

Cacti in distress: how to enhance ex situ conservation strategies through living collections

THAÍS MOREIRA HIDALGO DE ALMEIDA^{*1,2} 
DIEGO RAFAEL GONZAGA^{1,3}  and ARIANE LUNA PEIXOTO^{1,2} 

Abstract Living plant collections play a crucial role in ex situ conservation, but their conservation value hinges on assessment of their composition, data quality and on strategic planning for optimization of the collection that takes into account species diversity, conservation status and allocation of resources. Cactaceae is one of the most threatened plant families globally and has a broad distribution in Brazil, with two of the seven centres of diversity for this group and a total of 276 known species. Climate change could escalate the threat to cacti, potentially placing 90% of species at risk by 2050. We conducted a case study of Cactaceae in the living Cactarium collection of the Rio de Janeiro Botanic Garden, evaluating the diversity of the collection and recommending strategic actions to enhance its conservation value. In 2022, we inventoried all specimens in the collection and cross-referenced them with the institutional specimen registry system, Jabot. The collection contains 156 cacti species that naturally occur in Brazil (57% of the total), including 43 species categorized as threatened on the Brazilian Red List and 57 categorized as threatened on the IUCN Red List. We recommend research to map cacti species that are threatened but not covered by in situ conservation in the country, list the priority species for acquisition by the collection, and make recommendations that will facilitate improved contribution of the Rio de Janeiro Botanic Garden to the conservation of the Brazilian flora.

Keywords Botanic gardens, Cactaceae, ex situ conservation, flora of Brazil, Red List, Rio de Janeiro Botanic Garden, succulent plants, threatened species

The supplementary material for this article is available at doi.org/10.1017/S0030605324000012

Introduction

Ex situ conservation initiatives developed by botanic gardens have proven effective through the establishment of

long-term ecological research and species conservation programmes (Hultine et al., 2016). Well-curated living plant collections play a crucial role in supporting species conservation through research, horticulture and education whilst also providing seeds and plants for reintroduction (BGCI, 2014). These collections are expected to become increasingly important for conserving plant diversity, but to maximize their value a careful assessment of these collections is required, ensuring both species and genetic diversity, with a specific emphasis on threatened species (Grace & Majure, 2017). Botanic gardens directly support the Global Strategy for Plant Conservation, particularly its Target 8, which aims to conserve 75% of threatened species in ex situ collections, preferably in their home countries, with at least 20% being available for recovery and restoration programmes (Wyse Jackson & Kennedy, 2009; CBD, 2011).

At the Rio de Janeiro Botanic Garden, one of the cultivated collections is the Cacti and Succulents Themed Collection (referred to here as the Cactarium), which brings together succulent species from various botanical families. Approximately 31% of Cactaceae are threatened globally (Goettsch et al., 2015), and the family Cactaceae is well represented in this collection. This family is particularly important in Brazil, where two of the seven global centres of Cactaceae diversity (the Caatinga and Atlantic Forest) are located (Barthlott et al., 2015), with 38 genera, including 15 endemic, and a total of 276 species and 102 subspecies (Flora e Funga do Brasil, 2023). The diversity and endemism of this family form a compelling argument for its conservation (Zappi et al., 2011).

Brazil has dedicated 24% of its land to the protection of native vegetation (Embrapa, 2020). However, there are reports of illegal extraction (Caitano et al., 2022), and some important areas for in situ conservation remain unprotected (Diniz et al., 2017). Amongst the Cactaceae, 46 native species (of which 17 are categorized as Critically Endangered, 19 as Endangered and three as Vulnerable) have distribution ranges entirely outside these protected areas, probably a result of the limited geographical distribution and high micro-endemism amongst cacti (Goettsch et al., 2019; IUCN, 2023), and therefore lack in situ conservation.

One of the predicted effects of global climate change is that arid and semi-arid environments will cover over half of the terrestrial surface of the Earth by the end of this century, a 45% increase compared to today (Huang et al., 2016). Although these environments may favour cacti, most of which have crassulacean acid metabolism, the impact of

*Corresponding author, thidalgo@jbrj.gov.br

¹Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, Jardim Botânico, Rio de Janeiro, Brazil

²Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, Escola Nacional de Botânica Tropical, Rio de Janeiro, Brazil

³Universidade Federal do Oeste do Pará, Instituto de Biodiversidade e Florestas, Santarém, Brazil

Received 14 April 2023. Revision requested 26 September 2023.

Accepted 5 January 2024. First published online 17 October 2024.

climate change on cacti will go beyond physiology. Ecological factors, including dependence on pollinators and nurse plants, also play a key role in their survival (Reyes-García & Andrade, 2009; Goettsch et al., 2015). Some authors have suggested cacti are not vulnerable to the potential impacts of climate change (Larios et al., 2020), but others have emphasized the risks they face because of low population growth rates (Shryock et al., 2014) and their limited natural ranges (Barthlott et al., 2015; Hultine et al., 2016), which could affect population regeneration and success in reintroduction programmes (Carrillo-Angeles et al., 2016).

The uncertainty that surrounds the potential impact of climate change on cactus diversity is a challenge for conservation planning. Nevertheless, the number of threatened species of Cactaceae is projected to rise, particularly in hotspots such as the Atlantic Forest and Caatinga, with up to 90% of species potentially threatened by 2050 (Pillet et al., 2022).

Numerous globally threatened cacti, including Critically Endangered species, have not yet been secured in ex situ collections (Oldfield & Hunt, 2010). The Cactarium collection of the Rio de Janeiro Botanic Garden, established in 1913 (Brasil, 1914), has recently strengthened its contribution to ex situ conservation, including prioritizing species diversity, mapping in situ populations and conducting field surveys. This has resulted in an increase in the number of threatened species present in the collection from 11 in 2014 to 64 in 2019 (Gonzaga et al., 2019).

Because of the importance of this collection, assessing its current holdings and planning future conservation actions

are vital to enable the Rio de Janeiro Botanic Garden to support the effective conservation of cacti both in the wild and in cultivated collections. Here we evaluate the diversity of the collection and recommend strategic actions to enhance its conservation value.

Methods

The c. 3,000 m² Cactarium of the Rio de Janeiro Botanic Garden (Gonzaga & Reis, 2019) is located in the Atlantic Forest and contains species of Cactaceae and other families. Specimens are cultivated in three greenhouses, a pergola and external beds for public viewing, and two further greenhouses, a pergola for shade plants and a technical reserve area for research. Specimens for public viewing (Plate 1a–c) are planted in the ground and arranged in groups for landscaping and educational purposes. Research specimens are maintained in vases (Plate 1d,e) for conservation and study. We inventoried all plants in this living collection during January–May 2022, counting all specimens and recording label data in a digital database. Specimens of Cactaceae were the most abundant in the collection, and identifications were confirmed by the curator of the Cactarium, who is a taxonomist specializing in this family.

