H. berlengiana* and *A. pachycarpa,* to assess their vulnerability to the invasion of *C. edulis*. Frequency distribution maps were prepared for each species based on phytosociological relevées (Braun-Blanquet, 1964).

A digital terrain model (DTM) of Berlenga was obtained (1×1 m resolution) from digital altimetry (1:5000 at original scale). This DTM was the source used to obtain the geophysical variables (aspect, altitude and inclination). No climatic data were included because the nearest meteorological station is 10 km away (located at the mainland) and these data could not be applied in the island.

MLR was used to elaborate predictive occurrence maps of *C. edulis* and the endemics, and a logit transformation was also applied. A simple linear regression (SLR) between the predictive maps was used to estimate the habitat competition between *C. edulis* and the three target species. The dependent variable was always the endemic predictive map and the independent variable was *C. edulis* predictive map.

2.3.3. Results and discussion

The resulting ecological model for *C. edulis* was: $0.0788 + 0.0121\,\textit{altitude} + 0.0223\,\textit{aspect} - 0.0836\,\textit{inclination}$ with a low adjusted R^2 of 0.4378, $P<0.0021$. The assessment of the resulting equation indicates that the values of the coefficients of the variables are near zero. This result means that the topographic characteristics considered are not a limiting factor for *C. edulis* within the study area. The same processes were carried on the other endemics and the resulting MLR were:

$$A.\ berlengensis = -0.3565 + 0.0133\ altitude - 0.0068\ aspect + 0.3563\ inclination$$

Adjusted $R^2 = 0.4361,\ P < 0.0001.$

$$A.\ pachycarpa = -0.1775 + 0.0001\ altitude + 0.0029\ aspect + 0.1783\ inclination$$

Adjusted $R^2 = 0.6266,\ P < 0.0001.$

$$H.\ berlengiana = 0.0788 + 0.2123\ altitude + 0.0010\ aspect - 0.0241\ inclination$$

Adjusted $R^2 = 0.6738,\ P < 0.0001.$

Fig. 6 shows target species and *C. edulis* predicted distribution on Berlenga island. The predictive distribution map created for *A. berlengensis* (Fig. 6b) indicates that this species is widespread on the island, although it seems to have preference for cliffs. This result agrees with the positive coefficient obtained for this taxon with the degree of inclination, as *A. berlengensis* has strong thin roots that allow it to occupy rocky and inclined habitats. The correlation coefficients obtained indicate that neither exposure nor altitude are ecological requirements for this species.

The predictive map of the occurrence of *A. pachycarpa* (Fig. 6c) indicates, as in the previous species, a preference for cliff habitats. *A. pachycarpa* is more scarce that *A. berlengensis* and only occurs in places with a steep slope. The location of this species is always on cliffs, never spreading out through the plateau. Thus, the coefficient that affects altitude in the regression equation is very low. The inclination is the variable with the highest coefficient value. The predictive map for *H. berlengiana* (Fig. 6d) shows a wide presence in the island but with a preference for flat areas. It is interesting to point out that, contrary to the previous two species, *H. berlengiana* avoids cliffs and occurs mainly on the plateau. *H. berlengiana* appears in zones of very thin soil, while in the valley and in other areas with soil accumulation it is replaced by species with a stronger root system. The growth of *C. edulis* causes a decrease of these three endemics, but *A. pachycarpa* is the species most threatened by *C. edulis* as shown by the slope regression (Table 1). The coefficient of determination (R^2) between *H. berlengiana* and *C. edulis* presents a value near zero, which indicates a low interaction between them. This may be because *C. edulis* does not yet occupy the optimal areas for this species. However, with the continuing spread of *C. edulis* it may interact with this endemic in the future.

With these results, the reserve manager can design actions to minimise the effect on the most threatened species. Now that we know which species are the most threatened, the question that remains to be answered is "where" are the priority places where action is needed.

Other interactions not considered here, such as rabbit–*Carpobrotus* relationships (D'Antonio, 1990) should be taken in consideration before an action plan is designed.

