Sonoran Desert ex situ conservation gap analysis: charting the path toward conservation .

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Sonoran Desert *ex situ* conservation gap analysis: charting the path toward conservation

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Abstract

Plant biodiversity is under threat. With two out of five plants at risk of extinction, preserving taxa through *ex situ* conservation approaches must be considered a priority. The Sonoran Desert, a highly biodiverse ecoregion shared between Mexico and the United States is home to at least 4000 native plant taxa. In collaboration with institutions from both countries, we developed a method to determine conservation priorities. We analysed herbaria records and data from nine seed banks to identify gaps in previous conservation efforts. We prioritised taxa based on a Priority Score (PS) and modelled their potential distribution to identify priority hotspots. 4029 native taxa were reported. 1441 of them have accessions in seed banks, but only 412 have been collected inside the SD. The PS considers some potentially endemic (126) and threatened taxa (112) as the most urgent to preserve. It also includes information about the storage behaviour (3236 orthodox), useful plants (1406), and taxa without populations in protected areas (230) to categorise the species. Although most of the SD flora is not represented in seed banks, at least 80% is predicted to produce desiccation-tolerant seeds and thus can be cost-effectively stored. Spatial analysis shows that the central region of the Baja California Peninsula stands out for its species richness and endemism. Our study presents the first *ex situ* conservation gap analysis of the SD flora and provides a replicable methodology for identifying priority species and potential areas for *ex situ* collection.

Keywords

Arid zones, endemism, priority areas, seed banking, threatened taxa.

1. Introduction

Global plant diversity is under threat (Antonelli et al., 2020). The causes are highly diverse, ranging from habitat loss and climate change to the overexploitation or illegal trade of species (Breman et al., 2021; Corlett, 2016; Margulies et al., 2022). It has been estimated that two out of five species of plants might be at risk of extinction, which highlights the urgency of implementing alternatives for their conservation (CBD, 2012). When *in situ* conservation is not viable or complementary protection is required, *ex situ* conservation plays a fundamental role in safeguarding biodiversity (Li and Pritchard, 2009; Maxted, 2013).

One of the most widely implemented approaches for *ex situ* conservation is storage in seed banks, where seeds are preserved at low moisture content and temperature, allowing their long-term survival (Breman et al., 2021). This method has advantages over conservation in botanic gardens, such as reducing storage costs and increasing the potential for preserving genetic diversity (Gargiulo et al., 2019; Li and Pritchard, 2009; Potter et al., 2017). While this alternative may not be feasible for some taxa, such as exceptional species (Pence et al., 2020), it is an adequate method to protect biodiversity, providing a dynamic collection to carry out research or be a source of material for reforestation projects (Hay and Probert, 2013; Merritt and Dixon, 2011).

The Millennium Seed Bank is the largest repository of wild plant species, banking more than 2.4 billion seeds from almost 40,000 species (Breman et al., 2021; RBG Kew, 2023; White et al., 2023). Its collaboration with institutions in over 100 countries or territories also stands out, consolidating the Millennium Seed Bank Partnership (MSBP) as the world's largest ex situ conservation programme (Liu et al., 2018). Despite the relevance of its collections, the representativeness of specific priority groups in the seed banks must be evaluated individually. For example, endangered species, useful plants, or entire floras from specific regions (Godefroid et al., 2011; Liu et al., 2023; Ramírez-Villegas et al., 2010; Rivière and Müller, 2018; Teixido et al., 2017). Gap analyses are a useful methodology to identify opportunity areas, propose priorities, and improve future conservation efforts, especially important in highly diverse and threatened regions (Carver et al., 2021; Scott et al., 1993; Sowa et al., 2007).

The Sonoran Desert (SD), located in Mexico and the United States, meets those criteria, making it a relevant area of study and potential conservation action. The SD is the hottest and most diverse desert in North America, including a wide variety of plant life forms, from columnar cacti and woody shrubs to winter and summer annual herbs (Burquez et al., 1999; Robichaux, 1999; Weiss and Overpeck, 2005). The environmental variation, rainfall regimes, and community composition are such that at least seven subdivisions have been proposed to differentiate specific areas within the SD (Shreve and Wiggins, 1951; Turner and Brown, 1982). Regarding specific diversity, calculations estimate that between 3,200 and 3,400 species of plants are distributed in its territory (McLaughlin and Bowers, 1999). Keystone species such as the saguaro cactus (*Carnegiea gigantea*) or unique parasitic plants like *Pholisma sonorae* (Fig. 1A and B) stand out for their environmental and cultural relevance (Drezner, 2014).

However, this biodiversity is facing all kinds of threats such as climate change and the spreading of invasive species (Tinoco-Ojanguren et al., 2016; Weiss and Overpeck, 2005; Wilson et al., 2002). Recent studies on annual plants reported a potential increase in the species' extinction risk if rainfall regimes continue changing (Cuello et al., 2022). Also, analyses of specific taxa, such as members of the Cactaceae family, have shown the potential decline of their populations in the face of climate change (Breslin et al., 2020). Some modifications in the limits of the SD have also been predicted, so the distribution of its species could be modified in the future (Weiss and Overpeck, 2005).

Fig. 1. Examples of the Sonoran Desert flora. (A) *Carnegiea gigantea*. (B) *Pholisma sonorae*. (C) *Agave pelona*. (D) *Encelia ravenii*. Images by Marianne Skov (A), Alfredo Fuentes (B), Carlos Velazco (C) and Erik (D) from iNaturalist.

Since the native biodiversity of the SD is at risk, its storage in seed banks should be considered in future conservation actions. This study is focused on the analysis of prior knowledge of the SD flora, using herbaria records and seed bank data to determine the gaps in previous collection efforts. Priority taxa were suggested based on a Priority Score (PS), which was calculated considering six individual scores, and priority areas for *ex situ* conservation were identified using presence records and species distribution models (SDM).

2. Materials and methods

2.1. Site delimitation and data collection

The SD area includes the Sonoran Desert and Baja Californian Desert ecoregions of the Level III Ecoregions of North America (EPA, 2023). This approach corresponds to previous delimitations for the SD (Shreve and Wiggins, 1951; Turner and Brown, 1982) and the phytogeographic region classification of the Baja California Peninsula proposed by Gonzalez-Abraham et al. (2010).

Presence records were downloaded from the consortium of herbaria SEINet (2023) selecting the quadrant 42.2°N, 22.5°N, 124.5°W, 108.2°W, which includes the states of Arizona and California in the United States and Baja California, Baja California Sur, and Sonora in Mexico. Hidden records were requested from the Symbiota Portal Hub to include distribution data for protected species. On the other hand, seed bank accessions were compiled from the MSBP Data Warehouse, and the data provided by seven associated collaborators (Table 1). All records (N=1,045,471) were cleaned, their taxonomy was matched against The World Checklist of Vascular Plants and the native SD species were selected (Govaerts et al., 2021). Data cleaning, analysis, and visualisation were done using R version 4.2.3 (R Core Team, 2023), a summary of the used packages can be found in Supplementary Material 1.

Table 1. Seed data providers, number of accessions, and taxa collected for each institution. The total number of accessions is reported.