We consulted information on the inventoried plants in the institutional specimen registry system, Jabot (Silva et al., 2017). We checked and updated scientific names, following *Flora e Funga do Brasil* (2023) for native species, and the Tropicos database (Tropicos, 2023) and the Plants



PLATE 1 Rio de Janeiro Botanic Garden Cactarium, Brazil: (a) aerial view, (b) greenhouse for visitation, (c) outdoor flower beds, (d) pergola with the shade plant collection, (e) greenhouse for research. Photos: (a) A. Machado; (b–e) T.M.H. Almeida.

of the World Online database (POWO, 2023) for exotic species. We used Flora e Funga do Brasil (2023) as the source of information on the status of species (native, endemic, exotic) and their distribution in phytogeographical domains.

We defined knowledge of the municipality of origin of each specimen as representing provenance data and we used the term ‘duplicate’ to refer to different specimens of the same taxon and provenance data (locality and/or collector) or to specimens of the same taxon but without known provenance data. In a second database we listed all native Brazilian species and subspecies of Cactaceae, following Flora e Funga do Brasil (2023), with information on the species name, endemism in Brazil and occurrence in phytogeographical domains, to map the cultivated diversity in the collection.

For the threatened species analysis we considered two systems: the Brazilian Red List (Brasil, 2022) and the IUCN Red List (IUCN, 2023). We evaluated ex situ conservation value by analysing the provenance data of the specimens and taxa in the collection, and comparing these data with those on the two Red Lists.

Results

We inventoried a total of 5,227 specimens of 413 taxa (Supplementary Table 1). Cactaceae was the most numerous, with 249 species (native and exotic) and 3,303 specimens, representing 63% of the cultivated plants (Table 1). Among these, 1,113 specimens and 93 species are exotic. Other cultivated plants belong to 18 additional families (Supplementary Table 2). Of 739 records in cultivation at the time of the inventory (some records are represented by more than one specimen), we identified 650 (88%) to species or subspecies, 74 (10%) only to genus and 15 (2%) only to family.

Many species had numerous duplicates in cultivation, both specimens with known provenance data and specimens that lack provenance data and have been in the collection for a long time. Notably, the species with the most holdings are mostly represented by specimens of unknown provenance. For example, *Pilosocereus arrabidae* (Lem.) Byles & Rowley had the highest number of duplicates (173). Sixteen other species had > 40 specimens in the collection (Table 2), requiring significant space and maintenance. Of these 16 species, seven did not have voucher specimens in the institutional herbarium.

Of the 276 Brazilian Cactaceae species (Flora e Funga do Brasil, 2023), 156 (57%) are in cultivation in the Cactarium, with 133 (48%) having known provenance data. Considering species and subspecies, 170 taxa are in cultivation (141 with provenance data). All Brazilian phytogeographical domains are represented in the collection: Cerrado with 68 species (68% of the species of Cactaceae that occur in this domain), Atlantic Forest with 70 species (63%), Caatinga with 68 species (61%) and Pantanal with

16 species (55%). These four domains have the highest representation, and the Amazon and the Pampa domains are the least represented, with five (36%) and nine species (16%), respectively. Of the native species and subspecies not in the collection, 109 are endemic to Brazil, distributed across the phytogeographical domains: 10 in the Amazon, 43 in the Caatinga, 30 in the Cerrado, 40 in the Atlantic Forest, 49 in the Pampa and 13 in the Pantanal.

Of the 78 species of Cactaceae categorized as threatened on the Brazilian Red List (12 Critically Endangered, 46 Endangered and 20 Vulnerable; Brasil, 2022), 43 (55%) are in cultivation in the Cactarium (eight Critically Endangered, 25 Endangered and 10 Vulnerable), of which 36 species (46% of the total) have provenance data (Plate 2, Table 3). Of the 113 species of Cactaceae in Brazil categorized as threatened on the IUCN Red List (28 Critically Endangered, 52 Endangered and 33 Vulnerable; IUCN, 2023), 57 (50%) are in cultivation in the Cactarium (14 Critically Endangered, 26 Endangered and 17 Vulnerable), of which 48 species (43% of the total) have provenance data. On the two Red Lists combined, 74 species in cultivation in the Cactarium are categorized as threatened.

Discussion

Since its establishment in 1913, the Cactaceae collection at the Rio de Janeiro Botanic Garden has gathered many specimens for which provenance data have been lost. Although not useful for conservation, these specimens are now well adapted to the local climatic conditions of the Garden and contribute to the Garden’s other missions, such as environmental education and awareness, research and public contemplation.

Although we considered the municipality of origin as known provenance data, we acknowledge that additional information is important, including not only taxonomic data but also the biotic and abiotic characteristics of the collection site, the collection date, geographical coordinates and the herbarium voucher specimen associated with the collection. These data establish a connection between the taxon and its natural habitat, potentially providing insights that could be useful for species reintroduction (Gratzfeld, 2016).

Species of Cactaceae are generally underrepresented in herbarium collections because of the difficulty of preparing specimens and the risk posed by their spines and glochids (Walters et al., 2011). Ninety-five species in cultivation in the Rio de Janeiro Botanic Garden are absent from the Garden’s herbarium (herbarium code RB). It is, however, crucial to deposit material in the herbarium, even if doing so requires sacrificing plants, as herbarium voucher specimens provide essential information on the species and their traits, phenology, environment and occurrence, supporting evidence-based conservation decisions (Greve et al., 2016).

TABLE 1 The 133 species of Cactaceae with known provenance data in cultivation in the Rio de Janeiro Botanic Garden Cactarium, Brazil (Plate 1), as of January–May 2022, with the number of specimens in cultivation, whether a voucher specimen is present in the institute's herbarium (herbarium code RB), and categorization on the Brazilian (Brasil, 2022) and global (IUCN, 2023) Red Lists for species assessed as threatened.

