The Role of Botanical Gardens in the Conservation of Cactaceae

KEVIN R. HULTINE, LUCAS C. MAJURE, VERONICA S. NIXON, SALVADOR ARIAS, ALBERTO BÚRQUEZ, BÁRBARA GOETTSCH, RAUL PUENTE-MARTINEZ, AND J. ALEJANDRO ZAVALA-HURTADO

The family Cactaceae contains some of the most iconic species of succulent plants, many of which are valued for their cultural, economic, and ecological value. However, over 75% of all species of cacti are in decline, largely because of the effects global environmental changes (GEC), including climate change. Mitigating the impacts of GEC on cacti will require a coordinated effort that combines conservation, research, and education. Botanical gardens are uniquely positioned to lead such an effort because their living collections and programs focus on conservation and research. A coordinated network of botanical gardens—with living collections serving as experimental gardens—could become a crucial hub for studying the impacts of climate change on cacti. A network of botanical gardens could open previously untapped funding avenues to support the research, education, and conservation of cacti and provide resources for underfunded botanical gardens in Latin America.

Keywords: botany, climate change, conservation, deserts, endangered species

Among the most notable of the approximately 30 lineages of succulents are cacti (Cactaceae), which includes the most spectacular New World radiation of succulent plants, with 1450–1850 species distributed throughout arid and semi-arid regions of the Americas (Pinkava 1999, Anderson 2001, Arakaki et al. 2011). Cacti are widely regarded for their cultural, economic, and ecological value, and some serve as important foundation species supporting numerous and highly specific pollinators, seed dispersers, and frugivores (Fleming et al. 1996, Wolf and Martinez del Río 2003). To persist in harsh arid environments, cacti have evolved many recognizable features, such as their photosynthetic stems that in many species store massive amounts of water and other resources to support growth, reproduction, and survival during hot and dry conditions. The remarkable diversity in stem geometry and size, as well as growth form in general (Hernández-Hernández et al. 2011), displayed within and among species makes cacti unique among plants in terms of their physiology and morphology.

Superimposed on the already stressful conditions that cacti thrive in are global environmental changes caused largely by expanding human enterprise, including intensive land clearing for agriculture, urban development, mining, air pollution (e.g., ozone and nitrogen deposition), the introduction and invasion of exotic species, and climate change (see Goettsch et al. 2015). Given that species of cacti often have very small distributions, the impact of global environmental change (GEC) has the potential to be dramatic and for many species devastating. Of the 1478 species of cacti evaluated by the Global Cactus Assessment (GCA), 31% were found to be threatened, listed as *critically endangered*, *endangered*, or *vulnerable* (IUCN 2014, Goettsch et al. 2015) following the IUCN Red List Categories and Criteria (IUCN 2001), with at least 75% of these species currently in decline (IUCN 2014). The large majority of threatened cacti are endemic to developing nations (figure 1), where conservation programs and multinational cooperation to mitigate the impacts of GEC are limited or severely lacking (although see Duarte et al. 2014). Many of these threatened species face extinction before the end of the twenty-first century, whereas others are almost certain to experience significant demographic declines and contraction of geographic distribution ranges.

Mitigating the impacts of GEC on cacti and the resources that flow from species of cacti to dependent consumers and human populations will require a coordinated effort that combines conservation, research, and education leading to government and community support (Primack and Miller-Rushing 2009). Botanical gardens are uniquely positioned to lead such an effort as a result of their programs that focus specifically on plant, systematics, conservation, and long-term ecological research. In this article, we discuss the crucial resources that botanical gardens provide for leading research and conservation efforts of threatened plant species in the face of GEC, particularly climate change. Our discussion will focus on plants in the family Cactaceae because of the considerable cultural, ecological, and economic importance and high levels of threat to these taxa throughout the

