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Contributed Paper

Global gap analysis of cactus species and priority sites for their conservation

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Abstract: *Knowing how much biodiversity is captured by protected areas (PAs) is important to meeting country commitments to international conservation agreements, such as the Convention on Biological Diversity, and analyzing gaps in species coverage by PAs contributes greatly to improved locating of new PAs and conservation of species. Regardless of their importance, global gap analyses have been conducted only for a few taxonomic groups (e.g., mangroves, corals, amphibians, birds, mammals). We conducted the first global gap analysis for a complete specious plant group, the highly threatened Cactaceae. Using geographic distribution data of 1438 cactus species, we assessed how well the current PA network represents them. We also systematically identified priority areas for conservation of cactus species that met and failed to meet conservation targets accounting for their conservation status. There were 261 species with no coverage by PAs (gap species). A greater percentage of cacti species (18%) lacked protection than mammals (9.7%) and birds (5.6%), and also a greater percentage of threatened cacti species (32%) were outside protected areas than amphibians (26.5%), birds (19.9%), or mammals (16%). The top 17% of the landscape that best captured covered species represented on average 52.9% of species ranges. The priority areas for gap species and the unprotected portion of the ranges of species that only partially met their conservation target (i.e., partial gap) captured on average 75.2% of their ranges, of which 100 were threatened gap species. These findings and knowledge of the threats affecting species provide information that can be used to improve planning for cacti conservation and highlight the importance of assessing the representation of major groups, such as plants, in PAs to determining the performance of the current PA network.*

Keywords: Cactaceae, conservation priorities, IUCN Red List of Threatened Species, protected areas, threatened species

Análisis del Vacío Mundial de Especies de Cactáceas y Sitios Prioritarios para su Conservación

Resumen: *El conocimiento sobre cuánta biodiversidad es captada por las áreas protegidas (AP) es importante para cumplir los compromisos de cada país con los acuerdos internacionales sobre conservación, como la Convención sobre la Diversidad Biológica, y el análisis de los vacíos en la cobertura de especies por las AP contribuye enormemente a una ubicación mejorada de AP nuevas y a la conservación de especies. Sin considerar su importancia, los análisis de vacío global se han realizado solamente para unos cuantos grupos taxonómicos (p. ej.: mangles, corales, anfibios, aves, mamíferos). Realizamos el primer análisis de vacío global para un grupo completo de especies de plantas, las Cactaceae, que se encuentran bajo seria amenaza. Evaluamos que tan bien representa la red actual de AP a las cactáceas con datos de distribución geográfica de 1438 especies de cactus. También identificamos sistemáticamente las áreas prioritarias de conservación para especies de cactus que cumplieron o fallaron los objetivos de conservación considerando el estado de conservación de las cactáceas. Hubo 261 especies sin cobertura en las AP (especies vacío). Un mayor porcentaje de especies de cactus (18%) careció de protección comparado con los mamíferos (9.7%)*

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y las aves (5.6%), y también encontramos un mayor porcentaje de especies amenazadas de cactus (32%) fuera de las áreas protegidas comparado con los anfibios (26.5%), aves (19.9%) o mamíferos (16%). El 17% máximo del paisaje que mejor capturó a las especies cubiertas representó el 52.9% de la extensión de las especies. Las áreas prioritarias para las especies vacío y la porción desprotegida de la extensión de las especies que sólo cumplieron parcialmente con sus objetivos de conservación (es decir, el vacío parcial) capturaron en promedio el 75.2% de la extensión de las cactáceas, de las cuales 100 eran especies vacío amenazadas. Estos hallazgos y conocimiento sobre las amenazas que afectan a las especies proporcionan información que puede usarse para mejorar la planeación de la conservación de cactáceas y también resalta la importancia de la evaluación de la representación de grupos importantes, como las plantas, en AP para determinar el desempeño de la red contemporánea de AP.