Taxon	Number of specimens	Voucher present	Brazil Red List ¹	IUCN Red List ¹
<i>Arrojadoa albiflora</i> Buining & Brederoo	2	No		CR
<i>Arrojadoa dinae</i> Buining & Brederoo	1	No		VU
<i>Arrojadoa eriocaulis</i> Buining & Brederoo	1	Yes	EN	EN
<i>Arrojadoa marylandiae</i> Soares Filho & M. Machado	2	No		CR
<i>Arrojadoa penicillata</i> (Gürke) Britton & Rose	1	No		
<i>Arrojadoa rhodantha</i> (Gürke) Britton & Rose	4	No		
<i>Arthrocereus glaziovii</i> (K.Schum.) N.P. Taylor & Zappi	4	Yes	EN	EN
<i>Arthrocereus grandiflorus</i> D.R. Gonzaga & Menini Neto	7	Yes		
<i>Arthrocereus melanurus</i> (K. Schum.) Diers et al., subsp. <i>melanurus</i>	6	Yes	EN	VU
<i>Arthrocereus melanurus</i> subsp. <i>odorus</i> (Ritter) N.P. Taylor & Zappi	1	Yes	EN	
<i>Arthrocereus rondonianus</i> Backeb. & Voll	10	Yes	EN	
<i>Arthrocereus spinosissimus</i> (Buining & Brederoo) Ritter	5	Yes		
<i>Brasilicereus estevesii</i> (Hofacker & P.J. Braun) N.P. Taylor & M. Machado	2	No		VU
<i>Brasilicereus markgrafii</i> Backeb. & Voll	5	Yes	EN	VU
<i>Brasiliopuntia brasiliensis</i> (Willd.) A. Berger	10	Yes		
<i>Cereus albicaulis</i> (Britton & Rose) Luetzelb.	2	No		
<i>Cereus bicolor</i> Rizzini & A. Mattos	2	No		
<i>Cereus fernambucensis</i> Lem. subsp. <i>fernambucensis</i>	20	Yes		
<i>Cereus fernambucensis</i> subsp. <i>sericifer</i> (F. Ritter) N.P. Taylor & Zappi	2	Yes		
<i>Cereus jamacaru</i> DC	10	Yes		
<i>Cereus mirabella</i> N.P. Taylor	1	No	VU	EN
<i>Cereus saddianus</i> (Rizzini & Mattos) P.J. Braun	3	No		CR
<i>Cipocereus bradei</i> (Backeb. & Voll) Zappi & N.P. Taylor	10	Yes	VU	VU
<i>Cipocereus crassisepalus</i> (Buining & Brederoo) Zappi & N.P. Taylor	1	No	EN	EN
<i>Cipocereus minensis</i> (Werderm.) Ritter subsp. <i>minensis</i>	22	Yes	VU	
<i>Cipocereus minensis</i> subsp. <i>leiocarpus</i> N.P. Taylor & Zappi	2	No		
<i>Cipocereus pleurocarpus</i> F. Ritter	2	Yes		
<i>Cipocereus pusilliflorus</i> (Ritter) Zappi & N.P. Taylor	3	No	CR	CR
<i>Coleocephalocereus braunii</i> Diers & Esteves	2	No		CR
<i>Coleocephalocereus decumbens</i> Ritter	3	No		
<i>Coleocephalocereus diersianus</i> P.J. Braun & Esteves Pereira	1	No		CR
<i>Coleocephalocereus fluminensis</i> (Miq.) Backeb.	9	No		
<i>Coleocephalocereus goebelianus</i> (Vaupe) Buining	2	No		EN
<i>Coleocephalocereus pluricostatus</i> Buining & Brederoo	1	No		EN
<i>Discocactus catingicola</i> Buining & Brederoo	1	Yes	VU	
<i>Discocactus heptacanthus</i> (Rodrigues) Britton & Rose	3	No		
<i>Discocactus horstii</i> Buining & Brederoo	2	No	CR	VU
<i>Discocactus placentiformis</i> (Lehm.) K. Schum.	15	Yes		
<i>Discocactus pseudoinsignis</i> N.P. Taylor & Zappi	2	No	CR	EN
<i>Discocactus zehntneri</i> Britton & Rose subsp. <i>zehntneri</i>	3	No		CR
<i>Discocactus zehntneri</i> subsp. <i>boomianus</i> (Buining & Brederoo) N.P. Taylor & Zappi	10	Yes	VU	VU
<i>Discocactus zehntneri</i> subsp. <i>petr-halfari</i> (Zachar) M.R. Santos & M.C. Machado	1	No	EN	EN
<i>Epiphyllum phyllanthus</i> (L.) Haw.	22	Yes	VU	
<i>Estevesia alex-bragae</i> P.J. Braun & Esteves	2	No		
<i>Facheiroa cephalomelana</i> subsp. <i>estevesii</i> (P.J. Braun) N.P. Taylor & Zappi	2	Yes		
<i>Frailia pumila</i> (Lem.) Britton & Rose	3	No	CR	CR
<i>Harrisia adscendens</i> (Gürke) Britton & Rose	2	No		CR
<i>Hattoria salicornioides</i> (Haw.) Britton & Rose	3	No		
<i>Leocereus bahiensis</i> Britton & Rose	1	No		CR
<i>Lepismium cruciforme</i> (Vell.) Miq	9	No		
<i>Lepismium houlettianum</i> (Lem.) Barthlott	2	No		EN
<i>Leuenbergeria aureiflora</i> (Ritter) Lodé	1	No		EN

TABLE 1 (Cont.)

