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RESEARCH

Botanic Gardens Are Important Contributors to Crop Wild Relative Preservation

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ABSTRACT

Humans rely on crop wild relatives (CWRs) for sustainable agriculture and food security through augmentation of crop yield, disease resistance, and climatic tolerance, among other important traits. Many CWRs are underrepresented in crop gene banks. With at least one-third of known plant species maintained in botanic garden living collections, the botanic garden community serves as an important global ex situ network that supports plant conservation and research around the world. We sought to characterize botanic garden holdings of CWRs and demonstrate capacity for cross-sector coordination in support of CWR ex situ preservation. To do this, Botanic Gardens Conservation International US (BGCI-US), in partnership with the United States Botanic Garden, used the BGCI PlantSearch database to conduct an ex situ survey of CWRs maintained in botanic gardens. We found 28.6% of global priority CWR taxa and 75.4% of US priority CWR taxa represented in botanic gardens. By comparing with priority CWR holdings in crop gene banks, botanic gardens maintain 22 global priority and 108 US priority CWR taxa not reported by crop gene banks. A combination of crop gene bank and botanic garden holdings results in broader taxonomic coverage. Looking more closely at 10 US priority CWR species, findings demonstrate that botanic gardens have the capacity to fill critical CWRs gaps in crop gene bank collections, and botanic gardens maintain samples from wild populations not represented in crop gene banks. We call on the crop gene bank and botanic garden communities to use an integrated collections development approach for further coordination, complementarity, and duplication of ex situ CWR plant genetic resources.

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Abbreviations: BGCI, Botanic Gardens Conservation International; CWR, crop wild relative; GRIN, Germplasm Resources Information Network.

Crop wild relatives (CWRs), plants that have "an indirect use derived from its relatively close genetic relationship to a crop," provide important genetic diversity needed by breeders and scientists to develop a wide range of crop plant adaptations (Maxted et al., 2006, p. 2680). Benefits such as increased production, better nutrition, drought tolerance, and pest and disease resistance have been made possible through the use of CWRs and allowed for more consistent and sustainable yields of conventional crops for decades (Dempewolf et al., 2017; Guarino and Lobell, 2011; Hajjar and Hodgkin, 2007; Maxted et al., 2006, 2012). Like many plant species, CWRs face several threats including climate change, habitat fragmentation and degradation, invasive species, overexploitation, and agricultural expansion (Kell et al., 2012; Vincent et al., 2013). Studies have found that significant ex situ gaps exist among crop gene bank collections of CWRs (Castañeda-Álvarez et al., 2016; Khoury et al., 2019). Findings by Castañeda-Álvarez et al. (2016), for example, that nearly one-third of global CWRs have no ex situ germplasm accessions, and <5% are considered adequately represented in crop gene banks, suggest that the current ability to adequately preserve CWRs in crop gene banks is lacking.

Botanic garden holdings include the use of living plant specimens in traditional display beds indoors or outdoors, as well as nursery collections, common garden plantings, seed orchards, or field gene banks, as well as a growing number of world-class

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facilities with preserved tissues and seed accessions. The origin, or source, of plant material maintained in botanic gardens can vary broadly, from cultivated or horticultural origin, to documented wild origin. The PlantSearch database is used to network and connect >1100 botanic garden living plant, seed, and tissue collections around the world (BGCI, 2018). PlantSearch reveals that botanic gardens maintain at least 30% of all known plant species in ex situ collections, including >41% of species assessed as globally threatened (Mounce et al., 2017). In the United States, botanic gardens maintain an estimated 40% of native threatened plant species (Kramer et al., 2011). While many botanic gardens maintain plant collections with ornamental and aesthetic value for public enjoyment, a growing number of botanic gardens around the world collect and maintain genetically diverse and wild-origin plant material to support research and conservation (Dosmann and Groover, 2012; Friedman et al., 2016). When combined, these collections form a metacollection of plants that can be maintained, augmented, and shared in coordinated and intentional ways to support research and conservation (Griffith et al., 2019).

The globally distributed network of botanic gardens serves as an important safety net for wild plant genetic resources, as well as valuable contributors to ongoing dialogues within the scientific community and the general public. The ex situ metacollection of wild species maintained in botanic gardens likely includes CWR germplasm valuable for the future of crop breeding and food security. Botanic gardens also offer world-class facilities and expertise in ex situ preservation and plant breeding and provide valuable outreach opportunities to >500 million botanic garden visitors and students each year on topics including crop diversity and food security (Krishnan et al., 2019; Miller et al., 2015; O'Donnell and Sharrock, 2018).