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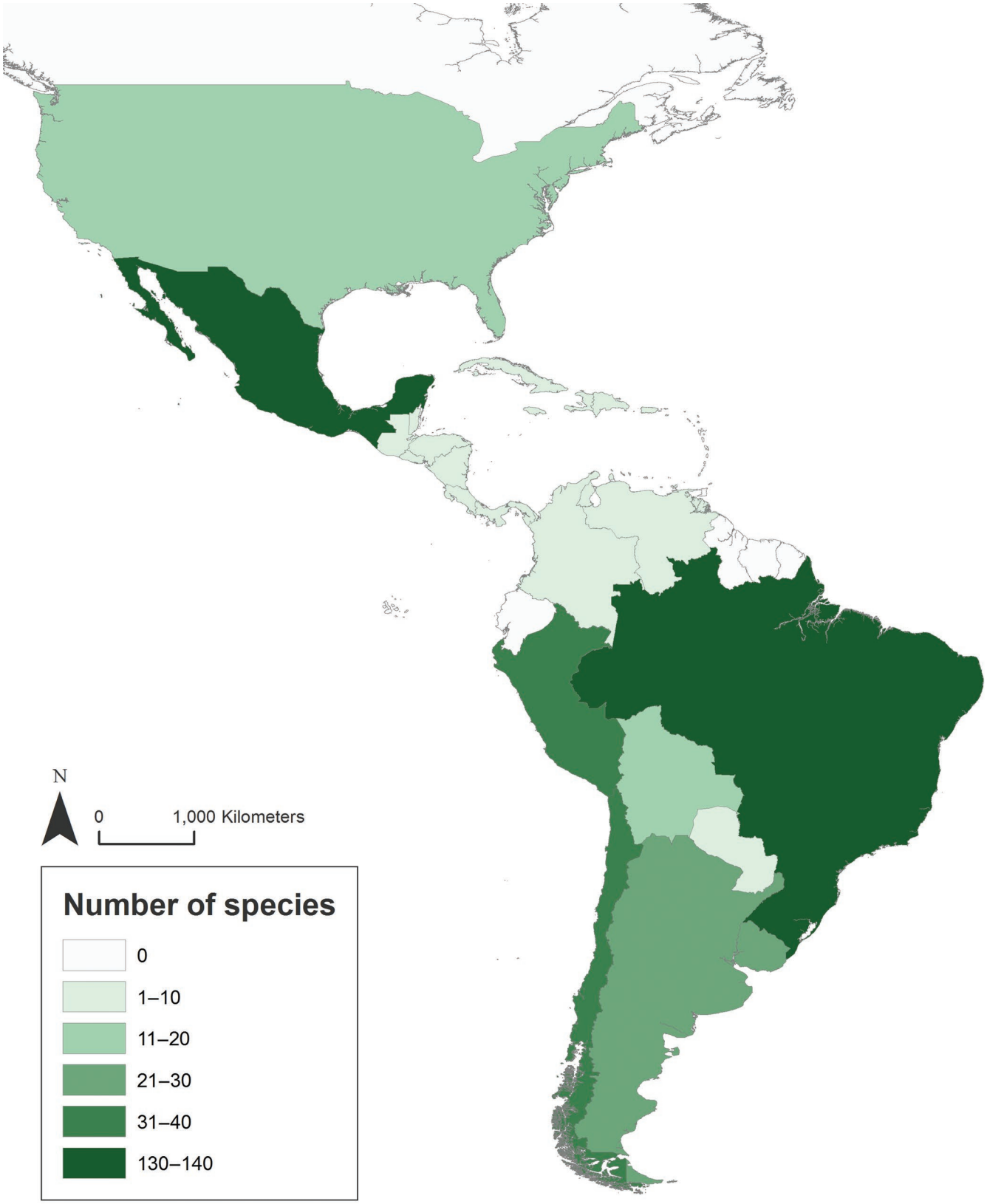

Figure 1. A map showing the number of threatened cactus species (Cactaceae) per country throughout the Americas. Data were compiled from The International Union for the Conservation of Nature Red List of Threatened Species.

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Americas. We will establish a framework for developing a coordinated international network to study the effects of climate change on cactus physiology, reproductive phenology, and productivity. Our framework will highlight data visualization tools that, if coupled with traditional botanical garden resources, would lay the groundwork for identifying conservation strategies for protecting cacti given the environmental changes that are predicted by different international agencies.

Climate-change impacts on species of Cactaceae

Climate change is expected to bring substantially warmer atmospheric temperatures and increased aridity to the Earth's arid regions over the next century (Seager et al. 2007, Karl et al. 2009). These temperature increases have the potential to exert strong selection pressures on plants to the extent that many species will undergo considerable shifts in their biogeography, population structure, and physiology. Populations occurring in the warmest and driest extremes of current species ranges are most vulnerable to climate change, particularly where populations are adapted to a relatively narrow range of temperature regimes (O'Neill et al. 2008). For example, the endangered *Copiapoa solaris* (F. Ritter) from the Antofagasta region in Chile has populations that are already being affected by extended droughts as a likely product of climate change (Walter et al. 2013). The ability for *C. solaris* and other species to cope with shifting environmental conditions will determine its long-term distribution and survival in the face of climate change and other global change processes (Parmesan 2006).