Palabras Clave: áreas protegidas, Cactaceae, especies amenazadas, Lista Roja de Especies Amenazadas de las UICN, prioridades de conservación

摘要: *了解保护地包含了多少生物多样性, 对国家履行其对全球保护协议 (如《生物多样性公约》) 的承诺十分重要, 分析保护地覆盖物种的空缺还有助于新保护地更好的选址及相应物种的保护。目前全球空缺分析的研究只关注了少数几个类群, 不论它们重要与否, 如红树林、珊瑚、两栖类、鸟类和哺乳类。我们首次对高度濒危的仙人掌科这整个植物类群进行了全球空缺分析。利用 1438 种仙人掌的地理分布数据, 我们评估了目前的保护地网络对它们的覆盖情况。我们还根据仙人掌的保护状况, 系统地确定了那些达到与未达到这些物种保护目标的优先保护区域。有 261 个种不在任何保护地中 (空缺种) 。保护不足的仙人掌物种比例 (18%) 高于哺乳类 (9.7%) 和鸟类 (5.6%) 中的比例, 在保护地之外的受胁迫仙人掌物种所占比例 (32%) 也高于两栖类 (26.5%) 、鸟类 (19.9%) 和哺乳类 (16%) 的情况。最大程度地覆盖了仙人掌物种的前 17% 的景观平均占物种分布范围的 52.9% 。而空缺种的优先保护区域和没有完全达到保护目标的物种 (即部分空缺种) 分布区中未保护的区域, 平均占据它们分布区的 75.2%, 其中包括了 100 种受胁迫的空缺种。我们的发现结合物种受到威胁的知识, 可以为更好地为仙人掌的保护规划提供信息, 同时也强调了应评估主要类群 (如植物) 在保护地中被覆盖的情况, 以确定当前保护地网络的有效性。***【翻译: 胡怡思; 审校: 聂永刚】**

关键词: 保护地, 受胁迫物种, 仙人掌科, 优先保护, 《IUCN受胁迫物种红色名录》

Introduction

It is well established that the most effective way to ensure the long-term survival of biodiversity in situ is through the designation of protected areas (PAs), where anthropogenic impacts are mitigated (Margules & Pressey 2000; Barnes et al. 2016). It is also well known that most of the global network of PAs has not been designed and created through careful consideration of the main features that it is supposed to protect (i.e., species, in particular threatened ones and their habitats). For this reason and because PAs are a key indicator of conservation success in international agreements such as the Convention on Biological Diversity (CBD) and its Aichi Targets (CBD 2010), in recent decades 1 of the main objectives in the field of conservation science has been to measure to what extent biodiversity is represented within the current system of PAs (Rodrigues et al. 1999; Brooks et al. 2004; Rodrigues et al. 2004*a*, 2004*b*; Ceballos et al. 2005; Gaston et al. 2008; Craigie et al. 2010; Cantú-Salazar et al. 2013; Butchart et al. 2015).

Global gap analyses (i.e., analysis of how well the current protected-area system captures the geographic ranges of species) have now been conducted for several taxonomic groups (e.g., amphibians [Rodrigues et al. 2004*a*, 2004*b*; Butchart et al. 2015], turtles [Rodrigues et al. 2004*a*, 2004*b*; Butchart et al. 2015], birds [Rodrigues et al. 2004*a*, 2004*b*; Butchart et al. 2015], and mammals [Rodrigues et al. 2004*a*, 2004*b*; Ceballos et al. 2005; Cantú-Salazar et al. 2013; Butchart et al. 2015]). However, gap analyses for plant species have been carried out mainly at the country or regional level (Riemann & Ezcurra 2005; Araújo et al. 2007; Gove et al. 2008; Akasaka & Tsuyuzaki 2009; Jackson et al. 2009; Duarte et al. 2014), and even then there are few examples of evaluation of complete taxonomic groups (Callmander et al. 2007; Hernández & Gómez-Hinostrosa 2011). Globally, only the species-poor seagrasses (72 species) and mangroves (67 species) have been analyzed in this manner (Butchart et al. 2015). This state of affairs is troubling given that most of life on Earth depends on plants, that over 11,500 species of plants are assessed as threatened by the International Union for Conservation of Nature (IUCN 2016), and that 22–33% of plant species are estimated to be threatened with global extinction (Pimm & Joppa 2015). Undoubtedly, the main obstacle to conducting global gap analyses for complete major groups of plant species has been the lack of suitable comparable data on the global distributions of individual species (Goettsch et al. 2015).