Institution	**Abbreviation**	**Total number of seed accessions**	**Total number of native SD taxa preserved**	**Number of accessions in the SD**	**Number of native SD taxa preserved in the SD**
California Botanic Garden	CalBG	2188	766	740	248
Facultad de Estudios Superiores de Iztacala	FESI	455	342	244	160
Millennium Seed Bank	MSB	1881	1028	666	289
Santa Barbara Botanic Garden	SBBG	16	10	0	0
San Diego Botanic Garden	SDBG	28	21	5	5
San Diego Zoo Wildlife Alliance	SDZWA	319	190	106	53
University of California Santa Cruz	UCSC	216	65	6	4
The Arboretum at Flagstaff	thearb	80	36	10	2
Total		**5183**		**1777**	

2.2. Species prioritisation

Additional data were obtained and analysed for all the native SD taxa. Six individual scores were calculated for each of the species: 1) Endemism Score (EndS), 2) Conservation Status Score (ConsStS), 3) Storage Capacity Score (StorS), 4) Useful Plants Score (UsefS), 5) In-situ Conservation Score (InSituS), and 6) Seed Bank Accessions Score (SBS). The possible values for those scores are specified in Table 2.

A Priority Score (PS) going from 0 to 1 was calculated using the formula:

$$PS = \frac{EndS + ConsStS}{2} \times 0.5 + \frac{StorS + UsefS + InSituS + SBS}{4} \times 0.5$$

With this approach, the potentially endemic and threatened taxa are prioritised considering the goals of this project and the Target 8 of the Global Strategy for Plant Conservation, which is directed to the inclusion of endangered species in *ex situ* programmes (CBD, 2012). The taxa with values closer to 1 have a higher level of priority.

Table 2. Possible values for each taxon in the six individual scores of the Priority Score (PS).

Individual score and possible categories	**Value**
1. Endemism Score (EndS)	
a. No endemic to the SD	0
b. Endemic to the SD	1
2. Conservation Status Score (ConsStS)	
a. IUCN Red List	
i. No evaluated taxa	0
ii. Data Deficient (DD)	0.5
iii. Least Concern (LC)	0
iv. Near Threatened (NT)	0.25
v. Vulnerable (VU)	0.5
vi. Endangered (EN)	0.75
vii. Critically Endangered (CR)	1
b. NOM-059-SEMARNAT-2010	
i. No evaluated taxa	0
ii. Sujeta a protección especial (Subject to special protection) (Pr)	0.33
iii. Amenazada (Threatened) (A)	0.66
iv. En peligro de extinción (Endangered) (P)	1
c. The United States Endangered Species Act (ESA)	
i. No evaluated taxa	0
ii. Threatened	0.5
iii. Endangered	1
3. Storage Capacity Score (StorS)	1-probability of recalcitrance given by the tool
4. Useful Plants Score (UsefS)	(# Uses per spp / 10 (maximum))
5. In-situ Conservation Score (InSituS)	
a. At least one population inside a PA in the SD	0
b. At least one population inside a PA outside the SD	0.5
c. No populations inside PA	1
6. Seed Bank Accessions Score (SBS)	
a. High or medium-high usability accessions in the SD	0
b. High or medium-high usability accessions outside the SD	0.25
c. Low or medium-low usability accessions in the SD	0.5
d. Low or medium-low usability accessions outside the SD	0.75
e. No accessions in seed banks	1

2.2.1. Endemism score (EndS)

The native taxa list was used as a starting point for the selection of potentially endemic species. Those having herbaria sites beyond the SD polygon were filtered out.

2.2.2. Conservation status score (ConsStS)

The conservation status of the taxa was assessed using three sources of information, including both international and regional assessments. Information from the IUCN Red List of Threatened Species (IUCN, 2023) was extracted. Because there is evidence that "Data Deficient" taxa likely include a significant number of threatened species, they received a value of 0.5 (Borgelt et al., 2022; Parsons, 2016).

Mexican regional assessments were recovered from the Norma Oficial Mexicana NOM-059-SEMARNAT-2010 (SEMARNAT, 2010). United States regional assessments from the United States Endangered Species Act were obtained from the Nature Serve Explorer (NatureServe, 2023).

2.2.3. Storage Capacity Score (StorS)

The probability of recalcitrance of the species was calculated using the Seed Storage Behavior Predictor tool (Wyse and Dickie, 2018). The score was obtained by subtracting the predicted value from one, prioritising those taxa predicted to have orthodox behaviour.

2.2.4. Useful Plants Score (UsefS)

The number of reported uses per species was obtained from the World Checklist of Useful Plant Species Database. Then it was divided by the maximum number of uses (10): medicines, materials, environmental uses, human food, gene sources, animal food, poisons, social uses, fuels, and invertebrate food (Diazgranados et al., 2020).

2.2.5. In-situ Conservation Score (InSituS)

Protected Areas (PA) shapefiles were downloaded from Protected Planet: The World Database on Protected Areas (UNEP-WCMC & IUCN, 2023). The presence of populations within protected areas, both inside and outside the SD, was evaluated.

2.2.6. Seed Bank Accessions Score (SBS)

The presence and usability of native taxa accessions were analysed separately: 1) inside the SD and 2) outside the SD. This distinction was made since accessions in the SD would have more relevance to the aims of this study, and even though some taxa might have backup collections in other regions, their SD populations should also be preserved.

The usability of the collections was evaluated using five individual scores modified from previous gap analyses (Viruel and Quintana, in prep): 1) Accessions Score (AccS), considering the number of accessions per taxon, regardless of its institution of origin. 2)

Seed Count Score (SCS), which evaluates the presence or absence of a seed count (either a current count or an adjusted count). 3) Seed Number Score (SNS), modified from previous recommended target numbers (Way, 2003). 4) Germination Test Score (GerTestS), which evaluates the presence or absence of a germination test, and 5) Viability Score (ViabS), defined as the value of the reported viability divided by 100. The possible values given for each taxon are specified in Table 3.

A Seed Accessions Usability Score (SeedUsS) going from 0 to 1 was calculated using the formula:

$$SeedUsS = \frac{(AccS + SCS + SNS + GerTestS + ViabS)}{5}$$

The taxa with values closer to 1 have higher usability in their collections and, therefore, less priority in the PS. Four usability categories were proposed: 1) High usability (SeedUsS = 0.75-1); 2) Medium-high usability (SeedUsS = 0.5-0.75); 3) Medium-low usability (SeedUsS = 0.25-0.5); and 4) Low usability (SeedUsS = 0-0.25).

Table 3. Possible values for each taxon in the five individual scores of the Seed Usability Score (SeedUsS).

Individual score category	Value
1. Accessions Score (AccS)	
a. 1	0
b. 2-5	0.2
c. 6-9	0.4
d. 10-19	0.6
e. 20-29	0.8
f. >=30	1
2. Seed Count Score (SCS)	
a. No	0
b. Yes	1
3. Seed Number Score (SNS)	
a. <500	0
b. 500-1000	0.2
c. 1000-5000	0.4
d. 5000-10000	0.6
e. 10000-20000	0.8
f. >20000	1
4. Germination Test Score (GerTestS)	
a. No	0
b. Yes	1
5. Viability Score (ViabS)	Viability/100

2.3. Geographical prioritisation

Collection density maps using a logarithmic scale were created to visualise the sampling effort of both data sources: herbarium collections and seed banks (Fig. 2). To obtain priority hotspot maps, species distribution models (SDMs) were generated when the taxa had more than ten records. To include information about taxa with less than ten records, buffered points with a radius of 2 km were created around the presence coordinates (Brown et al., 2014; Tovar et al., 2023). SDMs and buffer maps were joined to obtain presence density maps.