2.4. Ecogeographical survey for seed sites collecting

2.4.1. Purpose of study

A conservation project started in Spring 2001 focused on the collection and storage of germplasm from an area that is going to be flooded by the construction of the Alqueva dam (Alentejo, Portugal). This reservoir will cover 25,000 ha of land in the Guadiana basin and it will be the largest one of its kind in Europe. The Portuguese Guadiana basin is considered a rich botanical area with almost 550 species, 97 of them with conservation interest in Portugal (Capelo, 1996).

The need to collect a large amount of germplasm in a short period has led to search for ways to optimise the process of seed collection. In this study, the main goal was to define a methodology for optimising germplasm collection, covering maximum genetic diversity. This methodology is based on the assumption that seed genetic diversity is maximum when collections are from distinct ecogeographical units within the species' distribution range. An ecogeographical approach synthesizes ecological, geographic and taxonomic information (Maxted et al., 1997).

In this work two approaches were taken: (a) multispecies target areas where we will collect several species under particular conditions, and (b) species-specific target areas in order to collect all the ecological range of the target taxon (Painting, 1996).

The current project is a mitigation action that aims (a) to minimise the loss of genetic resources that will be caused by the construction of the Alqueva dam, and (b) to become a tool for further conservation actions

Table 1
Simple linear regression of the presence of three Berlenga endemics using the presence of *Carpobrotus edulis* as independent variable

	Intercept	Slope	r^2
Armeria berlengensis	0.05541	−0.02896	8.77
Angelica pachycarpa	0.03875	−0.09513	3.2
Herniaria berlengiana	0.03648	−0.00403	0.21

(habitat reestablishment, reintroductions, population reinforcements...) in the area.

2.4.2. Material and methods

The target area of this survey is in the Guadiana basin on the border between Spain and Portugal (Alentejo region). It comprises a section of ca. 90 km of river (Fig. 1).

In the species-specific target, the plant cartography produced by Draper et al. (2000a,b) was used. The distribution of *Marsilea batardae* Launert in the Guadiana River has been chosen to illustrate the approach. The distribution of *M. batardae* was obtained between 1999 and 2001 with a field resolution of 1 ha (Ballester-Hernández et al., 2000) and complemented with cartography of the absence of the species, so the input information has a binary structure: "one" when *Marsilea* is present and "zero" when it is absent.

The DTM was elaborated from a vectorial altimetric model of the area with a contour interval of 1.5 m supplied by EDIA, S.A., the building dam enterprise. Data resolution used was 25 m^2 for all the variables used. Climatic variables were obtained on the base of this DTM. Due to the neighbourhood to Spain, the climatic model follows Sánchez-Palomares et al. (1999) for the