Temperature increases may affect stem succulents, such as cacti, in several distinct ways. Because of their stem shape and mass, cacti in desert habitats can attain some of the highest tissue temperatures experienced by vascular plants (Smith et al. 1984). Cactus stems typically have an exceptionally high heat capacity, especially those with high volume–to–surface area ratios (V:S) resulting in inefficient heat dissipation by convection (Smith et al. 1984). For example, the iconic giant saguaro, *Carnegia gigantea* (Engelm.), can attain surface temperatures of over 55 degrees Celsius (°C). Warmer temperatures may extend tissue temperatures of succulent stems beyond their thermal tolerances, especially on the warm edge of a species distribution. Likewise, species that primarily use the Crassulacean acid metabolism (CAM) photosynthetic pathway, including almost all species of cacti, may be among the most vulnerable taxa to the effects of rising temperature. CAM plants usually open their stomata at night to reduce water loss as they acquire carbon dioxide (CO_2), but temperature increases are expected to be most profound during nighttime hours (Karl et al. 1993). Warmer nighttime temperatures will result in a higher evaporative demand and consequently higher rates of water loss from cactus plants during CO_2 uptake. Higher water losses may result in extended periods of critical water limitations, especially during periods of extreme drought.

For many species of cacti, the direct effects of climate change on physiology, growth, and fitness may actually be small compared with disruptions in plant–pollinator systems caused by climate change–induced shifts in flowering phenology. Some plants have developed specialized relationships with obligate pollinators and may therefore be more susceptible to climate change than are plants that have evolved more generalized pollinator systems (Fensinger 1983, Bond 1994, Fleming et al. 2001). For example, the majority of columnar cacti in the tribe Pachycereeae (approximately 300 species) have specialized pollination relationships with nectar-feeding bats (Valiente-Banuet et al. 1996, Nassar et al. 2003, Bustamante et al. 2010). Many species of bats are migratory, and their timed arrival and departure at any one place are expected to synchronize with the timing of flowering. As a consequence, shifts in flowering phenology could have critical impacts on fruit set, seed dispersal, and the subsequent population structure and geographic distribution of a large number of cacti species. Many studies have now documented shifts in flowering phenology related to a warming climate (Parmesan and Yohe 2003, Visser and Both 2005, Manzel et al. 2006). The columnar cactus species, *Stenocereus thurberi* (Emgelm.), is one example in which the flowering phenology is closely linked to the variance in temperature prior to flowering and ecologists have documented years in which the timing of flowering is decoupled from the arrival of pollinating bats (Bustamante and Búrquez 2008, Bustamante et al. 2010).

Why botanical gardens for global change research and conservation of Cactaceae?

Botanical gardens have a rich tradition for leading plant research and conservation programs. In fact, Botanic Gardens Conservation International (BGCI; *www.bgci.org*), a network of 500 botanic gardens, is recognized as the largest plant conservation network in the world. Many of the most impressive living plant collections, seed banks, and herbaria are located in botanical gardens. The Royal Botanic Gardens Kew, for example, is internationally recognized for its extensive collections and databases that catalogue plant biodiversity around the globe. Likewise, the Missouri Botanical Garden's Center for Conservation and Sustainable Development works with many groups around the globe to promote plant research and conservation. Both Kew and the Missouri Botanical Garden spearhead collaborations with other botanical gardens to document and mitigate the impacts of GEC, including climate change. These gardens take full advantage of their extensive collections and expertise to build large-scale programs to combat the effects of climate change on global plant biodiversity. These programs, in turn, are important models for establishing specific research and conservation programs to protect plants in the family Cactaceae, since coordinated efforts to study and protect this plant family are currently lacking.

Because their plant collections originate from diverse regions, botanical gardens effectively mimic common

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garden settings that, in turn, make them an important asset for research and conservation. The remarkable variety of plant species from different geographic areas provides a unique opportunity to monitor a wide range of physiological and phenotypic traits of plants growing under shared local conditions (Primack and Miller-Rushing 2009). The living collections at the Desert Botanical Garden (DBG), for example, located on the northern edge of the Sonoran Desert in Phoenix, Arizona, include 1319 species of cacti, well over half of the total number of species recognized in the cactus family. The broad taxonomic representation at DBG and other botanical gardens makes available an unprecedented resource to conduct comparative evolutionary, ecological, methodological, and phylogenetic studies of cacti and other plant taxa (Miller-Rushing et al. 2007, Donaldson 2009, Hernández-Hernández et al. 2011, Majure et al. 2012a, 2012b, 2013, Majure and Puente 2014, Sánchez et al. 2014).