Taxon	Number of specimens	Voucher present	Brazil Red List ¹	IUCN Red List ¹
<i>Melocactus bahiensis</i> (Britton & Rose) Luetzelb.	1	Yes	VU	
<i>Melocactus concinnus</i> Buining & Brederoo	3	No		
<i>Melocactus ernestii</i> subsp. <i>longicarpus</i> (Buining & Brederoo) N.P. Taylor	2	No	CR	VU
<i>Melocactus glaucescens</i> Buining & Brederoo	15	Yes		
<i>Melocactus oreas</i> Miq.	2	No	CR	EN
<i>Melocactus pachyacanthus</i> Buining & Brederoo subsp. <i>pachyacanthus</i>	3	No		CR
<i>Melocactus pachyacanthus</i> subsp. <i>viridis</i> N.P. Taylor	10	Yes	VU	VU
<i>Melocactus salvadorensis</i> Werderm.	4	No		VU
<i>Melocactus sergipensis</i> N.P. Taylor & M.V. Meiado	3	No		
<i>Melocactus violaceus</i> Pfeiff. subsp. <i>violaceus</i>	1	No	VU	
<i>Melocactus violaceus</i> subsp. <i>ritteri</i> N.P. Taylor	1	No	EN	
<i>Melocactus violaceus</i> subsp. <i>margaritaceus</i> N.P. Taylor	1	No		
<i>Micranthocereus albicephalus</i> (Buining & Brederoo) F. Ritter	1	No	EN	VU
<i>Micranthocereus auriazureus</i> Buining & Brederoo	1	No	EN	EN
<i>Micranthocereus estevesii</i> (Buining & Brederoo) F. Ritter	1	No		
<i>Micranthocereus flaviflorus</i> Buining & Brederoo	3	No		
<i>Micranthocereus purpureus</i> (Gürke) F. Ritter	1	No		
<i>Micranthocereus streckeri</i> Van Heek & Van Crieck.	2	No	CR	CR
<i>Micranthocereus violaciflorus</i> Buining	3	Yes	EN	EN
<i>Nopalea cochenillifera</i> (L.) Salm-Dyck	1	Yes		
<i>Opuntia monacantha</i> Haw.	8	Yes		
<i>Parodia ottonis</i> (Lehm.) N.P. Taylor	2	No		
<i>Pereskia aculeata</i> Mill.	12	Yes		
<i>Pereskia bahiensis</i> Gürke	8	No		
<i>Pereskia stenantha</i> Ritter	1	No		
<i>Pilosocereus arrabidaei</i> (Lem.) Byles & Rowley	4	Yes		VU
<i>Pilosocereus aureispinus</i> (Buining & Brederoo) Ritter	2	No		
<i>Pilosocereus aurisetus</i> subsp. <i>aurilanus</i> (F. Ritter) D.C. Zappi	2	No	EN	
<i>Pilosocereus aurisetus</i> (Werderm.) Byles & G.D. Rowley subsp. <i>aurisetus</i>	4	No		
<i>Pilosocereus azulensis</i> N.P. Taylor & Zappi	1	No	CR	CR
<i>Pilosocereus brasiliensis</i> (Britton & Rose) Backeb.	18	Yes		
<i>Pilosocereus densiareolatus</i> F. Ritter	2	No		
<i>Pilosocereus flexibilispinus</i> P.J. Braun & Esteves	1	No		
<i>Pilosocereus floccosus</i> Byles & Rowley	3	Yes		
<i>Pilosocereus frewenii</i> Zappi & N.P. Taylor	2	No		
<i>Pilosocereus fulvilanatus</i> (Buining & Brederoo) Ritter	6	Yes	EN	
<i>Pilosocereus machrisii</i> (E.Y. Dawson) Backeb.	1	Yes		
<i>Pilosocereus magnificus</i> (Buining & Brederoo) Ritter	1	No	EN	EN
<i>Pilosocereus pachycladus</i> F. Ritter	3	No		
<i>Pilosocereus parvus</i> (Diers & Esteves) P.J. Braun	3	No		VU
<i>Pilosocereus pentaedrophorus</i> (Cels) Byles & Rowley	1	No		
<i>Pilosocereus piauhensis</i> (Gürke) Byles & G.D. Rowley	2	No		
<i>Pilosocereus tuberculatus</i> (Werderm.) Byles & G.D. Rowley	1	No		
<i>Pilosocereus ulei</i> (K.Schum.) Byles & G.D. Rowley	4	No	EN	EN
<i>Praecereus saxicola</i> (Morong) N.P. Taylor	3	No		
<i>Quiabentia zehntneri</i> (Britton & Rose) Britton & Rose	7	Yes		
<i>Rhipsalis baccifera</i> (J.M. Muell.) Stearn	2	Yes		
<i>Rhipsalis barthlottii</i> Bauer & Korotkova	1	No		
<i>Rhipsalis burchellii</i> Britton & Rose	1	No		
<i>Rhipsalis cereoides</i> (Backeb. & Voll) Backeb.	4	Yes	CR	
<i>Rhipsalis cereuscula</i> Haw.	3	No		
<i>Rhipsalis clavata</i> F.A.C. Weber	1	No		
<i>Rhipsalis crispata</i> (Haw.) Pfeiff.	11	Yes		
<i>Rhipsalis dissimilis</i> (G. Lindb.) K. Schum.	2	No		EN
<i>Rhipsalis elliptica</i> G. Lindb. ex K. Schum.	13	Yes		
<i>Rhipsalis ewaldiana</i> Barthlott & N.P. Taylor	2	Yes		
<i>Rhipsalis flagelliformis</i> N.P. Taylor & Zappi	3	No	EN	

TABLE 1 (Cont.)

Taxon	Number of specimens	Voucher present	Brazil Red List ¹	IUCN Red List ¹
<i>Rhipsalis floccosa</i> subsp. <i>pulvinigera</i> (G. Lindb.) Barthlott & N.P. Taylor	6	Yes		
<i>Rhipsalis floccosa</i> Salm-Dyck ex Pfeiff. subsp. <i>floccosa</i>	2	No		
<i>Rhipsalis grandiflora</i> Haw.	6	No		
<i>Rhipsalis hoelleri</i> Barthlott & N.P. Taylor	1	No		
<i>Rhipsalis lindbergiana</i> K. Schum.	23	Yes		
<i>Rhipsalis mesembryanthemoides</i> Haw.	15	Yes	EN	CR
<i>Rhipsalis neves-armondii</i> K. Schum.	7	No		
<i>Rhipsalis oblonga</i> Loefgr.	1	No		VU
<i>Rhipsalis olivifera</i> N.P. Taylor & Zappi	3	No		
<i>Rhipsalis ormindoii</i> N.P. Taylor & Zappi	2	No	VU	
<i>Rhipsalis pacheco-leonis</i> subsp. <i>catenulata</i> (Kimnach) Barthlott & N.P. Taylor	2	No		
<i>Rhipsalis pacheco-leonis</i> Loefgr. subsp. <i>pacheco-leonis</i>	5	No	EN	EN
<i>Rhipsalis pachyptera</i> Pfeiff.	23	No		CR
<i>Rhipsalis paradoxa</i> (Salm-Dyck ex Pfeiff.) Salm-Dyck	8	Yes		
<i>Rhipsalis pentaptera</i> A. Dietr.	6	Yes	CR	CR
<i>Rhipsalis pulchra</i> Loefgr.	1	No		
<i>Rhipsalis puniceodiscus</i> G. Lindb.	1	No		
<i>Rhipsalis russellii</i> Britton & Rose	1	No		VU
<i>Rhipsalis shaferi</i> Britton & Rose	1	Yes		
<i>Rhipsalis teres</i> (Vell.) Steud.	19	Yes		
<i>Rhipsalis triangularis</i> Werderm.	12	Yes	EN	CR
<i>Rhipsalis trigona</i> Pfeiff.	1	No		
<i>Schlumbergera russelliana</i> (Hook.) Britton & Rose	2	No	EN	EN
<i>Schlumbergera truncata</i> (Haw.) Moran	3	No		VU
<i>Selenicereus setaceus</i> (Salm-Dyck) Berg	20	No		
<i>Strophocactus brasiliensis</i> (Britton & Rose) S. Arias & N. Korotkova	1	No		
<i>Tacinga braunii</i> Esteves	1	No	VU	VU
<i>Tacinga funalis</i> Britton & Rose	2	No		
<i>Tacinga inamoena</i> (K. Schum.) N.P. Taylor & Stuppy	26	Yes		
<i>Tacinga saxatilis</i> (Ritter) N.P. Taylor & Stuppy	3	Yes		
<i>Tacinga subcylindrica</i> M. Machado & N.P. Taylor	28	No		EN
<i>Tacinga wernerii</i> (Eggli) N.P. Taylor & Stuppy	1	No		
<i>Uebelmannia buiningii</i> Donald	1	No	CR	CR
<i>Uebelmannia pectinifera</i> Buining	10	No	EN	EN
<i>Xiquexique gounellei</i> subsp. <i>zehntneri</i> (Britton & Rose) Lavor & Calvente	1	Yes		

¹CR, Critically Endangered; EN, Endangered; VU, Vulnerable.

Significant progress has been made in the identification of cultivated specimens in the Cactarium collection of the Rio de Janeiro Botanic Garden. In the previous inventory, in 2002, only generic names were listed, and except for the Cactaceae family all other plants were categorized simply as succulents. By 2022, almost 90% of records had been identified to species and subspecies, with only 21 records identified to genus and only 15 records to family. Identifying specimens to species remains challenging because factors such as altitude, soil, temperature, precipitation and other, unknown, reasons could hinder flowering in the Garden. Flowering is often essential for accurate species identification, as reproductive structures are critical for distinguishing between closely related species (Hawthorne & Harris, 2006). Accurate plant identification is vital to increase the scientific

value of the collection and its utility for research, education and conservation (Aplin, 2014).