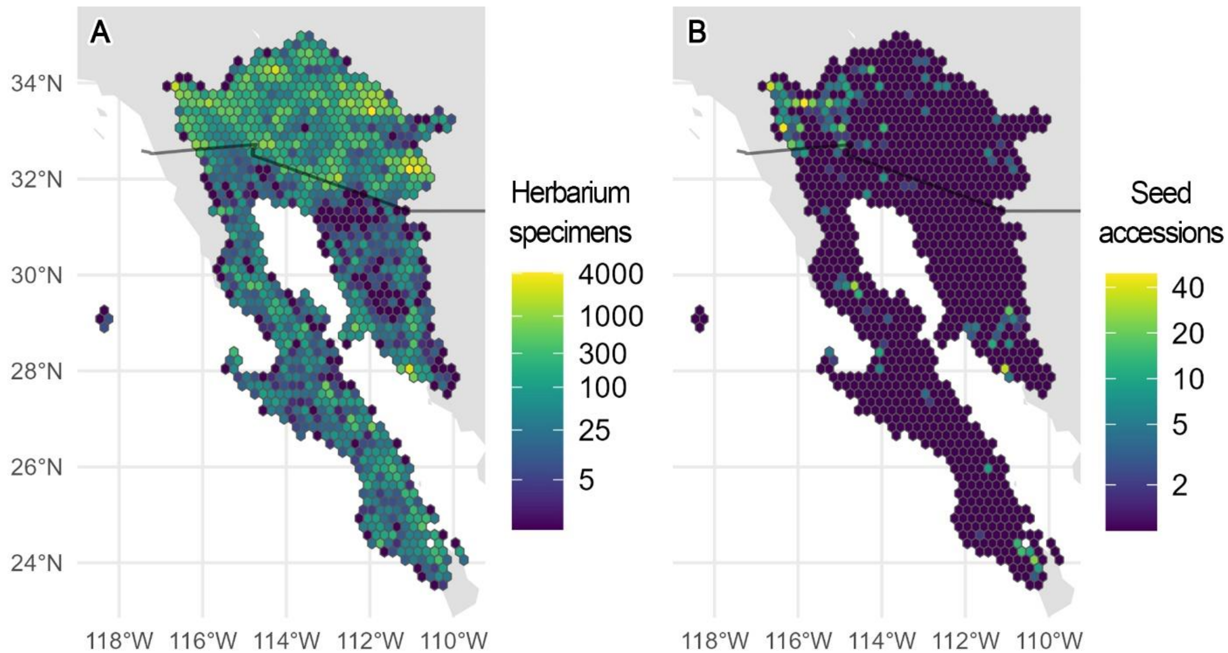

Fig. 2. Density of collections from herbaria (A) and seed banks (B) in the Sonoran Desert. The Mexico-US border is highlighted in black. A logarithmic transformation was applied to the data.

For the SDMs, the nineteen bioclimatic variables from WorldClim version 2.1 (Fick and Hijmans, 2017) and the elevation were considered. A Pearson correlation analysis with a threshold of 80% was carried out to reduce collinearity between the environmental variables and eight of them were selected to calculate the models (Supplementary Material 2) (Yin et al., 2022). The redundancy of the presence records was reduced by randomly choosing one record in a range of 1 km^2. After that, pseudo-absences were created considering a buffer of 10 km from the collections. The presence points were divided into 70% testing and 30% training for the models. Lately, the Random Forest algorithm was used for the modelling (Zhang et al., 2019) and the Area Under the Curve (AUC) was calculated to evaluate each prediction. Each model was converted into a binary (presence/absence) map using the "equal test sensitivity and specificity" threshold.

Heatmaps were generated: 1) using the 100 taxa with the highest PS (19 SDMs + 81 buffered areas), 2) considering potentially endemic taxa (24 SDMs + 102 buffered areas), and 3) modelling the potential distribution for threatened taxa (74 SDMs + 38 buffered areas).

3. Results

3.1. Status of the Sonoran Desert flora

4029 native taxa (species, subspecies, varieties, and hybrids) from 149 families were identified for the SD (Fig. 3). The families with the largest number of taxa were Asteraceae (611), Fabaceae (410), and Poaceae (249). Considering the reports on the specific diversity of the SD, this approximation may overestimate the number of taxa, future updates to the species list may be necessary.

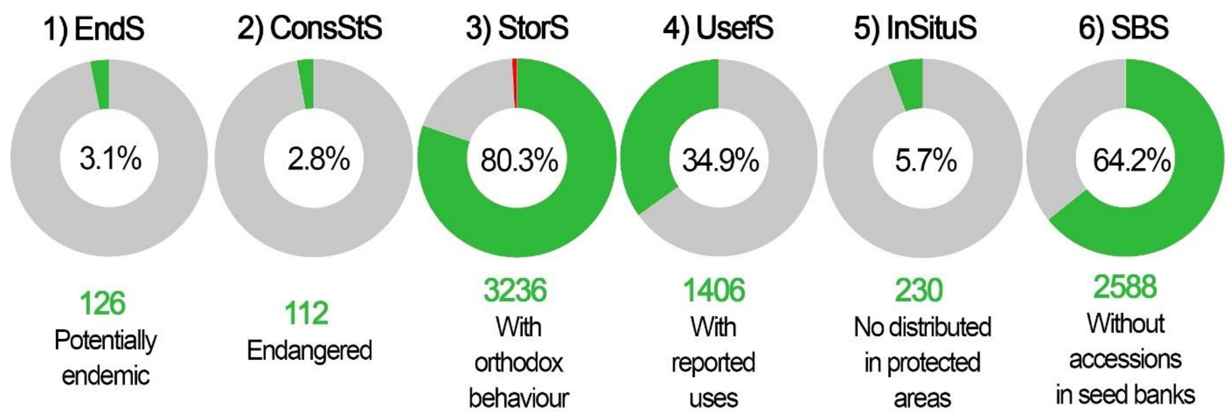

Fig. 3. Status of the 4029 taxa recorded for the Sonoran Desert according to the six individual scores. The proportion of taxa prioritised by the scores is shown in green. The proportion of taxa predicted to have recalcitrant seeds (0.8%) is shown in red in the third graph.

3.1.1. Endemism

126 taxa from 35 families were identified as potentially endemic from the SD (Supplementary Material 3). The most diverse families were Cactaceae (18), Asteraceae (15), and Polygonaceae (11). Eight of the potentially endemic species have been seed banked and only one of those has high usability accessions inside the SD (Fig. 4).

3.1.2. Conservation status

112 taxa are considered under threat according to the three studied data sources. 644 taxa have been assessed by the IUCN. 568 were defined as “Least Concern” and 16 were considered “Nearly Threatened”. 10 of the taxa were classified as “Data Deficient”. 50 taxa were considered threatened: 31 as “Vulnerable”, 17 as “Endangered”, and 2 as “Critically Endangered”. 55 taxa are listed in the NOM-059-SEMARNAT-2010. 36 of them as “subject to special protection”, 14 as “threatened”, and 5 as “endangered”. Five taxa were listed as endangered under the United States Endangered Species Act.

Only 43 of the 112 threatened taxa have been seed banked, 19 of them inside the SD (Fig. 4).