In addition to living collections, botanical gardens possess other resources to support research and conservation projects of succulent plants. The value of living collections is often enhanced by meticulous record keeping by highly trained and experienced research or horticultural staff. These records often contain information on the tolerance of plants to various environmental conditions, including extremes in temperature. Many botanical gardens also contain herbarium collections that capture a particularly rich source of historical information about the distribution, phenology, physiology, and genetics of plants growing either in their native ranges or in living collections. Taken together with various educational and outreach programs, botanical gardens have the potential to form an important "firewall" against extinction by studying and protecting highly threatened species of cacti from the effects of GEC. However, for research and conservation efforts to become effective across large geographic regions, programs will need to be coordinated across an international network of botanical gardens, government, and conservation-based institutions.

Wild-collected, live collections in botanical gardens that are curated with their respective locality data are of prime importance for research. These collections are especially important for plant clades that are hard to acquire and maintain, such as those in Cactaceae and Agavaceae families, which require considerable space and very specialized care and growing conditions. Collections of this type are important for evolutionary studies including cytogenetics, phylogenetics, and especially phylogenomic studies, in which larger amounts of fresh tissue may be necessary for the recovery of sufficient quantities of DNA. Collections at the DBG and the Botanical Garden of Instituto de Biologia (JBIB) in México City, for example, have been used for a variety of evolutionary and ecological studies. These include phylogenetic and cytogenetic studies of the prickly pear cacti or nopales and relatives (Majure et al. 2012a, 2012b, 2013, Majure and Puente 2014) and, more broadly, the entire family Cactaceae (Hernández-Hernández et al. 2011, Vázquez- Sánchez et al. 2013, Sánchez et al. 2014, Vazquez-Lobo et al. 2015, Cruz et al. 2016). Likewise, collections at DBG and JBIB are being used extensively in phylogenomic and ecophysiological studies (Williams et al. 2014, Hultine et al. 2016) to fill in evolutionary gaps in our knowledge of the family Cactaceae.

Similar to the role zoos play in wildlife conservation (Tribe and Bootha 2003), botanical gardens can serve as a repository for plants of conservation concern (Oldfield and Hunt 2010). Likewise, population-level collections (i.e., in which individuals from different populations are represented within a collection) can be maintained *ex situ* when enough space is available (e.g., Griffith et al. 2015). Those collections can be made available for conservation genetic studies of the species (Tew et al. 2012) to aid in the structuring of reintroduction and management plans for populations.

A group with around 1800 species, such as the family Cactaceae, offers a great opportunity for the application of DNA barcoding (i.e., developing a system of genetic markers specific to a given species). A barcoding database could also aid substantially in the identification of wild-collected specimens that may not present sufficient morphological characters for proper identification when grown in cultivation. Barcoding these often-threatened species also could aid in the identification of confiscated plant material and therefore substantially increase conservation efforts, especially for rare and endangered taxa. DNA barcoding has been attempted for Cactaceae but without sufficient resolution at the level of species (Yesson et al. 2011), so a more concerted effort using more variable plastid and nuclear loci would be necessary to develop a sufficiently robust data set.

DNA and seed banking are two other ways by which botanical gardens increase the quality of their collections, not only in terms of research of specific plant groups but also for aiding conservation efforts. Many gardens have substantial seed collections consisting of a remarkable number of species from desert regions of the Americas, which are used to boost living collections and to serve as a repository for threatened species, as well as for research purposes. Because it is well known that certain botanical gardens are very rich in some collections while deficient in others, cross-collaboration among botanical gardens for all of the above-stated types of projects would enrich the quality of any type of study or conservation effort.

A network of reciprocal common gardens

A major advantage that botanical gardens offer compared with other sites of long-term ecological research is that they often contain many species that can not be found growing together under natural conditions. Moreover, many botanical gardens contain species that were collected from diverse geographical areas providing rich phylogenetic diversity within their living collections.