However, the Cactarium still faces several challenges. It is currently at maximum capacity, with fully occupied greenhouses and beds, and with no space for new acquisitions. In addition to the 16 species listed with > 40 duplicates, many species have 20–40 duplicates. This duplication may be excessive given the current constraints on space.

A botanic garden is an institution holding documented collections of living plants for the purposes of scientific research, conservation, display and education (Smith & Harvey-Brown, 2017). Although undocumented plants have no utility for conservation, they can be used for scientific research, display and education. Making duplicates, even those undocumented, available to other Brazilian

TABLE 2 Cacti accessions with > 40 duplicates, with number of duplicates, in the Rio de Janeiro Botanic Garden Cactarium, whether there is a corresponding voucher specimen in the institute's herbarium and whether the species is native to Brazil.

Taxon	Quantity	Voucher	Native to Brazil
<i>Pilosocereus arrabidaei</i> (Lem.) Byles & Rowley	173	Yes	Yes
<i>Echinopsis calochlora</i> K. Schum.	161	Yes	Yes
<i>Cereus jamacaru</i> DC	123	Yes	Yes
<i>Thelocactus setispinus</i> (Engelm.) E.F. Anderson	93	No	No
<i>Stenocereus pruinosus</i> (Otto ex Pfeiff.) Buxb.	77	No	No
<i>Mammillaria standleyi</i> (Britton & Rose) Orcutt	76	No	No
<i>Echinopsis subdenudata</i> Cárdenas	75	No	No
<i>Espositoopsis dybowskii</i> (Rol.-Goss.) Buxb.	67	Yes	Yes
<i>Tacinga palmadora</i> (Britton & Rose) N.P. Taylor & Stuppy	59	Yes	Yes
<i>Gymnocalycium pflanzii</i> (Vaupel) Werderm.	58	Yes	No
<i>Melocactus bahiensis</i> (Britton & Rose) Luetzelb.	50	Yes	Yes
<i>Echinocereus pentalophus</i> (DC.) Lem.	49	Yes	No
<i>Ferocactus glaucescens</i> (DC.) Britton & Rose	49	No	No
<i>Cleistocactus winteri</i> D.R. Hunt	45	Yes	No
<i>Arrojadoa rhodantha</i> (Gürke) Britton & Rose	42	No	Yes
<i>Mammillaria elongata</i> DC.	42	No	No

institutions could be beneficial, facilitating the reciprocal sharing of plant material in the form of donations or exchanges. Botanic gardens need to work as a collective network (Raschke et al., 2022), and supporting other Brazilian botanical gardens is one of the stated missions of the Rio de Janeiro Botanic Garden. Contributing healthy, identified plants such as those in the Cactarium to other institutions fosters collaboration and mutual benefit, and is essential because of limitations in human, material and spatial resources. By planning strategically and optimizing resources and space through a planned approach for the number of specimens held it is possible to cultivate more species from a range of locations with the same available resources (Gratzfeld, 2016), and this would ensure the ongoing improvement of the conservation value of the collection. We recommend aiming for qualitative growth of this collection at the expense of quantitative increases in specimens. A similar approach has been followed at the Recife Botanic Garden, Brazil, where increases in species richness were facilitated by reducing excessive duplication (Pimentel & Maciel, 2018).

Diversity of Cactaceae in the collection

We note the importance of the Cactarium for Cactaceae conservation: of the 276 cacti species that occur in Brazil, 57% (48% with provenance data; Table 1) are in the collection, and this is 55% of the 78 threatened cacti species on the Brazilian Red List (Brasil, 2022). However, some groups have limited representation in the collection. For instance, *Parodia* Speg., which primarily occurs in the south of Brazil in the Pampa and Atlantic Forest (Flora e Funga do Brasil, 2023), is better represented at Porto Alegre Botanic Garden in the state of Rio Grande do Sul (R. Singer, pers.

comm., 2022). Similarly, *Melocactus* Link & Otto, mainly found in the north and north-east regions of Brazil, is the most diverse genus in the Cactarium Guimarães Duque at the Paraíba State Semi-arid National Institute collection (Gomes et al., 2020), and Embrapa Agroindústria Tropical (a research unit) in Ceará State that conducts ex situ Cactaceae conservation in the Caatinga region (Coelho et al., 2015).

This reinforces the importance of taking a regional approach to a global conservation problem. To that end, we recommend that the Rio de Janeiro Botanic Garden establishes collaborative networks with other institutions, each focusing on the ex situ conservation of the local threatened flora for which their specific climate and edaphic conditions are suitable (Costa et al., 2018). Such an approach would optimize conservation efforts and enhances the efficiency of ex situ conservation.

Prioritization of Cactaceae in cultivation

A recent study that mapped the coverage of Cactaceae in protected areas (Goettsch et al., 2019) could guide prioritization of species for ex situ conservation that are not covered by in situ conservation in protected areas. Although 16 of these species are cultivated in the Cactarium, 26 are not (Table 4) and these should be prioritized for future collection acquisitions. Of these, *Melocactus conoideus* Buining & Brederoo, *Melocactus ferreophilus* Buining & Brederoo, *Melocactus lanssensianus* P.J. Braun and *Micranthocereus polyanthus* (Werderm.) Backeb. are cultivated in the Paraíba State Semi-arid National Institute collection (Gomes et al., 2020), *Freilea curvispina* Buining & Brederoo, *Parodia arnostiana* (Lisal & Kolarik) Hofacker, *Parodia crassigibba* (Ritter) N.P. Taylor, *Parodia fusca* (Ritter)



PLATE 2 Some of the threatened species in the Rio de Janeiro Botanic Garden Cactarium (Plate 1): (a) *Arthroocereus rondonianus*, (b) *Echinopsis calochlora*, (c) *Melocactus glaucescens*, (d) *Parodia ottonis*, (e) *Rhipsalis pilocarpa*, (f) *Uebelmannia pectinifera*. Photos: (a–c, f) D.R. Gonzaga; (d,e) A. Machado.

Hofacker & P.J.Braun, *Parodia gaucha* M.Machado & Larocca, *Parodia muricata* (Otto) Hofacker and *Parodia neohorstii* (S.Theun.) N.P.Taylor are cultivated in the Porto Alegre Botanic Garden (R. Singer, pers. comm., 2022), and in August 2022 a specimen of *Cereus insularis* Hemsl. was acquired, with provenance data, for the Rio de Janeiro Botanic Garden Cactarium. Thus 11 of the 26 species are already being conserved ex situ in other Brazilian institutions. The remaining 15 species should be priorities for both in situ and ex situ conservation.