Given the gaps in gene bank CWR collections, and the capacity of botanic gardens to maintain such species, there appears to be significant potential for additional collaboration and alignment of CWR preservation by the global crop gene bank and botanic garden communities. To explore this potential, we set out to characterize the depth and breadth of botanic garden CWR holdings, describe the level of documentation and types of CWR collections maintained, and demonstrate current and potential capacity for botanic garden living collections to support CWR preservation, breeding, and research.

MATERIALS AND METHODS

We used two published lists of *priority* CWR taxa, one global in scope and the other focused on the United States. The global list included 1103 CWR taxa identified as globally valuable for food security, income generation, and sustainability (Castañeda-Álvarez et al., 2016), many of which were found to require further conservation action. The US list included 232 priority, underrepresented CWRs and wild utilized species with native distributions in the United States, many of which have been assessed as threatened in the wild (Khoury et al., 2013). Both lists were aligned with synonyms based on Germplasm Resources Information Network (GRIN) Taxonomy (USDA-ARS-NPGS, 2018b) to ensure a comprehensive cross-reference of botanic garden holdings.

The Botanic Gardens Conservation International (BGCI) PlantSearch database, a taxon-level, global repository of botanic garden collections data, includes nearly 1.5 million collection records from >1100 botanic garden living plant, tissue, and seed bank collections worldwide. PlantSearch is used to track ex situ conservation progress for threatened and priority plant taxa (BGCI, 2018). PlantSearch also connects thousands of online research requests for information and material to botanic garden collection managers each year. Each taxon record reported by an institution to PlantSearch means that at least one accession and at least one living or viable specimen is present in that garden's collection. To assess representation of CWRs in living collections maintained in botanic gardens, the CWR lists were matched with plant names reported to PlantSearch as of May 2018. The resulting inventory allowed us to analyze presence and absence of priority CWRs maintained in botanic gardens.

We also compared botanic garden holdings with crop gene bank holdings to assess complementarity and potential synergy between the botanic garden and crop gene bank communities. To do this, we used a list of active accessions in Genesys, a database of plant genetic resources for food and agriculture maintained in gene banks worldwide (Genesys, 2019).

We also sought to characterize infraspecific diversity and documentation of botanic garden holdings of CWRs, so we selected 10 species from the US priority CWR list from Khoury et al. (2013) for a more detailed look at accessions provenance. The target species were selected to represent a range of associated crops and uses, geographic distributions, growth habits, and presence ex situ collections. Botanic garden holdings were identified for survey based on PlantSearch data, and in July 2018, we contacted curatorial staff at 46 botanic gardens via e-mail with a request for provenance data associated with all living accessions of the 10 target species. We compiled accession records from each botanic garden into standardized fields including provenance type, collection year, source, and country, municipality, county, and locality of origin. Using this information, we assessed approximate ex situ representation of wild populations. To directly compare botanic garden holdings with crop gene bank holdings, we mapped the historical natural range provided by Bartosh (personal communication, 2018) with wild origin collections for *Juglans hindsii* (Jeps.) R. E. Sm. reported by crop gene banks and botanic gardens.

RESULTS

Using the lists of priority global and US CWRs and BGCI's PlantSearch database, we found a significant number of CWRs maintained in botanic gardens. Nearly one-third (315, 28.6%) of global priority CWR taxa and three quarters (175, 75.4%) of US priority CWR taxa were reported to PlantSearch by botanic gardens (Fig. 1). The most common CWR taxa reported by botanic gardens are long-lived ornamental species widely available in the nursery trade (Table 1).