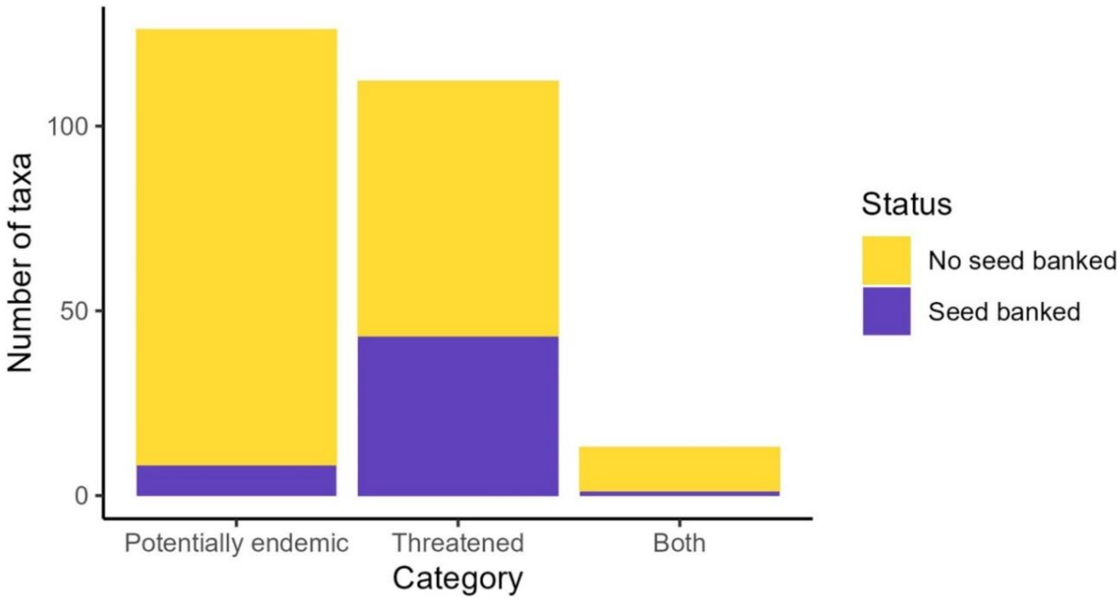

Fig. 4. Status of the potentially endemic and threatened taxa in seed banks.

3.1.3. Storage Capacity Score

3177 taxa were predicted to have orthodox behaviour (80%). Only 34 were classified as recalcitrant and belonged mainly to the genus *Quercus* (22 taxa). There was not enough information to assign the potential behaviour of 818 taxa.

3.1.4. Useful Plants

1406 taxa are included in the World Checklist of Useful Plant Species with at least one use. 137 of them have five or more reported uses. In this study, all the uses were considered to have the same importance. Nevertheless, specific categories, such as gene sources, could be analysed separately depending on the study goals.

3.1.5. In-situ Conservation

230 taxa do not have any populations inside protected areas. 989 taxa have at least one record inside a protected area outside the SD polygon, and 2810 are distributed in protected areas inside the SD.

3.1.6. Seed Bank accessions

5183 accessions from 1441 native SD taxa have been preserved in eight seedbanks, but only 1777 accessions from 412 of them have been collected inside the SD polygon (Table 1). 101 of those 412 taxa have more than five accessions. According to the SeedUsS, 6 of the 412 collected taxa inside the SD have high usability accessions, 189 reported medium-high usability, 191 medium-low usability, and 26 low usability. On the other hand, 76 of the 1029 taxa outside the SD had high usability accessions, 437 medium-high usability, 407 medium-low usability, and 109 low usability (Fig. 5).

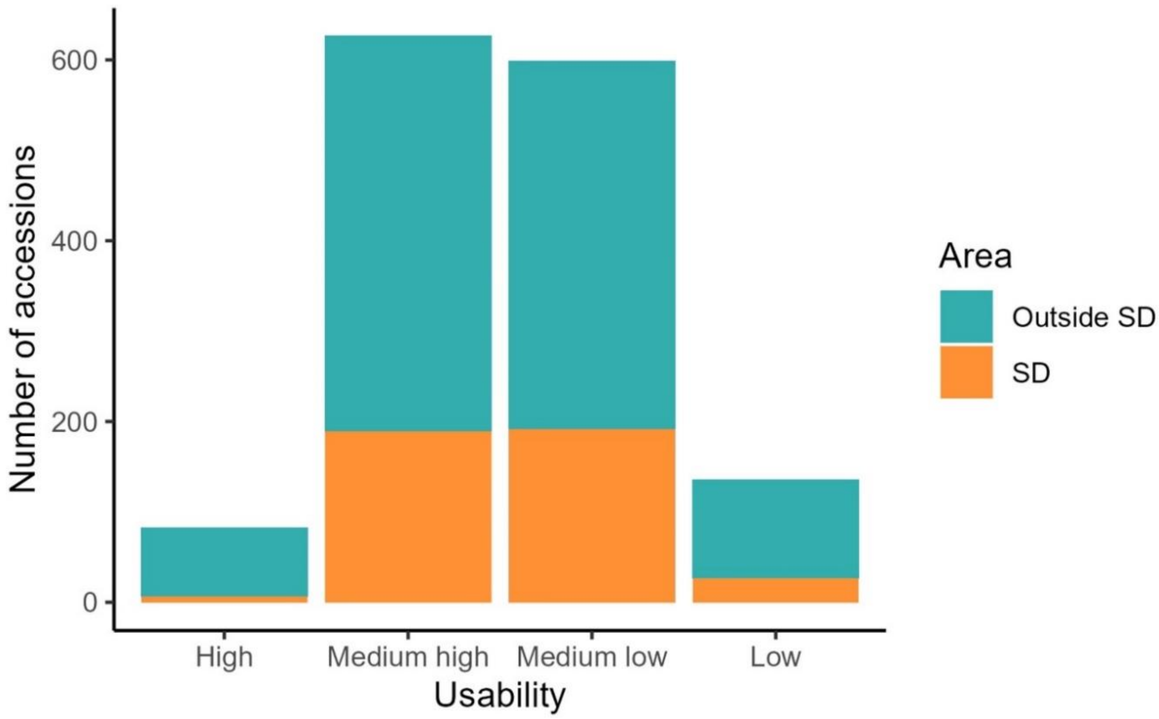

Fig. 5. Usability of the seed accessions of native SD taxa considering the values of the Seed Usability Score.

3.2. Species prioritisation

Native SD taxa were ranked according to their PS. A top 100 was selected as a priority for seed banking (Supplementary Material 4). The families with more included taxa were Cactaceae (14), Asteraceae (13), Polygonaceae (8), and Asparagaceae, Fabaceae, and Rubiaceae (6). 95 potentially endemic and 16 endangered taxa are included in the selection. The genus *Agave*, specifically the species *A. pelona* (Fig. 1C), *A. turneri,* and *A. zebra*, occupied high positions in the top.

3.3. Geographical prioritisation

The density of herbarium collections is higher than the density of seed bank accessions in the SD (Fig. 2). Likewise, the collection bias in the United States portion of the region is evident but differs according to the data source. While herbarium collections are concentrated in Arizona, seed bank accessions are skewed towards California.

The area under the curve (AUC) for 98% of the models was at least 0.7, and 83% was greater than 0.9. Therefore, we consider that the models are acceptable based on previous studies (de Souza and De Marco, 2014; Girardello et al., 2009).