Regional knowledge of environmental conditions is also important for successful ex situ conservation. We recommend that the Cactarium should firstly direct its efforts towards the acquisition of regional flora, such as species that occur in the Atlantic Forest, and secondly towards species from the Cerrado, which have historically shown adaptability

to the environmental conditions in Rio de Janeiro. For species that occur in the Amazon, Caatinga, Pampa and Pantanal, partnering with institutions in these regions could improve conservation efficiency, ensuring cultivation of Cactaceae in environmental conditions similar to those in which they occur naturally. However, because of potential future risks to cacti from climate change (Pillet et al., 2022), cultivation of all species of Brazilian Cactaceae that could feasibly grow in a particular location, regardless of current threat status, is also advisable. Whichever species are cultivated, curation of full provenance data and registration in the institutional digital system is crucial to ensure the conservation value of the collection and the sharing of data between institutions.

Given resource limitations, personnel constraints and lack of space, and to collaborate with the National Plan for Cactus Conservation (Ribeiro-Silva et al., 2011), Rio de

TABLE 3 Number of threatened cacti species on the Brazilian Red List (Brasil, 2022) and IUCN Red List (IUCN, 2023), and the number (and per cent) of these in cultivation in the Rio de Janeiro Botanic Garden Cactarium.

Threat category	Brazilian Red List	Present in collection (%)	IUCN Red List	Present in collection
Critically Endangered	12	8 (66.7)	28	14 (50.0)
Endangered	46	25 (54.3)	52	26 (50.0)
Vulnerable	20	10 (50.0)	33	17 (51.5)
<i>Total</i>	78	43 (55.1)	113	57 (50.4)

TABLE 4 Cactaceae species occurring in Brazil that are not covered by protected areas, in cultivation or not in cultivation in the Rio de Janeiro Botanic Garden Cactarium, with IUCN Red List category, whether provenance data are available for species in cultivation, phytogeographical domain and states of occurrence (list of species modified from Goettsch et al., 2019).

Taxon	IUCN Red List category ¹	Provenance data	Phytogeographical domain ²	States of occurrence ^{2,3}
Cultivated in Garden				
<i>Arrojadoa albiflora</i>	CR	Yes	Caatinga	BA
<i>Arrojadoa marylandiae</i>	CR	Yes	Caatinga	BA
<i>Coleocephalocereus braunii</i>	CR	Yes	Atlantic Forest	ES
<i>Coleocephalocereus diersianus</i>	CR	Yes	Atlantic Forest	ES
<i>Discocactus heptacanthus</i>	CR	Yes	Cerrado	TO, GO
<i>Estevesia alex-bragae</i>	CR	Yes	Unknown	
<i>Micranthocereus estevesii</i>	EN	Yes	Cerrado	TO, GO, MG
<i>Micranthocereus streckeri</i>	CR	Yes	Caatinga, Cerrado	BA
<i>Pilosocereus aureispinus</i>	VU	Yes	Cerrado	BA
<i>Pilosocereus frewenii</i>	CR	Yes	Cerrado	MG
<i>Rhipsalis hoelleri</i>	DD	Yes	Atlantic Forest	ES
<i>Parodia magnifica</i>	EN	No	Atlantic Forest, Pampa	RS
<i>Parodia stockingeri</i>	EN	No	Pampa	RS
<i>Rhipsalis crispata</i>	EN	No	Atlantic Forest	BA, PE, RJ, SP, SC
<i>Tacinga palmadora</i>	LC	No	Caatinga	AL, BA, CE, PB, PE, PI, RN, SE
<i>Tacinga saxatilis</i> subsp. <i>estevesii</i>	EN	No	Caatinga	BA, MG
Not cultivated in Garden				
<i>Arrojadoa multiflora</i>	EN		Caatinga	BA
<i>Cereus estevesii</i>	CR		Cerrado	MG
<i>Coleocephalocereus uebelmanniorum</i>	EN		Cerrado	ES, MG ⁴
<i>Frailea buenekeri</i>	EN		Pampa	RS
<i>Frailea curvispina</i>	EN		Pampa	RS
<i>Frailea fulviseta</i>	EN		Pampa	RS
<i>Frailea mammifera</i>	EN		Pampa	RS
<i>Melocactus conoideus</i>	CR		Caatinga, Cerrado	BA
<i>Melocactus deinacanthus</i>	EN		Caatinga	BA
<i>Melocactus ferreophilus</i>	CR		Caatinga	BA
<i>Melocactus lanssensianus</i>	EN		Caatinga	PB, PE
<i>Micranthocereus polyanthus</i>	EN		Caatinga, Cerrado	BA
<i>Parodia arnostiana</i>	CR		Pampa	RS
<i>Parodia carambeiensis</i>	LC		Atlantic Forest	PR
<i>Parodia crassigibba</i>	CR		Pampa	RS
<i>Parodia fusca</i>	VU		Pampa	RS
<i>Parodia gaucha</i>	EN		Pampa	RS
<i>Parodia horstii</i>	EN		Atlantic Forest, Pampa	RS
<i>Parodia muricata</i>	EN		Atlantic Forest, Pampa	RS
<i>Parodia neohorstii</i>	CR		Pampa	RS
<i>Parodia rechensis</i>	CR		Atlantic Forest	RS
<i>Parodia rudibuenekeri</i>	EN		Pampa	RS
<i>Parodia warasii</i>	EN		Atlantic Forest	RS
<i>Pilosocereus flexibilispinus</i>	DD		Caatinga, Cerrado	TO, BA, GO
<i>Pilosocereus splendidus</i>	DD		Caatinga	BA
<i>Rhipsalis sulcata</i>	DD		Atlantic Forest	ES

¹CR, Critically Endangered; EN, Endangered; VU, Vulnerable; LC, Least Concern; DD, Data Deficient.

²From Flora e Funga do Brasil (2023).

³AL, Alagoas; BA, Bahia; CE, Ceará; ES, Espírito Santo; GO, Goiás; MG, Minas Gerais; PB, Paraíba; PE, Pernambuco; PI, Piauí; PR, Paraná; RJ, Rio de Janeiro; RN, Rio Grande do Norte; RS, Rio Grande do Sul; SC, Santa Catarina; SE, Sergipe; SP, São Paulo; TO, Tocantins.

⁴Data obtained from POWO (2023).

Janeiro Botanic Garden should also explore long-term ex situ conservation through seed banks (O'Donnell & Sharrock, 2017; Rivi re & M ller, 2017). Many cactus species have orthodox seeds (Almeida et al., 2009; Abud et al., 2010) that can be successfully stored. However, some of the challenges include limited knowledge of the seed biology of native Brazilian cacti (Assis et al., 2011) and the limited numbers of seeds per fruit and fruits per plant in many species (Ribeiro-Silva et al., 2011), which present difficulties for acquiring sufficient quantities of seeds for storage.