Followed by conifers with just over 600 species, the cactus family is the most species rich (approximately 1,500 species) plant group to have been fully assessed for the IUCN Red List of Threatened Species (IUCN 2016) and for which an almost complete global data set of species range maps exists. Several factors make conferring protection on cactus species particularly challenging and thus a valuable group for which to conduct a global gap analysis. First, this charismatic plant family, endemic to the Americas with the exception of 1 species (*Rhipsalis baccifera*; Hunt et al. 2006), exhibits high levels of endemism (e.g., Hernández & Godínez 1994; Hernández & Bárcenas 1995, 1996; Mourelle & Ezcurra 1997; Hernández et al. 2001). For instance, 75% of the 595 species reported for Mexico are endemic (Goettsch et al. 2015), and within this country 229 species (38%) are endemic to the Chihuahuan desert region (Hernández et al. 2004). Second, a high proportion of species have particularly small geographic range sizes (<1,000 km^2 for 283 species [Goettsch et al. 2015]) and tend to have very patchy and disjunct distributions (Goettsch & Hernández 2006; Hernández et al. 2008). Third, a high percentage of species (31%) in this plant group is threatened; it is the fifth most threatened major taxonomic group according to IUCN criteria (Goettsch et al. 2015). Eighty-one to 83% of cactus species occur in protected areas (Goettsch et al. 2015; Ibisch & Mutke 2015). However, it remains unknown what proportion of their geographic ranges this coverage constitutes, and given the high incidence of small ranges within the Cactaceae, we expected a high proportion of species for which this is inadequate (Rodrigues et al. 2004*a*; Gruber et al. 2012; Akasaka et al. 2017).

We conducted a global gap analysis to establish how well the current protected-area network captures the geographic ranges of cactus species. This is the first study of its kind conducted for a complete and speciose group of plants at the global level.

Methods

Data

The extinction risk of all extant cactus species was assessed by the Global Cactus Assessment, the results of which are available within the IUCN Red List of Threatened Species (IUCN 2016). As part of this exercise, range maps were generated for a total of 1,438 species based on point data records collated from sources such as herbaria, the literature, personal, and global databases. The occurrence points were printed on paper maps, which included geographic features such as rivers, mountains, and cities, and then reviewed, corrected, and interpreted by regional cactus specialists to estimate the distribution of each species (see Goettsch et al. [2015] for details). We used these maps in the present gap analysis in the form of polygon vector files. Forty species assessed as data deficient had no maps and were therefore not included.

We obtained data on the spatial distribution of protected areas (PAs) on the American continent from the World Database on Protected Areas (IUCN & UNEP-WCMC 2016). These data comprise both polygons and point records with associated areas. Following Rodrigues et al. (2004*a*), records were eliminated for PAs for which their status was proposed, recommended, or not reported; point records were converted into circles of the stated area; point record circular areas were subsequently merged with those for which original polygon data were provided to generate a common polygon shapefile with a total of 33,547 records across the American continent (Supporting Information); and the polygons that shared a common boundary or that overlapped were dissolved.

Gap Analysis

To identify species occurring in PAs and gap species, we quantified the percentage of each species' range that was under protection by overlaying the distribution maps of each cactus species with the map of protected areas. Following Rodrigues et al. (2004*a*), we considered a species was a gap species if it was included in no protected areas and a covered species if a predetermined percentage of its geographic range was included in 1 or more PAs. This percentage is referred to as the "conservation target" for each species. For species with geographic ranges of ≤1,000 km^2 it was required that their entire range was covered, whereas for species with ranges of ≥250,000 km^2 only 10% of their geographical range was required to be included in PAs. We determined conservation targets for species with intermediate geographic ranges by interpolating between these 2 extremes (Rodrigues et al. 2004*a*). Those species whose conservation target was only partly covered by 1 or more PAs were defined as partial-gap species. Once covered, partial-gap, and gap species were determined, we quantified the proportion of species with different extinction risk in each group (Supporting Information).

Spatial Conservation Prioritization Analysis

We identified priority areas for cacti conservation using Zonation (Moilanen et al. 2005), a spatial conservation planning tool that optimizes the representation of a feature (e.g., species ranges) in a gridded landscape. The Zonation algorithm operates by successively removing those grid cells whose loss results in the smallest reduction in the value of the feature in the remaining landscape, thereby producing a ranking of the contribution of each cell. This results in a hierarchical prioritization in which the most valuable 5% of the landscape is within the most valuable 10%, the top 2% is in the top 5%, and so on. The removal order of cells depends on the cell removal rule, which determines which cell leads to the smallest marginal loss of the feature value (Moilanen et al. 2005). In our analyses, we used the core-area cell removal rule, in which each species distribution is considered separately, securing locations that gather a high proportion of a species' distribution range, thus favoring the rarest species in the resulting priority areas. This is considered a better approach to target conservation efforts in comparison with species richness (i.e., additive-benefit-function cell removal rule in Zonation). Zonation uses species' distribution ranges in the form of rasters, which were generated from vector files as presence-absence grids at 8-km^2 resolution (details in Goettsch et al. 2015).