Identifying the impacts of climate change on cacti and the many ecosystem services they provide will require a comprehensive monitoring program that incorporates a large number of species across broad geographical areas and climate gradients. Botanical gardens, because of their diverse

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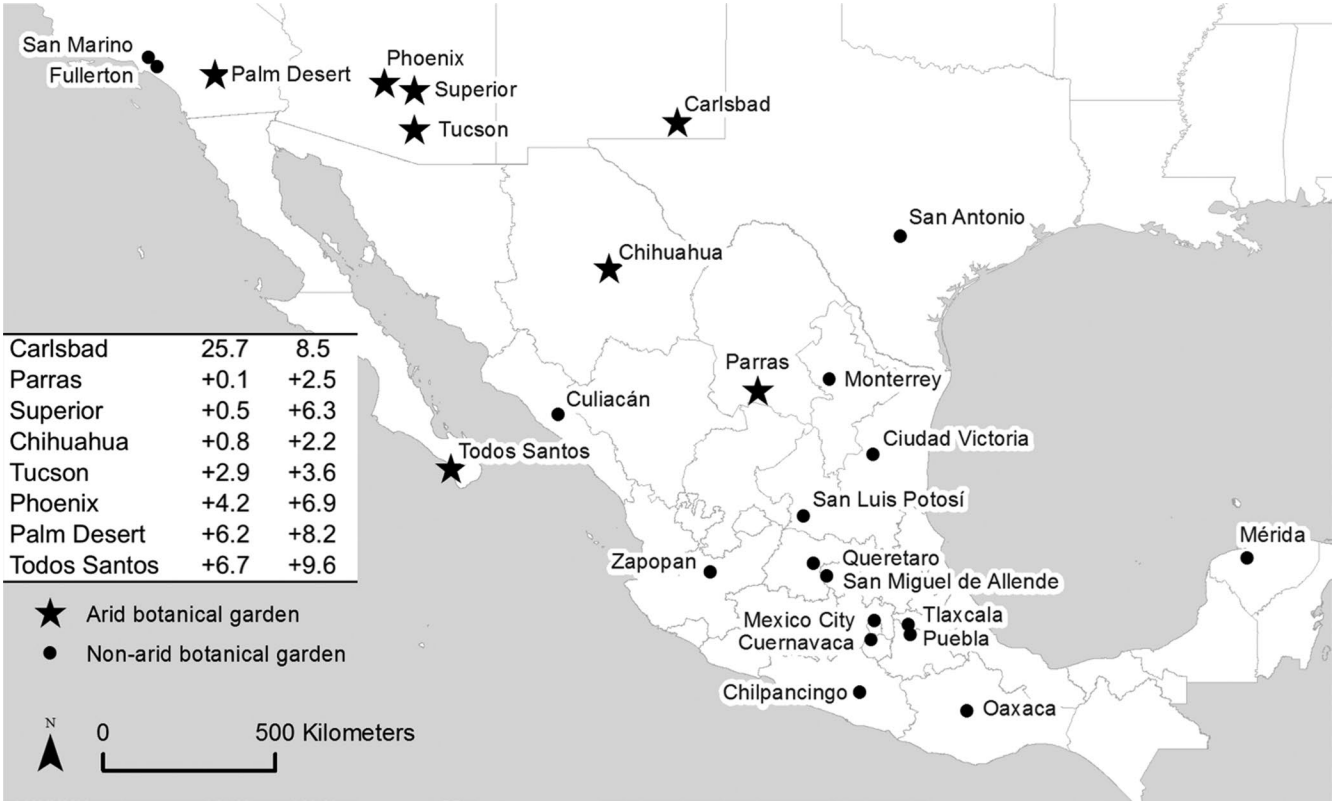

Figure 2. The locations of major botanical gardens in the southwestern United States and in Mexico. The garden locations depicted with stars are those that occur within one of the major deserts of North America, including the Chihuahuan, Mojave, and Sonoran Deserts. The table inset shows the temperature difference (mean annual max and min degrees Celsius, °C) between Carlsbad, New Mexico, United States (garden location in the coolest climate), and each garden location in desert regions.