Ex situ conservation involves techniques to conserve genetic diversity and reduce the extinction risk of species (Costa & Bajgielman, 2016). Therefore, assessing a collection, defining a target species list and prioritizing regional flora with a focus on rare and threatened species are all important but are not endpoints in themselves. Collection of genetic material in the wild, following appropriate guidelines, is required (Griffith et al., 2021), in particular seed collection. Ex situ conservation can then be achieved through seed banks and living collections, research on cultivation and propagation protocols and study of species biology (Assis et al., 2011). Seedlings propagated from high-quality seeds produced through in vivo cross-pollination, cultivated specimens and stored seeds can be used for reintroduction into suitable natural habitats, followed by monitoring (Costa & Bajgielman, 2016). Such ex situ conservation and reintroduction benefit from the development of networked collections and periodic reassessments of the effectiveness of conservation efforts (Gratzfeld, 2016; Griffith et al., 2021).

The Cactarium of the Rio de Janeiro Botanic Garden has made significant progress in seeking to meet Target 8 of the Global Strategy for Plant Conservation in terms of analysing the diversity of and data quality for the plants in cultivation. However, to maximize the value of living plant collections for conservation, we recommend that collection assessments consider the current conservation status of species, both in situ and ex situ, to ensure the ongoing relevance of the collection. In addition, we recommend that identification and provenance data are made available online, to maximize the value of cultivated living collections for the conservation of native flora.

Author contributions Study design: THMA, DRG; data collection: THMA, DRG; data analysis: THMA, DRG; writing: all authors.

Acknowledgements We thank the Cactarium interns Thiago F. Gonalves and Ricardo M. Tortorelli for their assistance with the inventory; Cactarium gardeners Jorge Ronaldo Sim o and Vin cius Apareciano Loureno for their assistance with plant maintenance during the inventory; Marcus A.N. Coelho, curator of the Rio de Janeiro Botanic Garden living collection, for supporting this assessment; Associao de Amigos do Jardim Bot nico, and Sylvia Aranha and family for supporting this collection; and the reviewers for their helpful critiques. This research received no specific grant from any funding agency or commercial or not-for-profit sectors.

Conflicts of interest None.

Ethical standards This research abided by the *Oryx* guidelines on ethical standards.

Data availability The data that support the findings of this study are openly available in the Jabot Rio de Janeiro Botanic Garden database at rb.jbrj.gov.br/v2/consulta.php.

References

- ABUD, H.F., GONALVES, N.R., REIS, R.G.E., PEREIRA, D.S. & BEZERRA, A.M.E. (2010) Germinao e express o morfol gica de frutos, sementes e pl ntulas de *Pilosocereus pachycladus* Ritter. *Revista Ci ncia Agron mica*, 41, 468–474.
- ALMEIDA, T.M.H., ANDRADE, A.C.S. & LOPES, H.M. (2009) Brazilian cacti seed germination under different temperature and substrate conditions. *Seed Science and Technology*, 37, 474–479.
- APLIN, D. (2014) A global survey of living collections. *BGjournal*, 11, 26–29.
- ASSIS, J.G.A., RESENDE, S.V., BELLINTANI, M.C., COELHO, P.J.A., CORREIA, D., MARCHI, M.N.G. et al. (2011) Conservao ex situ. In *Plano de Ao Nacional para Conservao das Cact ceas, S rie Esp cies Ameaadas no. 24*, p. 111. Instituto Chico Mendes de Conservao da Biodiversidade, Bras lia, Brazil.
- BARTHLOTT, W., BURSTEDDE, K., GEFFERT, J.L., IBISCH, P.L., KOROTKOVA, N., MIEBACH, A. et al. (eds) (2015) *Biogeography and Biodiversity of Cacti*. Universit tsverlag Isensee, Oldenburg, Germany.
- BOTANIC GARDENS CONSERVATION INTERNATIONAL (2014) *Building Living Plant Collections for Conservation: A Guide For Public Gardens*. Montgomery Botanical Center, Coral Gables, USA. montgomerybotanical.org/media/Plant.Conservation.Collections.Guide.pdf [accessed 7 December 2023].
- BRASIL (1914) *Relat rio do Minist rio da Agricultura*. memoria.bn.gov.br/docreader/DocReader.aspx?bib=873730&pagfis=21025 [accessed 3 October 2023].
- BRASIL (2022) *Lista Nacional de Esp cies Ameaadas de Extino*. *Di rio Oficial da Uni o*. in.gov.br/en/web/dou/-/portaria-mma-n-148-de-7-de-junho-de-2022-406272733 [accessed 13 February 2023].
- CAITANO, H. de A., DUTRA, V.F., VALADARES, R.T. & CALAZANS, L.S.B. (2022) Reintroduction of illegally extracted *Melocactus violaceus* (Cactaceae) in Brazil. *Oryx*, 56, 155–158.
- CARRILLO-ANGELES, I.G., SUZAN-AZPIRI, H., MANDUJANO, M.C., GOLUBOV, J. & MARTINEZ- VALOS, J.G. (2016) Niche breadth and the implications of climate change in the conservation of the genus *Astrophytum* (Cactaceae). *Journal of Arid Environments*, 124, 310–317.
- CBD (2011) *Global Strategy for Plant Conservation 2011–2020*. Convention on Biological Diversity, Montreal, Canada. cbd.int/gspc [accessed 10 February 2023].
- COELHO, P.J.A., FUCH JUNIOR, S.C.F. & NASCIMENTO, E. (2015) Coleta e conservao ex situ de cact ceas nativas do Estado do Cear . *Gaia Scientia*, 9, 183–192.
- COSTA, M.L.M.N. & BAJGIELMAN, T. (2016) *Estrat gia Nacional para a Conservao Ex Situ de Esp cies Ameaadas da Flora Brasileira*. Centro Nacional de Conservao da Flora – (CNCFlora), Jardim Bot nico do Rio de Janeiro: Andrea Jakobsson Est dio, Rio de Janeiro, Brazil.
- COSTA, M.L.M.N., WYSE JACKSON, P., FERNANDES, R.A. & PEIXOTO, A.L. (2018) Conservation of threatened plant species in botanic garden reserves in Brazil. *Oryx*, 52, 108–115.
- DINIZ, M.F., GONALVES, T.V. & BRITO, D. (2017) Last of the green: identifying priority sites to prevent plant extinctions in Brazil. *Oryx*, 51, 131–136.