To assess priority areas while taking into account the actual level of protection of each species, hence their conservation relevance, we incorporated the gap analysis results and the species extinction risk into the prioritization process. We carried out 2 prioritization strategies. The first included the protected extent of covered species ranges, hence indicating the distribution of priority areas within the existing PA network. This helped identify specific PAs that had a relatively high representation of species that meet the protection target. The second strategy included gap and the unprotected extent of ranges of partial-gap species. This identified the priority areas outside current PAs that best complemented the existing network by strategically increasing the overall coverage of gap and of partial-gap species. In both strategies species were weighted according to their extinction risk (Polaina et al. 2016) in line with IUCN (2017): 1, least concern (LC), no weight in Zonation; 2, near threatened (NT); 3, vulnerable (VU); 4, endangered (EN); and 5, critically endangered (CR). We calculated the level of representation of species ranges in the top 5% and 17% of the landscape (i.e., the highest-ranking percentage of the landscape that best represents cactus species geographic ranges).

Results

We identified 261 (18.1%) gap species of cactus, which is species that were not covered by any protected area (Fig. 1). According to species' conservation targets, 156 (10.84%) were fully covered while 1021 (71.0%) species were partially covered. A high number of cactus species had a small proportion of their range under protection (Supporting Information). The vast majority of species (1295 species) had <50% of their range protected, of which 748 (52.01%) had <10%. In contrast, only 40 (2.78%) species had >95% of their range protected (Supporting Information).

Relative to their extinction risk, of the 416 cactus species categorized as threatened (i.e., CR, EN, and VU), 32% (131 species) were gap species, whereas only 6% (25 species) were fully covered. Looking at the percentages of gap and fully covered species in each threatened category, for the 99 CR species 60% (60 species) were gap and 3% (11 species) were fully covered, for the 179 EN species 31% (56 species) were gap and 4% (6 species) were fully covered, and for the 139 VU species 11% (15 species) were gap and 6% (8 species) were fully covered (Fig. 2).

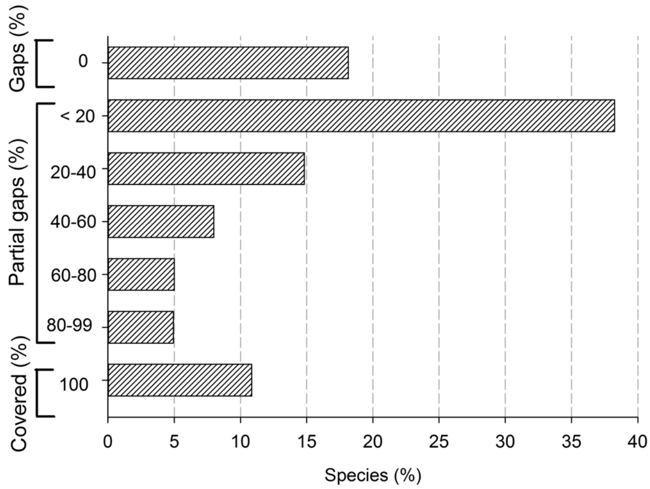

Figure 1. Percentage of covered, gap (not present in protected areas), and partial-gap cactus species. Percentages on the x-axis are the degree of fulfillment of the conservation target. Covered species are those with geographic ranges that completely overlap with protected areas or that meet a conservation target, for example, species with ranges ≥250,000 km^2 for which 10% of their range or more is protected. Partial-gap species are those that partially meet their conservation target.

Priority areas for covered cactus species (i.e., protected places that represent a relatively high proportion of cacti geographic ranges that met their conservation target) were mainly distributed in areas of the Sonoran desert (southwestern United States and the Baja California peninsula in Mexico); areas in the Mexican portion of the Chihuahuan desert; the Caribbean, mainly Cuba, the Dominican Republic, and mainland Colombia, and Venezuela; eastern Brazil; along the Andean region of Ecuador, Peru, Bolivia, and northern Argentina; northern Paraguay; the border of southeastern Bolivia and western Brazil; and the Atlantic Forest region of Brazil (Fig. 3a). Specifically, the top (i.e., highest-ranking) 5% and 17% of the landscape represented on average 26.8% and 52.9% of species ranges and encompassed the full ranges of 20 and 29 species, respectively. Of the fully covered species represented within the 17%, 7 were CR, 4 EN, 6 VU, and 12 LC.