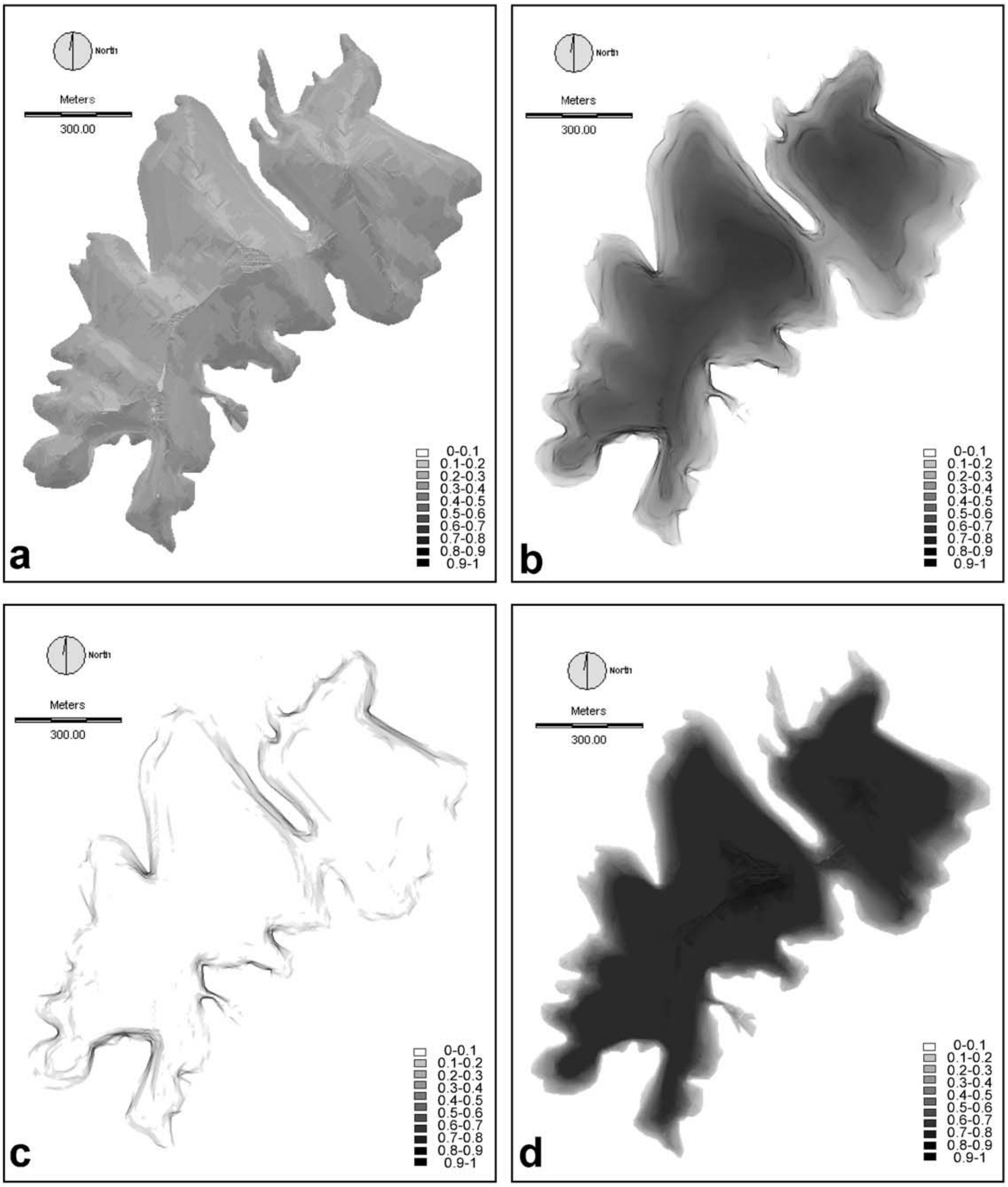

Fig. 6. Predictive maps of (a) *C. edulis*, (b) *A. berlengensis*, (c) *A. pachycarpa*, and (d) *H. berlengiana* in Berlenga. The legends show the intervals of probability according to the models.

Guadiana basin estimated from Spain. In order to comprise the widest ecological range of the area, the same variables cited in Section 2.1.2 as well as soil type and soil pH (C.N.A., 1983) were considered.

The analysis used was a clustering method based on an iterative, self-organising, unsupervised, maximum likelihood classifier. Homogeneous ecological units were defined with the help of geophysics and climatic variables. The seed image file used was a Landsat TM (1995) of the area considering the bands 3, 4 and 5.

The logistic regression (LR) was adopted as the most appropriate (Press and Wilson, 1978) considering the binary nature of the predictive variable and the qualitative nature of the edaphic variables as species-specific target.

2.4.3. Results and discussion

The selected variables were: altitude (m); aspect (°); water distance (m); annual mean rainfall (mm); minimum temperature (°C) and soil type.

The first results differentiated 40 different ecogeographical units (Table 2). Units <1 ha (14 clusters) were included in the neighbouring areas using a mode filter. These small units were not be considered as target collecting sites. However, they were individually prospected because they might contain a particular environment that could have a particular flora. The unit profile can be used to characterise the seed samples collected from a unit area. Thus, complementary information can be incorporated into the seed accession passport data.

Table 2

Clustering profile of the significant variables for the identification of ecogeographical units for seed collecting continuous variables were reclassified considering ± 1 S.D.