According to the heat map for the 100 taxa with the highest PS, the Baja California Peninsula is where the greatest diversity of priority taxa could be distributed (Fig. 6A). The Vizcaino Desert, the western part of the Central Desert, and the northern part of the Central Gulf Coast stand out, including the Ángel Guardían island in the Gulf of

California and the Cedros island in the Pacific Coast. The San Felipe desert on the northern side of Baja California is predicted to have adequate environmental conditions for at least eight taxa. Because the PS gives more value to the potentially endemic taxa, the prediction map for those species (Fig. 6B) is similar to the top 100 prediction. The west coast of the Baja California Peninsula is highlighted again as a zone of relevance. When considering threatened taxa, priority areas are located in the state of Baja California Sur. The Sierra de la Giganta and the Magdalena Plains stand out in the analysis, as well as the southern region of the SD in the state of Sonora and the northeast SD border in Arizona.

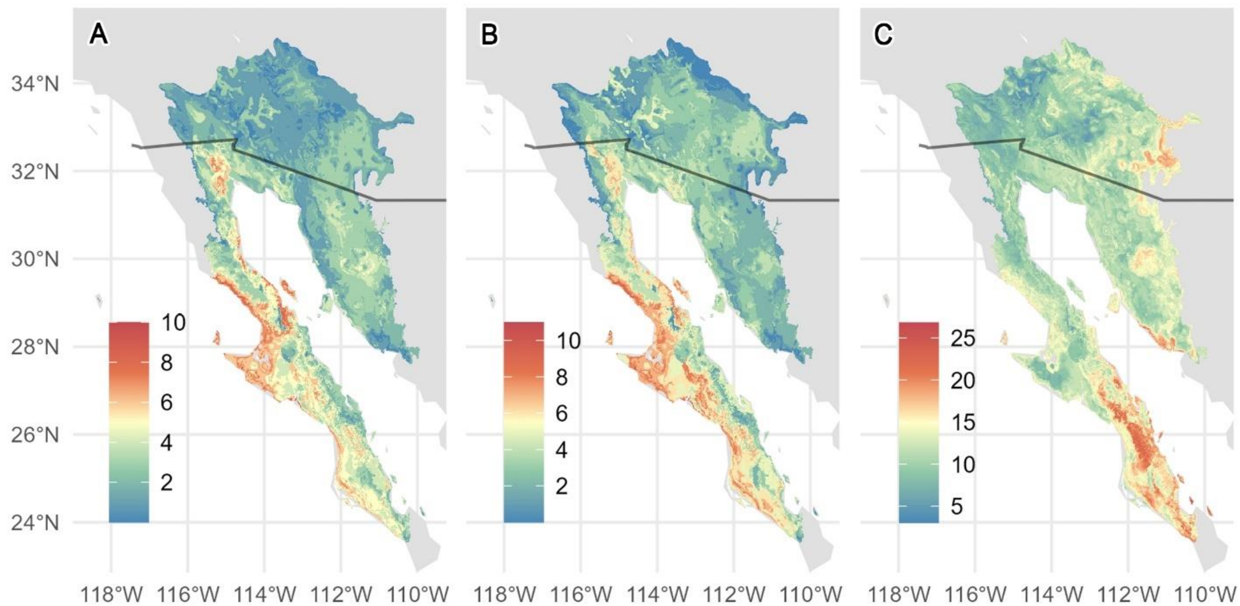

Fig. 6. Geographical prioritisation for future seed collections in the Sonoran Desert. (A) Top 100 taxa with the highest Priority Score. (B) Potentially endemic taxa (N=126). (C) Threatened taxa (N=112). The color gradient indicates the number of taxa for which the specific region has suitable climatic conditions for their potential distribution.

4. Discussion

4.1. SD flora and its representativeness in seed banks

Our results indicate that increasing the collection effort is essential to ensuring the representativeness of the SD flora in seed banks. Nearly 35% of the native taxa have been seed banked (Fig. 3), but only 10% of the total number of species have been collected inside the SD area (Table 1). Even though the arid zones of Mexico have been mentioned as priority areas for the collection and storage of seeds (van Slageren, 2003) there is still a lack of accessions in most of the Mexican part of the SD (Fig. 1). The number of projects and institutions focused on the study of desertic flora, as well as the time they have been in operation (for example, the Sonoran Desert Conservation Plan or the CPC's Partnership with the California Plant Rescue) could explain the collection bias in the United States, particularly in the state of California (Fig. 2).

Although most of the SD flora is not represented in seed banks, at least 80% is predicted to produce desiccation-tolerant seeds and thus can be cost-effectively stored in seed banks (Fig. 3). This pattern has been reported for drylands and it has been proposed that most of the arid zones species have intrinsic mechanisms that allow them to withstand low humidity conditions (Li and Pritchard, 2009; van Slageren, 2003). For species that cannot be seed banked, alternatives such as cryopreservation and cultivation in botanic gardens should be considered for their *ex situ* conservation (Pammenter and Berjak, 2013; Pence, 2013; Pence et al., 2020).

Seed collections should contain adequate material to conduct germination protocols and viability studies, as well as represent a valuable source of germplasm for reforestation projects (Breman et al., 2021; Merritt and Dixon, 2011). To achieve that, it is important to have either single high-usability accessions or multiple separate accessions. In this study, only 1.46% of the seed-banked taxa in the SD have high usability accessions (Fig. 5) and only 101 (2.5%) taxa have been collected more than five times in the SD. Besides usability, five is also the minimum number of collections needed to ensure a representative sample of the genetic diversity of the species (Liu et al., 2023), which highlights the relevance of carrying out re-samplings of some key species.

4.2. Species prioritisation

To reduce the *ex situ* conservation gap, priority species should be established depending on the objectives of the project and the available resources. In this work, endemic and threatened taxa were considered to have more relevance in the PS. Previous proposals highlight the relevance of taxa with restricted distribution, which most of the time are also under threat (Burlakova et al., 2011; Godefroid et al., 2011; Kraus et al., 2023). On the other hand, Target 8 of the Global Strategy for Plant Conservation mentions that having 75% of threatened species protected in seed banks, preferably in the country of origin, is essential to ensure their adequate representation in conservation efforts (CBD, 2012).

In the SD, only 6.3% of the potentially endemic taxa and 38.4% of the threatened species have been safeguarded. Countries such as Australia have reported that 84% of endemic flora and 67.7% of threatened species are already seed-banked (Martyn Yenson et al., 2021). As another example, almost 70% of the European flora and 27% or 44% of its species (depending on the threatened list considered) have backup collections in seed banks (Godefroid et al., 2011). These alarmingly low values for the SD flora only reinforce the idea of proposing new seed collection projects focused on these two large groups of taxa.

We propose a top 100 taxa (Supplementary Material 4) based on the PS values. Cactaceae stands out as the family with the highest number of taxa, which is relevant because there is evidence of both, the importance of this family in the composition and functioning of arid zones and the great threats faced by its species (Hultine et al., 2023, 2016; Ortega-Baes and Godínez-Alvarez, 2006). The genus *Agave* is also considered a priority, with three species included in the top 10. Their environmental and social relevance has been widely reported, mostly because of their close relationship with bats and their traditional use to produce alcoholic beverages (Burke et al., 2019; Trejo-Salazar et al., 2016). Also, most of the *Agave* species are included in the IUCN Red List (Alducin-Martínez et al., 2023).