Priority areas for gap species and the unprotected extent of partial-gap species, were mainly distributed in western United States, Mexico, Central America, the Caribbean, eastern, southeastern, and southern Brazil, Ecuador, coastal Peru and central Chile, southwestern Bolivia, and western Argentina (Fig. 3b). The top 5% and 17% of the landscape represented on average 51.8% and 75.2% of species ranges, respectively. These top percentages

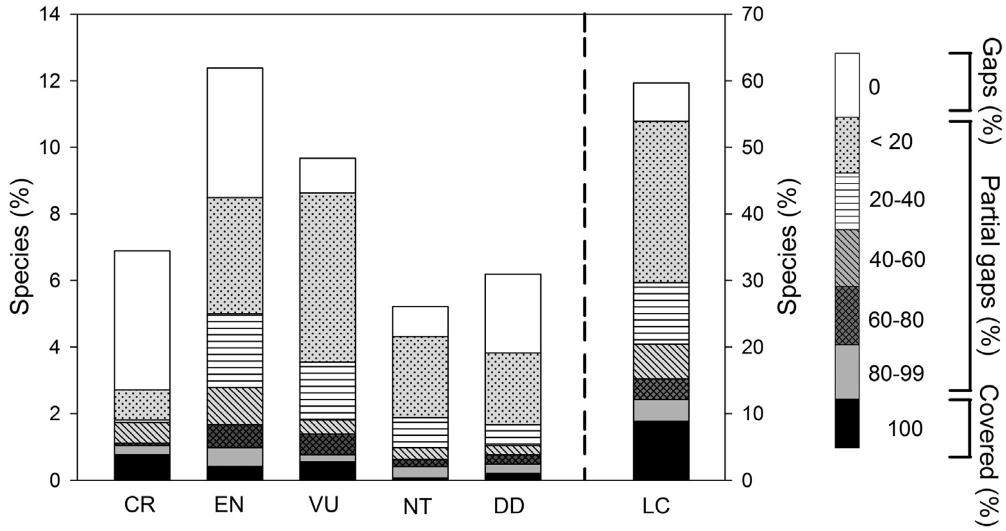

Figure 2. Percentage of covered, partial-gap, and gap (not present in protected areas) cactus species according to their International Union for Conservation of Nature Red List category. Percentages on the y-axis are the degree of fulfillment of the conservation target. Covered species are those with geographic ranges that completely overlap with protected areas or meet a conservation target or above, for example, species with ranges ≥250,000 km^2 for which 10% of their range or more is protected. Partial-gap species are those that partially meet their conservation target (CR, critically endangered; EN, endangered; VU, vulnerable; NT, near threatened; LC, least concern; DD, data deficient).