- EMBRAPA TERRITORIAL (2020) *Agricultura e Preservação Ambiental: Uma Análise do Cadastro Ambiental Rural*. embrapa.br/car/sintese [accessed 13 February 2023].
- FLORA E FUNGA DO BRASIL (2023) *Jardim Botânico do Rio de Janeiro*. floradobrasil.jbrj.gov.br/FB70 [accessed 3 October 2023].
- GOETTSCHE, B., DURÁN, A.P. & GASTON, K.J. (2019) Global gap analysis of cactus species and priority sites for their conservation. *Conservation Biology*, 33, 369–376.
- GOETTSCHE, B., HILTON-TAYLOR, C., CRUZ-PINÓN, G., DUFFY, J.P., FRANCES, A., HERNÁNDEZ, H.M. et al. (2015) High proportion of cactus species threatened with extinction. *Nature Plants*, 1, 15142.
- GOMES, V.G.N., CASSIMIRO, C.A.L., FREITAS, J.G., DO FELIX, C.M.P. & DA BATISTA, F.R.C. (2020) Ex situ conservation in the Brazilian semiarid: Cactaceae housed in the collection of the Guimarães Duque Cactarium. *Brazilian Journal of Development*, 6, 62608–62625.
- GONZAGA, D.R. & REIS, R.C.C. (2019) The importance of ex-situ conservation: The challenges of the Cactarium at Botanical Garden of Rio de Janeiro. In *Cacti: Ecology, Conservation, Uses and Significances* (ed. M.R. Santos), pp. 1–11. Nova Science Publishers, New York, USA.
- GONZAGA, D.R., REIS, R.C.C., & COELHO, M.A.C. (2019) A importância da conservação ex situ: os desafios do Cactário do Jardim Botânico do Rio de Janeiro. In *70º Congresso Nacional de Botânica* (eds L.R. Lima, G.C. Guapo, G.C. Justino, A.V.F. Pinto & E.A.C. Guedes), p. 297. Sociedade Botânica do Brasil & Universidade Federal de Alagoas, Maceió, Brazil.
- GRACE, O.M. & MAJURE, L.C. (2017) Horticulture and the conservation of threatened species: succulent plant collections in botanic gardens supporting ex situ conservation and research. *BGjournal*, 14, 34–35.
- GRATZFELD, J. (ed.) (2016) *From Idea to Realisation: BGCI's Manual on Planning, Developing and Managing Botanic Gardens*. Botanic Gardens Conservation International, Richmond, UK. bgci.org/resources/bgci-tools-and-resources/bgci-manual-on-planning-developing-and-managing-botanic-gardens [accessed April 2024].
- GREVE, M., LYKKEC, A.M., FAGGD, C.W., GEREAEU, R.E., LEWIS, G.P., MARCHANT, R. et al. (2016) Realising the potential of herbarium records for conservation biology. *South African Journal of Botany*, 105, 317–323.
- GRIFFITH, M.P., CARTWRIGHT, F., DOSMANN, M., FANT, J., FREID, E., HAVENS, K. et al. (2021) Ex situ conservation of large and small plant populations illustrates limitations of common conservation metrics. *International Journal of Plant Sciences*, 182, 263–276.
- HAWTHORNE, W. & HARRIS, S. (2006) Plant names and botanical publication. In *Plant Identification: Creating User-Friendly Field Guides for Biodiversity Management*, p. 68. Earthscan, London, UK.
- HUANG, J., YU, H., GUAN, X., WANG, G. & GUO, R. (2016) Accelerated dryland expansion under climate change. *Nature Climate Change*, 6, 166–171.
- HULTINE, K.R., MAJURE, L.C., NIXON, V.S., ARIAS, S., BÜRQUEZ, A., GOETTSCHE, B. et al. (2016) The role of botanical gardens in the conservation of Cactaceae. *BioScience*, 66, 1057–1065.
- IUCN (2023) *The IUCN Red List of Threatened Species 2023-1*. iucnredlist.org [accessed 13 April 2023].
- LARIOS, E., GONZÁLEZ, E.J., ROSEN, P.C., PATE, A. & HOLM, P. (2020) Population projections of an endangered cactus suggest little impact of climate change. *Oecologia*, 192, 439–448.
- O'DONNELL, K. & SHARROCK, S. (2017) The contribution of botanic gardens to ex situ conservation through seed banking. *Plant Diversity*, 39, 373–378.
- OLDFIELD, S. & HUNT, D. (2010) The conservation of cacti and succulents in botanic gardens. *BGjournal*, 7, 15–17.
- PILLET, M., GOETTSCHE, B., MEROW, C., MAITNER, B., FENG, X., ROEHRDANZ, P.R. & ENQUIST, B.J. (2022) Elevated extinction risk of cacti under climate change. *Nature Plants*, 8, 366–372.
- PIMENTEL, M.D.C.C. & MACIEL, J.R. (2018) Evolução do Cactário do Jardim Botânico do Recife: impactos de mudanças na política de gestão da coleção entre 2011–2017. *Revista Arrudea – A revista do Jardim Botânico do Recife*, 4, 11.
- POWO (2023) *Plants of the World Online*. Royal Botanic Gardens Kew, Richmond, UK. powo.science.kew.org [accessed 3 October 2023].
- RASCHKE, A.B., PEGRAM, K.V., MELKONOFF, N.A., DAVIS, J. & BLACKWELL, S.A. (2022) Collaborative conservation by botanical gardens: unique opportunities for local to global impacts. *Journal of Zoological and Botanical Gardens*, 3, 463–487.
- REYES-GARCÍA, C. & ANDRADE, J.L. (2009) Crassulacean acid metabolism under global climate change. *New Phytologist*, 181, 754–757.
- RIBEIRO-SILVA, S., ZAPPI, D., TAYLOR, N. & MACHADO, M. (organizers) (2011) *Plano de Ação Nacional Para a Conservação das Cactáceas*. Instituto Chico Mendes de Conservação da Biodiversidade, Brasília, Brazil.
- RIVIÈRE, S. & MÜLLER, J.V. (2017) Contribution of seed banks across Europe towards the 2020 global strategy for plant conservation targets, assessed through the ENSCONET database. *Oryx*, 52, 464–470.
- SHRYOCK, D.F., ESQUE, T.C. & HUGHES, L. (2014) Population viability of *Pediocactus bradyi* (Cactaceae) in a changing climate. *American Journal of Botany*, 101, 1944–1953.
- SILVA, L.A.E., FRAGA, C.N., ALMEIDA, T.M.H., GONZALEZ, M., LIMA, R.O., ROCHA, M.S. et al. (2017) Jabot – sistema de gerenciamento de coleções botânicas: a experiência de uma década de desenvolvimento e avanços. *Rodriguésia*, 68, 391–410.
- SMITH, P. & HARVEY-BROWN, Y. (2017) *BGCI Technical Review: Defining the Botanic Garden, and How to Measure Performance and Success*. Botanic Gardens Conservation International, Richmond, UK.
- TROPICOS (2023) *Tropicos*. tropicos.org/home [accessed 3 October 2023].
- WALTERS, M., FIGUEIREDO, E., CROUCH, N.R., WINTER, P.J.D., SMITH, G.F., ZIMMERMANN, H.G. & MASHOPE, B.K. (2011) *Naturalised and Invasive Succulents of Southern Africa*. ABC Taxa, Brussels, Belgium.
- WYSE JACKSON, P. & KENNEDY, K. (2009) The global strategy for plant conservation: a challenge and opportunity for the international community. *Trends in Plant Science*, 14, 578–580.
- ZAPPI, D., TAYLOR, N. & SANTOS, M.R. (2011) Conservação das Cactaceae do Brasil. In *Plano de Ação Nacional para Conservação das Cactáceas*, p. 111. Instituto Chico Mendes de Conservação da Biodiversidade, Brasília, Brazil.