Cluster	Area (ha.)	Average water distance (m)	Altitude	Aspect	Annual rainfall	Min. temp.	Litosols (%)	Cambisols (%)	Luvisols (%)
1	19184.63	78.468	1.912±0.57	2.769±1.36	1.897±0.57	2.255±0.66	61.69	2.74	35.56
2	19985.25	55.319	1.911±0.54	2.773±1.45	1.959±0.54	2.068±0.67	50.80	6.48	42.70
3	20021.25	44.782	1.982±0.46	2.745±1.52	2.036±0.52	1.966±0.6	45.73	4.89	49.36
4	12680.44	45.136	1.863±0.43	2.829±1.51	1.935±0.46	2.064±0.53	61.57	3.02	35.40
5	10729.88	37.108	1.94±0.36	2.798±1.53	2.002±0.41	1.993±0.49	51.51	3.53	44.95
6	8874.313	64.307	2.09±0.62	2.662±1.32	2.096±0.6	2.117±0.72	58.16	3.96	37.87
7	7824.75	58.293	2.165±0.6	2.668±1.47	2.2±0.66	1.953±0.67	43.30	5.07	51.62
8	8044.5	61.015	1.803±0.5	2.735±1.48	1.874±0.51	2.137±0.57	65.43	2.65	31.91
9	5709.313	33.979	1.931±0.34	2.832±1.53	1.997±0.39	1.97±0.46	42.36	3.42	54.20
10	6606.688	39.802	1.932±0.39	2.737±1.55	2.007±0.5	1.949±0.53	30.53	4.65	64.81
11	5433.313	29.193	1.985±0.39	2.885±1.52	2.025±0.46	1.993±0.57	34.94	3.96	61.08
12	5063.563	50.179	2.047±0.48	2.62±1.58	2.122±0.59	1.939±0.55	29.13	4.68	66.18
13	2690.313	68.578	2.431±0.66	2.459±1.34	2.424±0.66	1.972±0.64	35.82	4.39	59.78
14	2138.625	39.731	1.892±0.34	2.836±1.53	1.943±0.39	2.057±0.34	62.41	0.70	36.87
15	2092.313	132.517	1.26±0.49	2.171±1.77	1.641±0.46	1.927±0.67	57.69	4.07	38.22
16	2208.625	28.091	1.929±0.37	2.81±1.53	1.996±0.38	1.956±0.5	41.72	6.03	52.23
17	66.0625	34.469	1.955±0.28	2.762±1.53	1.995±0.34	2.02±0.28	56.20	0.34	43.45
18	55.0625	35.058	1.942±0.28	2.689±1.55	2.003±0.34	2.018±0.31	54.09	0.76	45.13
19	13.4375	78.488	2.205±0.61	2.546±1.56	2.339±0.75	1.833±0.62	31.19	6.68	62.12
20	10.1875	94.9	2.131±0.67	2.42±1.48	2.356±0.88	1.786±0.66	32.12	6.56	61.30
21	9.5625	24.511	1.837±0.43	2.874±1.5	1.955±0.49	1.848±0.56	43.38	13.41	43.19
22	2.1875	95.864	1.622±0.47	2.709±1.62	2.03±0.67	1.64±0.68	43.64	9.58	46.77
23	5.25	56.377	1.841±0.38	2.675±1.59	2.015±0.55	1.905±0.58	35.75	4.51	59.73
24	0.5	38.643	1.901±0.34	2.69±1.59	2.001±0.46	1.959±0.48	28.44	5.61	65.93
25	2.5625	105.101	1.254±0.39	2.446±1.71	1.882±0.49	1.743±0.67	51.39	7.18	41.41
26	1.0625	30.82	1.946±0.32	2.689±1.54	1.978±0.38	2.055±0.34	60.22	0.07	39.69
27	1.5	44.583	1.834±0.3	2.753±1.6	1.971±0.45	1.967±0.55	33.38	2.91	63.70
28	0.875	26.69	1.851±0.36	2.789±1.59	1.924±0.46	1.944±0.51	25.65	9.00	65.33
29	0.9375	74.057	1.531±0.35	2.782±1.52	1.901±0.54	1.764±0.68	40.19	3.97	55.83
30	0.5	21.437	1.878±0.23	2.936±1.42	2.045±0.42	1.795±0.61	53.40	0.72	45.87
31	0.125	19.636	1.9±0.18	2.609±1.45	2.022±0.34	1.69±0.5	52.02	1.07	46.90
32	0.5625	21.486	2.157±0.49	2.943±1.5	2.243±0.5	1.643±0.57	55.71	21.42	22.85
33	0.5625	156.617	2.128±0.34	2.106±1.89	2.128±0.34	2±0	80.85	0	19.14
34	0.4375	6.061	2±0	3.485±1.3	2±0	1.818±0.39	39.39	0	60.60
35	0.375	16.154	1.923±0.38	4±1.41	2.154±0.28	1.846±0.38	30.76	15.384	53.84
36	0.375	6.889	1.667±0	3.333±0.71	2±0.5	1.667±0.5	100	0	0
37	0.0625	186.2	1±0	0.4±0.89	1±0	2.6±0.55	0	0	100
38	0.25	54	2±0.58	2.75±2.06	1.5±0	2.5±0.58	0	0	100
39	0.1875	59.75	2±0	3±0.82	2±0	2±0	75	0	25
40	0.25	12	2.25±0.58	4.25±0.5	2.5±0.96	1.75±0.5	50	0	50