Nevertheless, additional studies on the endemic SD taxa should be performed, especially to provide a definitive list of endemism. An increment in the sampling of these species to know the status of their populations and their geographical distribution is also necessary. Since most of the plant species have not yet been assessed in the IUCN Red List (Bachman et al., 2018), studies of the risk status of the SD species should be considered a priority. In the last few years, the IUCN Sonoran Desert Plant Specialist Group has played an important role in this mission (Rowe and Montijo, 2020), but there is still a great opportunity area to improve the conservation actions for the SD flora.

4.3. Geographical prioritisation

The spatial analyses of this project show that there is a predominance in the herbarium collections over seed bank accessions (Fig. 2). Likewise, seed collections are restricted to some specific areas, mainly in the United States, the vicinity of Hermosillo, Sonora, and the southern region of SD in Baja California Sur (Fig. 2B). Since previously seed-banked taxa have less priority according to the PS, some of these areas might not correspond to the priority zones predicted by the SDMs (Fig. 6). Previous gap analyses in China report similar disparities between the collection zones and location of *ex situ* conservation facilities and the areas of greatest species richness or conservation priorities, often driven by socioeconomic factors (Ye et al., 2023). Considering these factors can help to understand the biases present in the SD as well as propose new collection efforts in the future.

Although those collection biases can also influence the results of spatial analyses, such as the prediction of suitable areas, they are one of the best alternatives to proposing priority conservation zones (Hughes et al., 2021). For this project, most of the endemic or threatened taxa did not have at least ten presence records to generate informative SDMs, so buffered areas were created to include the information of all the taxa. Still, this indicates that carrying out botanic sampling directed at these groups of plants remains to be done.

The predicted priority areas for the 100 taxa with the highest Priority Score are mainly located in the Baja California Peninsula (Fig. 6A). This region has been reported to be highly diverse, with at least 4000 species of plants and 30% of endemism (Rebman and Roberts, 2012; Wiggins, 1980). This diversity and endemism could be explained by the Peninsula’s isolation and its environmental heterogeneity (Riemann and Ezcurra, 2005). It also explains why the prediction of potentially endemic taxa (Fig. 6B) recognises almost the same areas as a priority. According to the threatened taxa list, the areas where the environmental variables allow the distribution of the species are mainly located in Baja California Sur. The ability to create hotspot maps for each list of species is especially advantageous for seed collection purposes, as maps may be developed based on the selected priority species.

4.4. Considerations for future approaches

Depending on the project objectives, other resources may be incorporated to the gap analysis. At the same time, the weight of each individual score may be modified. For example, considering the phylogenetic diversity of the targeted species (U. Liu et al., 2020) or measuring the genetic variation of the collected populations (Chapman et al., 2019). Additional feedback from expert botanists and partners, as well as further revision of the literature on the biology and distribution of the species, should be considered when selecting the targeted species for seed banking.

Once the species for seed banking have been selected, further planning on the dates of fieldwork should be done. For example, since periods of fruiting and dispersal are not uniform in wild species, they can vary throughout the geographical distribution, influencing the maturation state of the potential accessions (Hay and Probert, 2013). Also, since summer and winter ephemeral plants are predicted to represent half of the species in the SD (Robichaux, 1999), collection dates should be considered accordingly. In the case of endangered species or taxa with restricted distribution, finding an adequate number of individuals with seeds, or even just the populations of the species, could be difficult (Godefroid et al., 2011).

In the case of the SD, one of the biggest challenges is the disparity between conservation efforts depending on the country. The influence of political divisions not only affects how species conservation is approached but physical walls or divisions can interfere with the connectivity and gene flow of populations (J. Liu et al., 2020; Titley et al., 2021). Planning and executing conservation projects with a transboundary approach is the only way in which the floristic diversity of the SD can be adequately preserved, especially in the context of climate change and the potential modification of the geographic distribution of species (Dallimer and Strange, 2015; López-Hoffman et al., 2010; Mason et al., 2020; Weiss and Overpeck, 2005).

Despite the limitations, seed banking continues to be one of the best approaches to protect species (Liu et al., 2018). The integrated conservation actions (*in situ* and *ex situ*) and the importance of global partnerships are essential to carrying out successful conservation projects (Breman et al., 2021). This study presents the first *ex situ* conservation gap analysis from the SD flora and provides a replicable methodology for identifying priority species and potential areas for collection.

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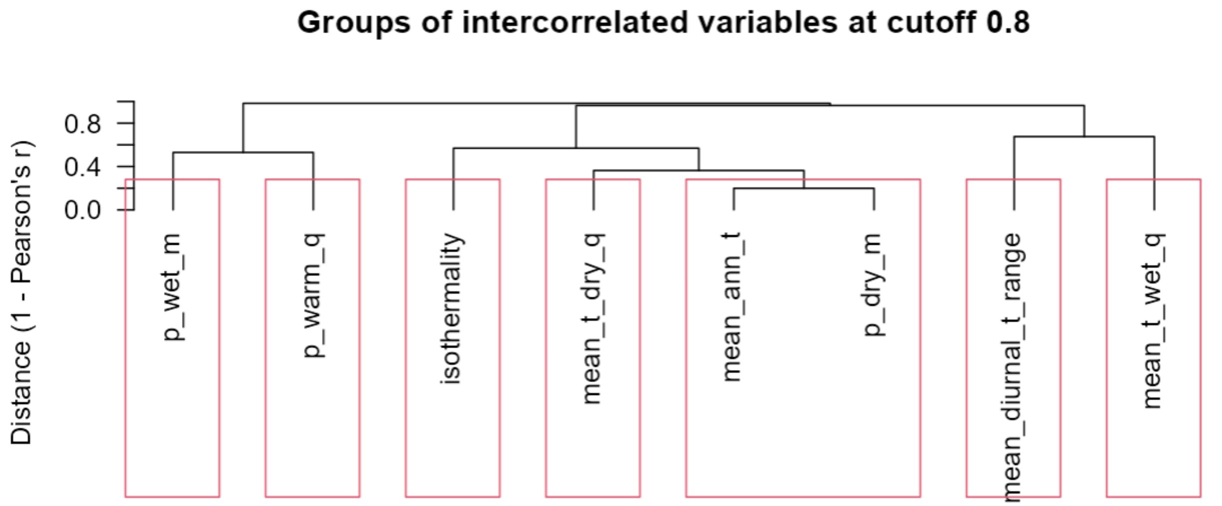
Supplementary Material 1. R packages used in this study	
R package	**Citation**
Data gathering and cleaning	
readr	Wickham, H., Hester, J., Bryan, J. 2023. _readr: Read Rectangular Text Data_. R package version 2.1.4, https://CRAN.R-project.org/package=readr
rredlist	Gearty, W., Chamberlain, S. 2022. _rredlist: 'IUCN' Red List Client_. R package version 0.7.1, https://CRAN.R-project.org/package=rredlist
rWCVP	Brown, M.J.M., Walker, B.E., Black, N., Govaerts, R., Ondo, I., Turner, R., Nic Lughadha, E. 2023. rWCVP: A companion R package to the World Checklist of Vascular Plants. New Phytologist. Version 1.0.3
tidyverse	Wickham, H., Averick, M., Bryan, J., Chang, W., McGowan, L.D., François, R., Grolemund, G., Hayes, A., Henry, L., Hester, J., Kuhn, M., Pedersen, T.L., Miller, E., Bache, S.M., Müller, K., Ooms, J., Robinson, D., Seidel, D.P., Spinu, V., Takahashi, K., Vaughan, D., Wilke, C., Woo, K., Yutani, H. 2019. "Welcome to the tidyverse." _Journal of Open-Source Software_, *4*(43), 1686. doi:10.21105/joss.01686, https://doi.org/10.21105/joss.01686
Analysis and visualisation	
corrplot	Taiyun, W., Viliam, S. 2021. R package 'corrplot': Visualization of a Correlation Matrix (Version 0.92), https://github.com/taiyun/corrplot
flexsdm	Velazco, S.J.E., Rose, M.B., Andrade, A.F.A., Minoli, I., Franklin, J. 2022. flexsdm: An R package for supporting a comprehensive and flexible species distribution modelling workflow. Methods in Ecology and Evolution, 13(8) 1661-1669. https://doi.org/10.1111/2041-210X.13874
ggplot2	Wickham, H. 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag New York
ggthemes	Arnold, J. 2021. _ggthemes: Extra Themes, Scales and Geoms for 'ggplot2'_. R package version 4.2.4, https://CRAN.R-project.org/package=ggthemes
hrbrthemes	Rudis, B. 2020. _hrbrthemes: Additional Themes, Theme Components and Utilities for 'ggplot2'_. R package version 0.8.0, https://CRAN.R-project.org/package=hrbrthemes
patchwork	Pedersen, T. 2022. _patchwork: The Composer of Plots_. R package version 1.1.2, https://CRAN.Rproject.org/package=patchwork
plotROC	Sachs, M.C. 2017. plotROC: A Tool for Plotting ROC Curves. Journal of Statistical Software, Code Snippets, 79(2), 1-19. doi:10.18637/jss.v079.c02
purrr	Wickham, H., Henry, L. 2023. _purrr: Functional Programming Tools_. R package version 1.0.1, https://CRAN.R-project.org/package=purrr
raster	Hijmans, R. 2023. _raster: Geographic Data Analysis and Modeling_. R package version 3.6-20, https://CRAN.R-project.org/package=raster
rgbif	Chamberlain, S., Barve, V., Mcglinn, D., Oldoni, D., Desmet, P., Geffert, L., Ram, K. 2023. _rgbif: Interface to the Global Biodiversity Information Facility API_. R package version 3.7.7, https://CRAN.R-project.org/package=rgbif
rnaturalearth	Massicotte, P., South, A. 2023. _rnaturalearth: World Map Data from Natural Earth_. R package version 0.3.2, https://CRAN.R-project.org/package=rnaturalearth
SDMtune	Vignali, S., Barras, A. G., Arlettaz, R., Braunisch, V. 2022. SDMtune: An