set of assets, have the networking capacity to lead such a program. Of the 3243 botanical gardens profiled worldwide by BGCI, 114 specifically list Cactaceae as a major part of their living collections, and Cactaceae plants are present at many other botanical gardens recognized by BGCI. Many of these gardens are located within one of the primary centers of cactus diversity in Mexico and the southwestern United States. For example, there are 25 gardens located in Mexico and the southwestern United States that span a remarkably broad climate gradient, including eight gardens that are located within the boundaries of the Mojave, Sonoran, or Chihuahuan Deserts (figure 2; the names and locations of these botanical gardens are listed in supplemental table S1). These eight desert botanical gardens alone could be used to establish a reciprocal garden network that spans a 6°C mean annual maximum and 10°C minimum temperature gradient (figure 2). It is unlikely that common species occur in all of these living collections. Nevertheless, there are many species, including those listed as threatened and those that offer strong foundational support for desert communities, that occur in two or more gardens, thereby providing a framework to study individual species occurring under a broad range of climatic and environmental conditions.

A recognized weakness to the common garden framework is that reciprocal genotypes are rarely distributed at multiple garden locations. This, in turn, will limit opportunities to evaluate patterns of local adaptation to environmental conditions at the level of genotype or population. However, the common garden concept can still provide critical data on species sensitivity given the remarkable diversity cacti species display in morphology and physiology. For example, species of cacti contain a range in stem volume–to–surface area ratio (V:S) that spans more than two orders of magnitude (Mauseth et al. 2000). Recent evidence suggests that stem V:S in cacti constrains plant sensitivity to extreme aridity (Williams et al. 2014, Hultine et al. 2016). A network of botanical gardens could provide a unique opportunity to test for theoretical relationships between stem morphology, growth, physiology, and climate-related stress because gardens have the capacity to grow many species together that could not be found growing together under natural conditions. Nevertheless, future programs should aim to expand the reciprocal common garden concept by assuring that whenever possible, common genotypes are identified and propagated at multiple gardens to study relationships between phenotypic trait expression and climate.

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Table 1. Suggested measurement priorities that could be reciprocated in a botanical garden research network that focuses on the study and conservation of species of Cactaceae.

Category	Subcategory	Frequency
Environmental	Air temperature	Subhourly–hourly
	Soil temperature	Subhourly–hourly
	Humidity	Subhourly–hourly
	Precipitation	Subhourly–hourly
	Watering schedule (if applicable)	Daily–monthly
	Shading	Monthly–annual
	Edaphic conditions	One time
Morphological/physiological	Plant surface temperature	Subhourly–hourly
	Height growth	Monthly–annual
	Lateral stem growth	
	Cuticle thickness	Monthly–annual
	Spine production	
Phenological	Flowering, fruit set	Weekly–monthly
	Pollinator presence and habit	Weekly–monthly
	Foliage habit (if applicable)	Monthly–annual
Accession or source population	Collection location with data on microenvironmental conditions	One time
	Number of genotypes per species	One time

In order to establish a climate-change monitoring program from living collections, curators, ecologists, and other researchers will need to identify a set of measurement variables and protocols that can be reciprocated across a network of botanical gardens. As we discussed earlier, living collections and herbaria provide unique opportunities to collect a diverse set of information on plants and their environment. Table 1 lists of variables that could be prioritized, broken into four primary categories: (1) environmental, including key climate variables; (2) morphological or physiological; (3) phonological; and (4) accession or source population information. For environmental information, data sets could be broken into subcategories that include climate (hourly to subhourly measurements of temperature, humidity, and precipitation); watering schedules (if any); microsite information, such as shading; and edaphic conditions.

Many botanical gardens already have weather stations operating on their property that could be incorporated into a single network using currently available communication and data cloud technology. Gardens that participate in a shared climate data network should consider incorporating standards for sensor choice, measurement frequency, and accessibility of real time and archived data sets. A web-based data clearinghouse that combines continuous data streams from weather stations with discrete data inputs from any number of plant and environmental parameters could be designed using data visualization platforms such as those used by the US Geological Survey's Water Information System (*http://waterdata.usgs.gov/nwis/rt*), the National Phenology Network (*www.usanpn.org*), or the National Meteorological Service (CONAGUA) of Mexico (*http://smn.cna.gob.mx*), among others. In addition to data streams, scientists and curators could share protocols and metadata files and other resources that would serve to homogenize data-acquisition standards across affiliated institutions. Such a network could follow the example of Project Budburst (*http://budburst.org/aboutus*), a partnership of researchers, educators, and citizen scientists. Spearheaded by the Chicago Botanic Garden, this program observes, records and shares data on plant phenophases throughout the year. Undoubtedly, staff at individual gardens will hold unique areas of expertise and resources that can be transferred to staff at other institutions within a data-sharing network. Once a data visualization platform is established, information on plant growth, physiology, and phenology can be easily compared with environmental conditions measured across broad gradients. In turn, the shared information from multiple institutions would greatly enhance our understanding of how species of cacti and other plants might respond to the effects of climate change and other global change processes.