When a target species is selected, the clustering map can be used as a stratification-sampling layer. We assayed this by creating the predictive map of *M. batardae* distribution and then crossing it over with the clustering map obtained before.

The predictive model was obtained by the LR: *M. batardae* = 1.3933−0.1617 *inclination*−0.0341 *water distance* + 1.0821 *minimum temperature*−0.2658 *number frost days/year*.

The percentages of correct attribution for the presence and absence of *M. batardae* were 97 and 92%, respectively ($n = 222$ ha).

The results of the crossing-over are illustrated in Fig. 7 for the probability interval between 0.7 and 1. These results show several useful features for collecting germplasm. They indicate where it will be easiest to find *M. batardae* and which particular conditions are affecting it. In the same way, they show where the species could

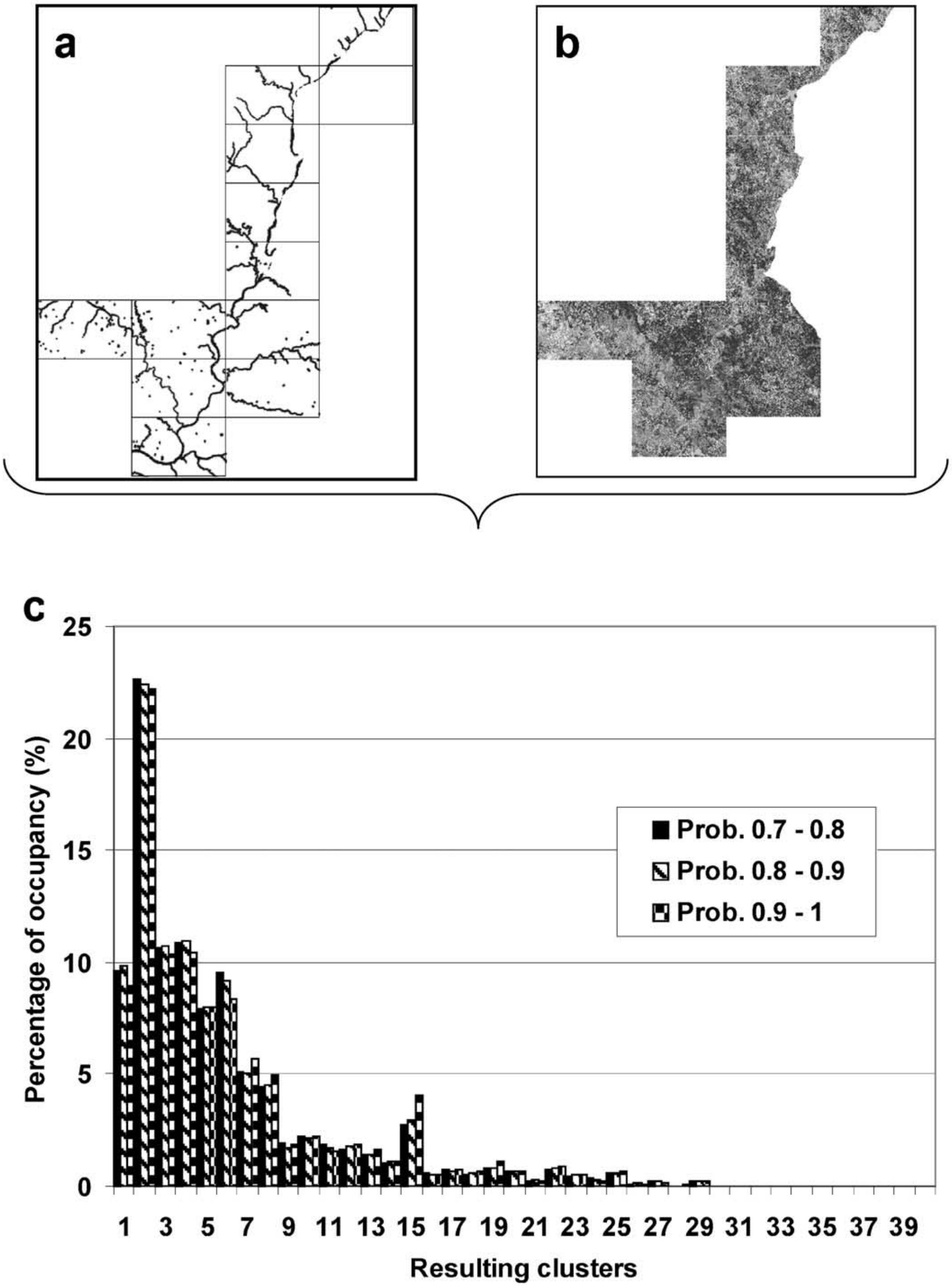

Fig. 7. Results of crossing-over (a) the predicted *M. batardae* distribution and (b) the clustering image; (c) frequency of the three highest intervals for each cluster unit.

be present but less represented. These locations could have a high interest for collection and representation in a germplasm collection. The frequency of each cluster illustrates the area covered by each interval so it can be taken as a descriptor of the sampling area.

3. Conclusions

The area occupied by a species is not homogeneous and the factors affecting its distribution may differ from one place to another. Thus, different factors can limit the spatial distribution of a species in different parts of its geographical distribution (Brown and Gibson, 1983). For instance, it is probable that *B. vogesiaca* is widely present in the Iberian Peninsula particularly in the highest ranges. Two main situations can be