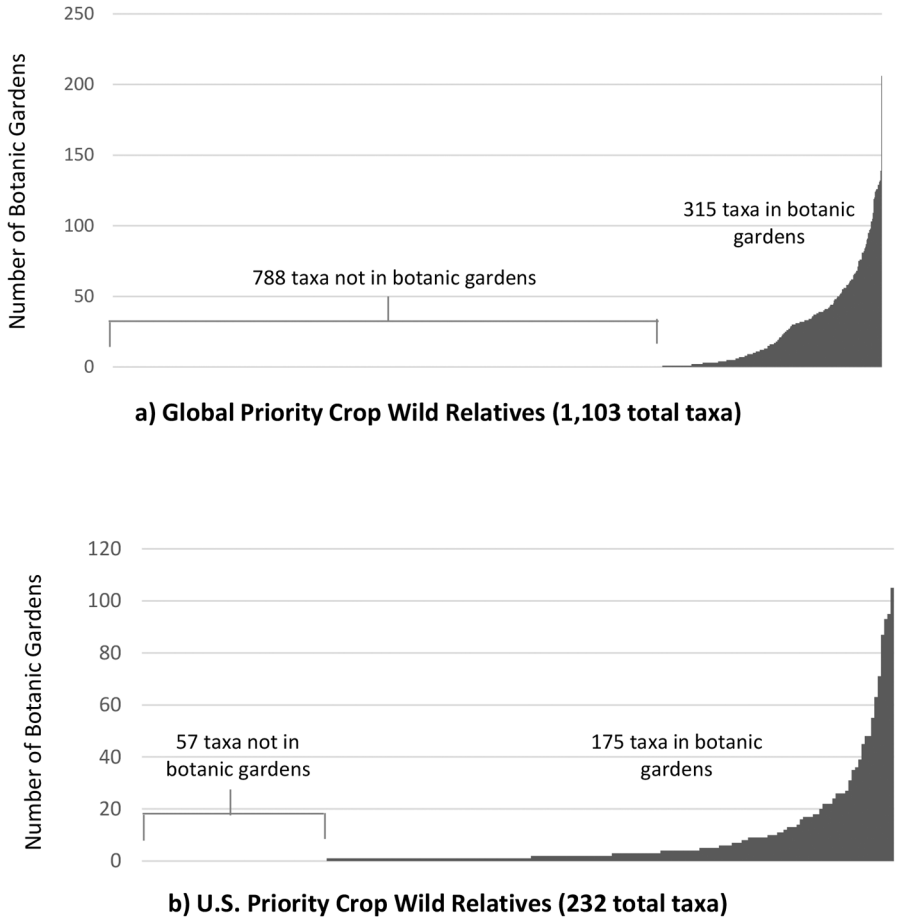

Fig. 1. Number of botanic gardens reporting (a) global priority crop wild relatives (Castañeda-Álvarez et al., 2016) and (b) priority crop wild relatives native to the United States (Khoury et al., 2013) to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

Table 1. Most common taxa reported by botanic gardens, among (a) global priority crop wild relatives and (b) priority crop wild relatives native to the United States. Based on crop wild relative information from Castañeda-Álvarez et al. (2016) and Khoury et al. (2013), and botanic garden collection data from the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

Taxon	Associated crop	Crop use	No. of botanic gardens
(a) Global priority crop wild relative			
Malus domestica	apple	food, fruit	206
Carica papaya	papaya	food, fruit	139
Prunus spinosa	almond, cherry, peach, etc.	food, fruit	132
Poncirus trifoliata	orange	food, fruit	131
Prunus avium	almond, cherry, peach, etc.	food, fruit	129
Theobroma cacao	cacao	food	129
Pyrus communis	pear	food, fruit	126
Malus toringo	apple	food, fruit	126
Saccharum officinarum	sugarcane	food	125
Asparagus officinalis	asparagus	food	124
(b) US priority crop wild relative			
Franklinia alatamaha	–	ornamental	105
Abies fraseri	–	medicinal	95
Roystonea regia	–	ornamental	93
Cupressus macrocarpa	–	forestry	87
Pinus radiata	–	forestry	71
Paxistima canbyi	–	ornamental	63
Astrophytum asterias	–	ornamental	55
Betula uber	–	forestry	48
Echinacea paradoxa	echinaceae	medicinal	48
Echinacea tennesseensis	echinaceae	medicinal	45

There are 528 botanic gardens that report plant holdings and 43 botanic gardens that report seed holdings of at least one global priority CWR taxon. There are 402 botanic gardens that report plant holdings and 24 botanic gardens that report seed holdings with at least one US priority CWR taxon. To illustrate the breadth of the global network of botanic gardens, Fig. 2 shows the botanic gardens with collections of US priority CWRs that are located around the world. Additionally, the majority of taxa (64% global priority CWRs and 68% US priority CWRs) are reported in at least one botanic garden seed bank (Table 2).

To further characterize institutional strengths, the botanic gardens that report the most priority CWRs are listed in Table 3. The most species-diverse collections of both global and US priority CWRs are found in Europe and North America. A variety of countries are represented in the list of top 10 global priority CWR collections, including several in Europe. Botanic gardens in the United States account for nine of the top 10 US priority CWR collections, most of which are located in California and Hawaii.

Global crop gene bank holdings of the 1103 global priority CWRs include 809 (73.3%) taxa represented by accessions recorded in the Genesys database, of which 243 taxa are represented by <10 accessions (Genesys, 2019). Botanic gardens maintain about one-third (315 taxa) of global priority CWRs, including 22 taxa not yet reported by crop gene banks (Table 1). Among botanic garden holdings, 201 taxa are maintained as seed bank accessions. Combining crop gene bank and botanic garden holdings results in a higher number of taxa (831) represented in collections (Fig. 3).