	R package to tune and evaluate species distribution models. Ecology and Evolution, 10(20), 11488–11506, https://doi.org/10.1002/ece3.6786
sf	Pebesma, E., Bivand, R. 2023. Spatial Data Science: With Applications in R (1st ed.). Chapman and Hall/CRC. https://doi.org/10.1201/9780429459016
terra	Hijmans, R. 2023. _terra: Spatial Data Analysis_. R package version 1.7-23, https://CRAN.R-project.org/package=terra
tidyterra	Hernangomez, D. 2023. tidyterra: tidyverse Methods and ggplot2 Helpers for terra Objects. https://doi.org/10.5281/zenodo.6572471, https://dieghernan.github.io/tidyterra/
viridis	Garnier, S., Ross, N., Rudis, R., Camargo, A.P., Sciaini, M., Scherer, C. 2021. Rvision - Colorblind-Friendly Color Maps for R. R package version 0.6.2.
virtualspecies	Leroy, B., Meynard, C.N., Bellard, C., Courchamp, F. 2015. “virtualspecies, an R package to generate virtual species distributions.” _Ecography_. doi:10.1111/ecog.01388

Supplementary Material 2. Environmental variables used on the SDMs



List of variables	
Precipitation of Wettest Month	Annual Mean Temperature
Precipitation of Warmest Quarter	Precipitation of the driest Month
Isothermality	Mean Diurnal Temp Range
Mean Temperature of Driest Quarter	Mean Temperature of Wettest Quarter

Supplementary Material 3. List of potentially endemic taxa from the Sonoran Desert	
Family	**Taxon name**
Acanthaceae	*Ruellia comonduensis*
	Justicia californica var. *californica*
Amaranthaceae	*Amaranthus tucsonensis*
Anacardiaceae	*Rhus kearneyi* subsp. *kearneyi*
Apiaceae	*Spermolepis infernensis*
Apocynaceae	*Vallesia baileyana*
Asparagaceae	*Agave sobria* subsp. *roseana*
	Agave gigantensis
	Agave vizcainoensis
	Agave azurea
	Agave zebra
	Agave pelona
	Agave turneri
Asteraceae	*Amauria carterae*
	Hofmeisteria anomalochaeta
	Verbesina oligocephala
	Acourtia palmeri
	Bajacalia moranii
	Verbesina felgeri
	Verbesina palmeri
	Hofmeisteria filifolia
	Encelia ravenii
	Heterotheca thiniicola
	Senecio pinacatensis
	Perityle ajoensis
	Chaenactis carphoclinia var. *peirsonii*
	Xylorhiza cognata
	Coreocarpus sonoranus var. *libranus*
Berberidaceae	*Berberis harrisoniana*
Boraginaceae	*Cryptantha maritima* var. *cedrosensis*
	Phacelia pauciflora
	Cryptantha maritima var. *vizcainensis*
	Cryptantha pondii
	Pholisma sonorae
Brassicaceae	*Lepidium lasiocarpum* subsp. *palmeri*
	Lyrocarpa linearifolia
	Dimorphocarpa pinnatifida

Cactaceae	*Cochemiea cerralboa*
	Cylindropuntia molesta subsp. *clavellina*
	Cylindropuntia ciribe
	Grusonia robertsii
	Cochemiea boolii
	Ferocactus emoryi subsp. *covillei*
	Echinocereus grandis
	Cochemiea estebanensis
	Cylindropuntia libertadensis
	Cylindropuntia ganderi subsp. *catavinensis*
	Grusonia marenae
	Cochemiea angelensis
	Echinocereus ferreirianus subsp. *lindsayi*
	Cochemiea thornberi
	Ferocactus emoryi subsp. *emoryi*
	Cylindropuntia × *congesta*
	Cylindropuntia × *kelvinensis*
	Escobaria alversonii
Campanulaceae	*Nemacladus australis*
Cistaceae	*Crocanthemum nutans*
Crassulaceae	*Dudleya rubens*
	Dudleya linearis
	Dudleya pachyphytum
	Dudleya cymosa subsp. *cymosa*
Cucurbitaceae	*Cucurbita cordata*
	Echinopepon minimus var. *minimus*
	Cucurbita cylindrata
Euphorbiaceae	*Acalypha saxicola*
	Euphorbia platysperma
Fabaceae	*Acmispon flexuosus*
	Acmispon nudatus
	Astragalus orcuttianus
	Hoffmannseggia peninsularis
	Lupinus arizonicus subsp. *setosissimus*
	Astragalus magdalenae var. peirsonii
	Lupinus brevior
	Astragalus newberryi var. *aquarii*
	Parkinsonia florida subsp. *peninsulare*
Lamiaceae	*Condea anitae*
	Monardella thymifolia