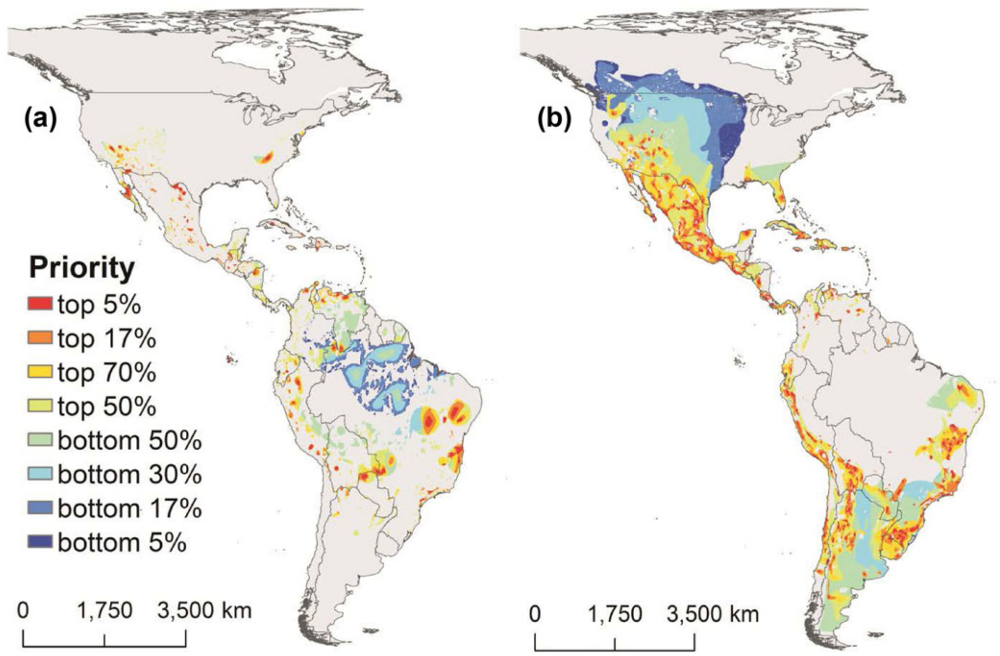

Figure 3. Distribution of priority areas for cactus conservation: (a) protected portion of the ranges of species that met their conservation target (covered species) (i.e., species with ranges of ≥250,000 km^2 for which only 10% of their geographical range was required to be included in protected areas to meet the target) and (b) portion of the range falling outside protected areas of species that partially met their conservation target (partial gap) and species completely outside protected areas (gap species). The top percentage of the landscape is the optimal solution that the prioritization algorithm finds to represent the features selected.

also encompassed the full ranges of 391 and 641 species, respectively. Of the species fully represented within the 17%, 50 were CR, 155 EN, 108 VU, 58 NT, and 269 LC. In addition, 183 species were gap species, of which 36 were CR, 49 EN, 15 VU, 11 NT, and 72 LC.

Discussion

Globally a larger percentage of cacti species were estimated to be absent from protected areas (18%) than has been found previously for mammals (9.7%) and birds (5.6%) and that this percentage was comparable with amphibians (21.9% [Butchart et al. 2015]). The pattern was yet more marked for threatened species; 32% of cacti not found in protected areas compared with 26.5% of amphibians, 19.1% of birds, and 16% of mammals. These outcomes likely followed from the small median geographic range sizes and high frequency of microendemism of cacti (and amphibians) relative to birds and mammals (Rodriguez et al. 2004*a*; Hernandez & Gomez-Hinostrosa 2011; Goettsch et al. 2015), hence the reduced probability of their range being captured within protected areas (although some protected areas have intentionally been established to protect narrowly distributed cacti species, e.g., Natural Protected Areas of Real de Guadalcázar in Mexico [Hernández et al 2001]). It is particularly troubling that 60% (60 species) of critically endangered cacti did not appear to reside within protected areas; these species were mainly found in Mexico, Brazil, and Peru (Supporting Information).

The countries with the highest proportion of threatened gap species were Argentina and Peru, with 51.8% and 45.2%, respectively (14 species each). It was unsurprising that the countries that were richest in cactus species and threatened cactus species, Brazil and Mexico, also had the highest number of threatened species that did not occur in PAs (39 and 37 species respectively). Many Brazilian threatened gap species were in Rio Grande do Sol, which is the main hotspot of threatened cacti (Goettsch et al. 2015) and currently has a very poor protected-area network (Supporting Information). However, these were also the 2 countries with the most threatened species occurring entirely within PAs (25 in Brazil and 9 in Mexico). Some of the threatened species in Brazil that were fully covered, according to the conservation targets, are relatively wide-ranging species (range $\geq$250,000 km^2) for which at least 10% of their range occurred within PAs. This was the case, for example, for *Cereus mirabella* and *Melocactus violaceus*, whose global populations have been significantly reduced (50% and 30%, respectively) because of habitat loss due to agroforestry and tourist development and are assessed as threatened under IUCN Red List criterion A based on population size reduction (and not based on range size [criterion B]). Even though it is well established that the use of conservation targets avoids being biased toward certain kinds of species (e.g., common species [Vimal et al. 2011]), the examples above highlight the importance of using additional prioritization features (e.g., species extinction risk [Fig. 2]) and not setting targets based exclusively on the representation of species' range size (Vimal et al. 2011). Although differentiated targets set more demanding representation thresholds for species with restricted ranges, they may disregard species which, despite having a large range, still face high levels of threats throughout their unprotected extent (Supporting Information).