The saguaro example

Giant saguaro plants (*Carnegia gigantea*) are not only beloved landscape elements but also unique organisms in terms of physiology, morphology, and genetic structure. Recently, it was found that the chloroplast genome of the saguaro is the smallest of all vascular plants yet documented—a feature potentially associated with extreme environments (Sanderson et al. 2015). This long-lived species occurs in one of the driest and least productive regions of subtropical America and is an important foundation species throughout its range (Fleming et al. 1996, Wolf and Martinez del Rio 2003). However, the capacity for giant saguaro to serve as a foundation species is dependent not only on rare surges of seedling establishment during moist years and survival through long, stressful periods of limited rainfall but also on the year-to-year success of flower and fruit production that other species feed on. A large flower crop and subsequent nectar production is crucial for protecting migratory corridors for nectarivores in the Sonoran Desert region, including the endangered lesser long-nosed bat (*Leptonycteris curasoae* Miller). The balance between the allocation of limited internal resources to flower or nectar production and other essential plant functions, such as resource acquisition, growth, and survival, is therefore a key aspect of the physiological ecology of giant saguaro and other desert perennials. Reproduction in giant saguaro commences only in plants greater than

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Figure 3. Giant saguaros (*Carnegia gigantea*) during the monsoon season at the Desert Botanical Garden in Phoenix, Arizona (upper photo), and giant saguaros during a winter storm at the Boyce Thompson Arboretum 90 kilometers east of Phoenix, where mean annual maximum temperatures are almost 4°C cooler than in Phoenix.

approximately 3 meters in height, depending on geographic location and moisture conditions. The size and age at which individuals reach reproductive maturity decline across gradients of increasing moisture availability (Drezner 2008), and interannual variation in flower and fruit production is highly correlated with precipitation (Steenbergh and Lowe 1977).

Because giant saguaro is a long-lived, slow-growing plant that is intolerant of frost, there are only a handful of botanical gardens that have mature native stands of saguaro as part of their living collections, including the Sonoran Desert Museum near Tucson, Arizona; the Boyce Thompson Arboretum in Superior, Arizona; and the Desert Botanical Garden in Phoenix, Arizona (all botanical gardens within the Sonoran Desert region; see figure 3). Where they do occur, these saguaro collections offer rare but invaluable opportunities to study the relationships among climate, plant growth, reproductive phenology, and pollinator–plant interactions of this iconic plant. Most botanical gardens have the infrastructure to provide supplemental irrigation that, if quantified, can turn watering schedules into research programs that investigate how precipitation patterns affect growth and reproduction. Watering treatments could become powerful tools for studying climate-change impacts on saguaro and other long-lived perennial plants if they can be replicated across a network of botanical gardens or other locations. For example, the mean mininum and maximum temperatures vary at the three Sonoran Desert gardens by about 4°C during the warmest month (July) and about 3°C during the coldest month (January). These temperature ranges mirror the expected increase of temperature in the Sonoran Desert region over the next several decades (Seager et al. 2007) and therefore provide an excellent gradient to study the potential impacts of climate change on saguaro productivity, phenology, and reproductive output.

In addition, the urban placement of many botanical gardens provides critical habitat connectivity along migration corridors. Supplemental watering could be an important asset for migrating frugivores and nectarivores by enhancing flower and fruit production of saguaro and other long-lived perennials. Because reproductive output in saguaros increases with precipitation (Drezner 2008), a highly reliable source of food for visiting consumers during drought years may be concentrated in living collections that receive supplemental irrigation.

Leveraging limited resources through a shared network: Strength in numbers

Arguably the greatest challenge that confronts many botanical gardens, museums, and other cultural institutions is economic instability, which is difficult to forecast over annual or even subannual cycles. Most botanical gardens acquire the majority of their revenue through visitation, private donation, and membership, all of which can rise and fall with

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local economic conditions. For many botanical gardens, the global economic collapse in 2008 resulted in massive budgetary shortfalls that forced institutions to cut programs and staff involved with horticulture, research, and conservation. The result of these cuts has forced many gardens to re-evaluate their capacity to maintain living collections, herbaria, research programs, and other assets that are essential to the core mission of most botanical gardens.