	Salvia palmetorum
	Hedeoma tenuiflora
	Salvia greatae
Loasaceae	*Mentzelia longiloba* var. *pinacatensis*
Malpighiaceae	*Malpighia watsonii*
Malvaceae	*Allobriquetia sonorae*
Martyniaceae	*Proboscidea parviflora* subsp. *gracillima*
	Martynia palmeri
Nyctaginaceae	*Mirabilis greenei*
	Mirabilis oligantha
Olacaceae	*Ximenia glauca*
Onagraceae	*Xylonagra arborea* subsp. *wigginsii*
Phrymaceae	*Erythranthe austrolatidens*
	Erythranthe regni
Plantaginaceae	*Mecardonia exilis*
	Penstemon vizcainensis
	Sairocarpus virga
Poaceae	*Distichlis bajaensis*
Polemoniaceae	*Dayia scabra*
	Dayia grantii
	Linanthus viscainensis
	Bryantiella palmeri
Polygonaceae	*Eriogonum pilosum*
	Eriogonum preclarum
	Eriogonum fasciculatum var. *emphereium*
	Eriogonum intricatum
	Chorizanthe flava
	Eriogonum wrightii var. *taxifolium*
	Eriogonum pondii var. *pondii*
	Chorizanthe mutabilis
	Chorizanthe rosulenta
	Eriogonum moranii
	Eriogonum angelense
Rubiaceae	*Galium mechudoense*
	Spermacoce lagunensis
	Galium volcanense
	Galium moranii subsp. *aculeolatum*
	Galium moranii
	Stenotis asperuloides var. *brandegeeana*
	Stenaria sanchezii

Rutaceae	*Thamnosma trifoliata*
Solanaceae	*Lycium densifolium*
	Lycium macrodon var. *macrodon*
	Lycium californicum var. *arizonicum*
	Datura arenicola
Verbenaceae	*Citharexylum roxanae*
	Verbena calinfera
	Citharexylum shrevei
Zygophyllaceae	*Viscainoa pinnata*

Supplementary Material 4. List of the 100 taxa with the highest values in the Priority Score		
Ranking	**Taxon name**	**PS**
1	*Agave pelona*	0.7748176
2	*Agave turneri*	0.7186245
3	*Vallesia baileyana*	0.7171772
4	*Agave zebra*	0.6998176
5	*Cochemiea boolii*	0.6449777
6	*Mirabilis greenei*	0.6374452
7	*Encelia ravenii*	0.6249030
8	*Lupinus brevior*	0.6248633
9	*Thamnosma trifoliata*	0.6247821
10	*Galium mechudoense*	0.6247392
11	*Grusonia marenae*	0.6244001
12	*Salvia palmetorum*	0.6241797
13	*Citharexylum shrevei*	0.6241074
14	*Stenaria sanchezii*	0.6232110
15	*Malpighia watsonii*	0.5830138
16	*Verbesina felgeri*	0.5623940
17	*Agave azurea*	0.5621962
18	*Grusonia robertsii*	0.5618948
19	*Cucurbita cylindrata*	0.5373470
20	*Agave gigantensis*	0.5248378
21	*Galium moranii*	0.5204545
22	*Agave vizcainoensis*	0.5202774
23	*Cochemiea angelensis*	0.5200333
24	*Cochemiea cerralboa*	0.5200225
25	*Swietenia humilis*	0.5062500
26	*Echinopepon minimus* var. *minimus*	0.5000000
27	*Allobriquetia sonorae*	0.5000000
28	*Ferocactus emoryi* subsp. *covillei*	0.5000000
29	*Rhus kearneyi* subsp. *kearneyi*	0.5000000
30	*Lycium californicum* var. *arizonicum*	0.5000000
31	*Dudleya cymosa* subsp. *cymosa*	0.5000000
32	*Astragalus newberryi* var. *aquarii*	0.5000000
33	*Stenotis asperuloides* var. *brandegeeana*	0.5000000
34	*Coreocarpus sonoranus* var. *libranus*	0.5000000
35	*Escobaria alversonii*	0.5000000
36	*Chorizanthe rosulenta*	0.4999321

37	*Phacelia pauciflora*	0.4999264
38	*Ruellia comonduensis*	0.4999210
39	*Hedeoma tenuiflora*	0.4999209
40	*Monardella thymifolia*	0.4999126
41	*Eriogonum pilosum*	0.4999114
42	*Acourtia palmeri*	0.4999114
43	*Verbena calinfera*	0.4999114
44	*Mirabilis oligantha*	0.4999084
45	*Galium volcanense*	0.4999066
46	*Verbesina palmeri*	0.4999066
47	*Senecio pinacatensis*	0.4999036
48	*Penstemon vizcainensis*	0.4999021
49	*Dudleya linearis*	0.4998935
50	*Dudleya pachyphytum*	0.4998932
51	*Linanthus viscainensis*	0.4998909
52	*Chorizanthe mutabilis*	0.4998791
53	*Heterotheca thiniicola*	0.4998779
54	*Cryptantha pondii*	0.4998745
55	*Chorizanthe flava*	0.4998701
56	*Dudleya rubens*	0.4998602
57	*Astragalus orcuttianus*	0.4998384
58	*Amaranthus tucsonensis*	0.4998334
59	*Spermacoce lagunensis*	0.4998179
60	*Verbesina oligocephala*	0.4998144
61	*Perityle ajoensis*	0.4997821
62	*Euphorbia platysperma*	0.4997723
63	*Datura arenicola*	0.4997392
64	*Eriogonum moranii*	0.4997363
65	*Lycium densifolium*	0.4997012
66	*Eriogonum preclarum*	0.4996476
67	*Eriogonum intricatum*	0.4996462
68	*Eriogonum angelense*	0.4996010
69	*Hoffmannseggia peninsularis*	0.4994551
70	*Amauria carterae*	0.4994200
71	*Bajacalia moranii*	0.4994116
72	*Bryantiella palmeri*	0.4994116
73	*Crocanthemum nutans*	0.4994116
74	*Hofmeisteria filifolia*	0.4994116
75	*Nemacladus australis*	0.4994086
76	*Cochemiea thornberi*	0.4994086

77	*Dimorphocarpa pinnatifida*	0.4994001
78	*Echinocereus grandis*	0.4993948
79	*Dayia scabra*	0.4993931
80	*Lyrocarpa linearifolia*	0.4993931
81	*Mecardonia exilis*	0.4993738
82	*Dayia grantii*	0.4993697
83	*Distichlis bajaensis*	0.4993404
84	*Acmispon nudatus*	0.4993021
85	*Acmispon flexuosus*	0.4992920
86	*Sairocarpus virga*	0.4992666
87	*Citharexylum roxanae*	0.4991428
88	*Hofmeisteria anomalochaeta*	0.4986101
89	*Cylindropuntia ciribe*	0.4984399
90	*Cochemiea estebanensis*	0.4984399
91	*Martynia palmeri*	0.4984399
92	*Cylindropuntia libertadensis*	0.4979493
93	*Lophophora williamsii*	0.4955078
94	*Viscainoa pinnata*	0.4942321
95	*Ximenia glauca*	0.4927364
96	*Cucurbita cordata*	0.4875000
97	*Acalypha saxicola*	0.4845721
98	*Opuntia ficus-indica*	0.4750000
99	*Hibiscus tiliaceus*	0.4747038
100	*Bernardia gentryana*	0.4659854