In terms of priority areas for the conservation of cacti, the species-rich countries (e.g., Mexico, Brazil) and regions (e.g., Caribbean and the Andes) contained the top percentages of the landscape that best represent both protected and unprotected species ranges. Identifying priority areas for the protected extent of species that meet the conservation target can provide valuable evidence for land-management decisions for the protected land in question. Although covered species represented just 10.8% of all cacti, we showed that by protecting the top 5% of the priority areas representing gap and the unprotected portion of partial-gap species (Fig. 3b), it is possible to represent on average 51.08% of the remaining species ranges, including 249 (60%) threatened cactus species. This potential large gain for the existing PA network is possible because cacti tend to have smaller than average ranges and the area needed to cover a large percentage of a species range is thus relatively small.

The Global Cactus Assessment (GCA) established the baseline information needed for a complete evaluation of the extinction risk of cactus species, including detailed information on threats. Our gap analysis is a second step in narrowing the conservation priorities for cacti at a global level. An obvious next step to conserve this threatened plant group is to design conservation action plans at the regional or country level involving all relevant stakeholders who can ensure their implementation (Cowling & Pressey 2003) and integrating relevant socioeconomic variables (Naidoo et al. 2006). Particular attention needs to be given to the top 5% of the landscape we identified because it can significantly increase the protection status of many cactus species. The geographic distribution of important areas for conservation paired with the information gathered during the GCA on threats affecting cacti in these areas gives an important insight into how best to plan conservation (IUCN-SSC Species Conservation Planning Sub-Committee 2017). In principle, and as has been suggested before for the Chihuahuan Desert (Hernández & Gómez-Hinostrosa 2011), a network of small protected areas to conserve cactus species would work in some regions.

Municipal and private PAs that are not included in WDPA may play an important role in this regard, and their relevance should be closely assessed at regional scales. This is exemplified by some incongruences between the gap analysis and 6 threatened-gap species (Supporting Information) that are reported to occur in municipal and private protected areas by the IUCN Red List. However, the management of the species or sites would depend greatly on the threats affecting them. Species, such as the critically endangered *Cleistocactus hoffmannii* in Peru and the endangered *C. winteri* in Bolivia, both gap species and with extents of occurrence of <250 km^2, are affected mainly by collection by locals. Therefore, establishment of protected sites and management plans combined with education programs may be an effective means to conserve them. For other gap species, such as the critically endangered *Matucana ritteri* from Peru, where it is illegally collected and exported (Ostalaza 2013), close monitoring of populations, national legal regulation, and enforcement of international conventions like CITES would be required, and this would be the case for many of the illegally collected cacti. Search expeditions are needed to verify the persistence of species such as the critically endangered *Consolea falcata* from Haiti, whose only known population does not occur within a protected area and may have disappeared because of flooding in 2008 (Negrón-Ortiz & Griffith 2013) and hurricanes in 2016. A similar situation pertains to other species such as the critically endangered and possibly extinct in the wild *Cereus estevesii* in Brazil, the last population seen in 2002 at the border of land converted to grow biofuels (Braun & Taylor 2010).

We have provided a broad picture of the extent of protection of 1438 cactus species by the current network of protected areas; identified the most threatened cacti species occurring outside protected areas and identified areas that, if protected and managed, can significantly improve the in situ conservation of cacti. We also confirmed the need to assess the representation of large taxonomic groups, including major groups of plants, in protected areas and to generate more data to be able to do so. Only then will it be possible to measure accurately how well conservation targets established by international conventions are being met and how best to expand the protected-area network to benefit as much biodiversity as possible.

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Supporting Information

Map of the geographic distribution of protected areas used in this study (Appendix S1), percentages of species in each conservation target category according to their IUCN Red List Category (Appendix S2), percentages of species and of their ranges that fell within protected areas (Appendix S3), list of all cactus species, their distribution range area, percentage of distribution range under protection, conservation target, coverage status (i.e., gap, partial gap), countries of occurrence, and IUCN Red List Category (Appendix S4), map showing the distribution of priority areas for cactus species conservation for gap and threatened-gap cactus species (Appendix S5), list of the top 17% priority sites, their priority ranking, geographic coordinates, and country of occurrence for covered, gap, and the unprotected range of partial-gap cactus species (Appendix S6), and species range size and the percentage of the range protected by IUCN threat category (Appendix S7) are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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