A legacy effect of the "great recession" has motivated many cultural institutions to identify new revenue streams and build diversified financial portfolios as protection from future economic instability (Powledge 2011). Although botanical gardens and other institutions are excellent at attracting visitors and building membership roles, they often lack the marketing and development expertise to attract funding from agencies and foundations focused on research and conservation. Stronger networking among botanical gardens is a promising approach for building visibility beyond the local and regional public. This "greater than the sum of its parts" approach could buffer key assets, such as living collections and highly trained staff, from economic instability. In addition to Project Budburst, a good starting point would be to follow the model started by the *Quercus* Multisite group as part of the American Public Garden Association's Plant Collections Network (*https://publicgardens.org/programs/plant-collections-network/napcc-collections/quercus-multisite*). The *Quercus* Multisite is a consortium of 15 gardens that are collectively dedicated to *Quercus* germplasm conservation. A similar consortium of institutions with cactus collections would greatly benefit efforts to maintain the rich taxonomic diversity within the cacti family.

Given the cultural significance of cacti throughout the Americas, a network of botanical gardens dedicated to research and protection of threatened species of cacti could provide many new avenues for funding from public agencies that support scientific research to private foundations that prioritize conservation programs. In particular, an international network of botanical gardens that leverage assets from living collections for research and conservation could yield currently untapped opportunities for funding from agencies such as the National Science Foundation in the United States and the National Council of Science and Technology in Mexico. In turn, these collaborative efforts could facilitate future long-term international connectivity and cooperation for the interdisciplinary research, education, and conservation of cacti and other threatened desert plants. Strong bi- or multinational collaborations that involve a network of botanical gardens and academic institutions would pave the way for student exchanges and cross-boundary training in desert plant ecology, plant systematics, molecular biology, and ecophysiology among other disciplines related to research and conservation of desert succulents.

Conclusions

The complexity and magnitude of threats to desert ecosystems and species of Cactaceae are well documented. Currently, almost one-third of all species of cacti are threatened, and many of these threatened species face potential extinction before the end of the twenty-first century, largely because of the impacts of intensive land-use change and climate change. Botanical gardens are uniquely positioned to lead a coordinated effort that combines research and education for the conservation and protection of cacti. Living collections, the hallmark of botanical gardens, can be turned into important assets for climate-change studies in which common species are probed simultaneously at multiple locations that span a broad geographical area and climate gradient. A coordinated botanical garden initiative, with living collections serving as a networked resource, could be used to launch critical studies on cactus plant fitness, productivity, and reproduction under controlled conditions. A network of botanical gardens throughout the Americas, for example, could open previously untapped avenues for funding from public agencies that support scientific research to private foundations that prioritize conservation programs. Botanical gardens that highlight Cactaceae as part of their living collections should work in collaboration to build a clear mission that emphasizes (a) collaborative research and conservation programs to protect species of cacti; (b) clear advocacy for desert and arid region conservation as part of each botanical garden's core mission; (c) the exhibition of living collections that promotes the conservation of cacti and the species they support; (d) educational programs that target K–12 students, college students, and adults that highlight the ecological, economic, and cultural importance of cacti; and (e) the commitment to acquire sufficient funding to support research and conservation activities and build collaboration within and across international boundaries. Botanical gardens, such as the Desert Botanical Garden in Phoenix, that already possess a comprehensive research program with dedicated staff and infrastructure are poised to lead such an effort.

Supplemental material

Supplementary data are available at *BIOSCI* online.

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Kevin R. Hultine (khultine@dbg.org), Lucas C. Majure, Veronica S. Nixon, and Raul Puente-Martinez are affiliated with the Department of Research, Conservation and Collections, at the Desert Botanical Garden, in Phoenix, Arizona. Salvador Arias is with Jardín Botánico of the Instituto de Biología at Universidad Nacional Autónoma de México. Alberto Búrquez is affiliated with Unidad Hermosillo of the Instituto de Ecología at the Universidad Nacional Autónoma de México, in Hermosillo, Sonora, Mexico. Bárbara Goettsch is affiliated with the Cactus and Succulent Specialist Group, Species Survival Commission, of the International Union for Conservation of Nature, in Cambridge, United Kingdom. J. Alejandro Zavala-Hurtado is affiliated with the Departamento de Biología at Universidad Autónoma Metropolitana, in Mexico.

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