considered after a field validation: the model is acceptable or it is rejected. In the first situation, we can assume that the factors of the distribution are the same all around its area of distribution. Otherwise, if the model is rejected because *B. vogesiaca* is absent in the areas with the highest probability we can assume that other factors need to be added in a new model or that the factors considered can only be applied to the area surrounding known localities. Relationships between space-scale phenomena may arise that appear to be difficult to solve. Nevertheless, correct answers can be obtained through the selection of an appropriate work scale that is dependent on the objective of the phenomenon (May, 1994). Gaston and Lawton (1990) pointed out that surveys of the same phenomenon carried out at different work scales could raise contradictory results. In the same way, Murphy (1989) considered that selection of a wrong scale could derive in dangerous generalisations when used in conservation projects. All these aspects should be taken in consideration in any conservation programme and they need to be integrated and analysed to obtain objective results that species or areas managers will use.

The working scale not only conditions strongly the resolution of the maps to be used, but also the features and variables considered and especially the objectives that can be attained. These study cases show that the appropriate work scale to be used is dependent on the purpose of the study (May, 1994). This kind of approach can also be useful in biogeographical interpretation and in some floristic studies. Unfortunately, the use of GIS is not yet usual as shown by the recent taxonomic and floristic work *Flora Briofítica Ibérica* (Gallego and Cano, 2000), despite the advantages pointed out by Draper and Sérgio (1999).

The criteria for the selection of protected areas are not standard or are there defined rules. Consequently, several criteria and priorities are taken into consideration in the selection of an area (Margules et al., 1988; Nantel et al., 1998). In general, this situation is more relevant the smaller the area to be protected. The increasing interest in the establishment of a micro-reserves plant network (Laguna, 1998) demands the improvement of selection methods. A first approach for selecting a network of reserves in Portugal, to encompass maximum biotic diversity, was proposed by Sérgio et al. (2000) and was illustrated with examples of bryophyte species in all Portuguese territory based on gap analysis. However, the scale used in this work was a severe limitation so an environmental GIS model was later proposed with the same objective but giving better results (Draper et al., 2001). Descriptors such as the number of threatened or endemic species could be good criteria for these selections.

Monitoring population dynamics of *C. edulis* and of *A. pachycarpa* will be crucial for an efficient management of Berlengas Natural Reserve in order to minimise the impact of *C. edulis* (D'Antonio, 1990) on this endemic as well as to protect the more sensitive habitats. Protection of the localities where the endemics are now present could reduce the future refuges for *C. edulis*.

When assessing the selection of protected areas there is a need to define conservation strategies that include more items than just the presence of the target species. These strategies could take into account the potential area for each species as well as several levels of suitability. In both cases a GIS approach can play an important role. Thus, the results obtained in Berlengas Natural Reserve can be a tool for further conservation actions (control of *C. edulis* expansion, protection of autochthonous flora, etc.). In conclusion, a GIS can provide a link between the decision-maker's point of view and the natural boundaries of a problem (Fedra, 1993).

The ecogeographical survey created for selection of seed-collecting sites was applied to *M. batardae* in order to exemplify this methodology. It is important to point out that this approach to germplasm collecting can be applied to specific target species as well as plant diversity in a territory, according to the available information. In any case, accurate geographical data is necessary in order to apply this method. In this way, selection of germplasm collecting sites can be made through the subdivision of the distribution area of the chosen species in homogeneous ecogeographical units. Moreover, the methodology proposed allows one to predict the presence/absence of a species or genotype based on its ecological preferences.

The applicability of this method in a wider context is now under evaluation and study. With appropriate adjustments related to the nature of each species, the proposed methodology could become a very useful tool for germplasm banks orientated to the conservation of plant genetic resources.

New challenges appear when extremely small areas are taken into consideration. With GIS, we usually use cartographic or topographic scales, rather lower than 1:1000. However, not all the processes can be understood at these scales and not all the effects can be explained at these levels. For instance, trying to integrate the space occupied by the subject of the survey without considering the interaction with other species may be acceptable at regional levels. However these interactions are essential when we work at microhabitat scales such as in the assessment of germination sites (Kameyama et al., 1999). New types of data layers and new algorithms are needed in these situations and much research is needed in this area. Considering that GIS surveys require an interdisciplinary approach, we hope that closer links between taxonomy, floristics, topography, biogeography and management may be established in the near future. This will be an essential factor in order to successfully support and design conservation programmes using GIS.

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Appendix. Climatic indices used to elaborate the environmental models

Emberger Index:

$$Q = \frac{100^{*}P}{M^2 - m^2}$$

where:

P = mean annual precipitation (mm)
M = maximum temperatures mean of the hottest month (°C)
m = minimum temperatures mean of the coldest month (°C)

Gorezynshy Index:

$$K = 1.7\frac{A}{\sin(L)} - 20.4$$

where:

A = annual temperature amplitude (mm)
L = latitude (°)

Gams Index:

$$Ic = \text{cotangent angle of } P/A$$

where:

P = mean annual precipitation (mm)
A = meteorology station altitude (m.a.s.l.)

Dantin-Revenga Index:

$$D = \frac{100^{*}T}{P}$$

where:

P = mean annual precipitation (mm)
T = mean annual temperature (°C)

De Martonne Index:

$$M = \frac{P}{T + 10}$$

where:

P = mean annual precipitation (mm)
T = mean annual temperature (°C)

Lang Index:

$$L = \frac{P}{T}$$

where:

P = mean annual precipitation (mm)
T = mean annual temperature (°C)

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