Crop gene bank holdings of the 232 US priority CWRs include 78 (33.6%) taxa represented in crop gene bank accessions (Genesys, 2019), a majority of which (67 taxa) are composed of <10 accessions. Botanic gardens maintain significantly more (175) priority taxa, including 108 taxa absent from crop gene banks. Among botanic garden holdings, 132 taxa are maintained as seed bank accessions. Combining crop gene bank and botanic garden holdings results in a significantly higher number of taxa (186) than crop gene banks alone (Fig. 4).

The botanic garden accessions survey of 10 threatened priority CWR species resulted in 552 total accessions from 21 ex situ sites, most of which were living plants (Table 4). We received at least one accession record for all target taxa except for *Ribes binominatum* A. Heller and *Ribes erythrocarpum* Coville & Leiberg. The majority of accessions (484) were specimens of *Eugenia koolauensis* O. Deg. maintained at a single ex situ site near its native range in Hawaii.

Overall, 525 (95.1%) of reported botanic garden accessions of the 10 target taxa were of wild origin, 21 accessions were of unknown origin, and six accessions were of cultivated or horticultural origin. Although the unknown origin accessions may be of wild provenance, these records, along with the cultivated origin accessions, were not included in further analysis due to lack of wild-origin collection information. Comparison of accessions recorded in Genesys (2019) with those reported by botanic gardens shows potential for synergistic metacollection efforts. *Eugenia koolauensis*, *Prunus havardii* (W. Wight) S. C. Mason, and *Santalum ellipticum* Gaudich are US priority CWRs without accessions in crop gene banks, but they are maintained in botanic gardens. The *Eugenia koolauensis* demonstrates a very focused and genetically diverse botanic garden collection geared toward species conservation.

Nearly all (521, 99.2%) wild-origin accessions lacked latitude and longitude coordinates for their wild collection

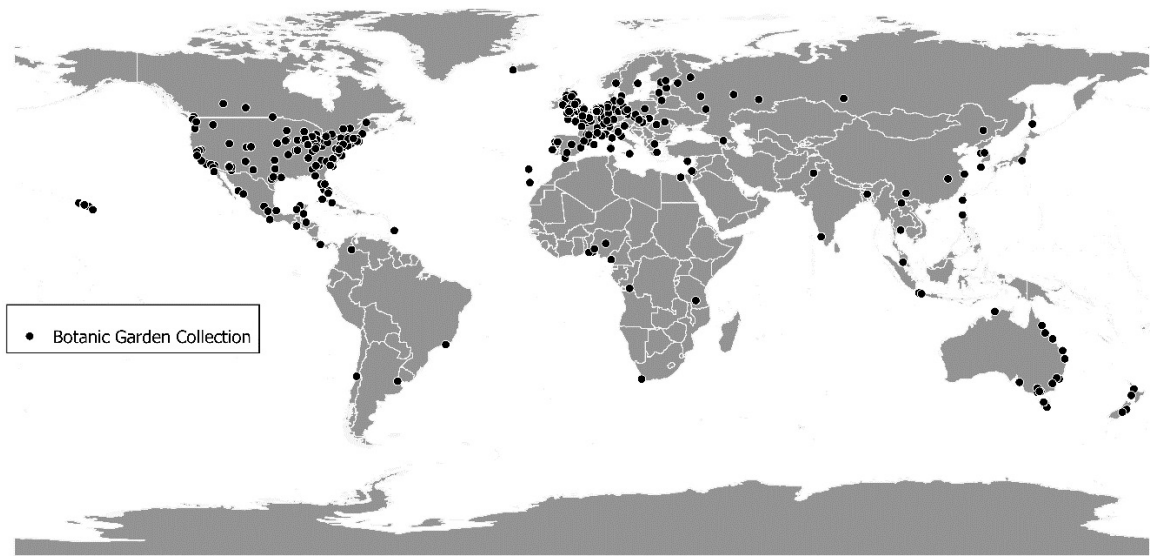

Fig. 2. Global distribution of 426 botanic gardens reporting holdings of at least one priority crop wild relative taxon native to the United States (Khoury et al., 2013) to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018). A total of 175 taxa were reported by 170 US botanic gardens and 256 non-US botanic gardens.

locations; however, we used locality data and descriptions within each accession record to georeference location points to a fairly precise level for 519 wild-origin accessions. This brought the total accessions with associated GPS coordinates to 523 (94.7%). The GPS coordinates allow comparison of wild-collection locations across a species' historical and remaining natural range and assess comprehensiveness of ex situ samples.

As a case study, we mapped wild-origin collection locations of accessions reported by crop gene banks and botanic gardens and compared them with historic natural populations of *Juglans hindsii*, a valuable CWR of English walnut (*Juglans regia* L.) (Fig. 5). Although it is outside the scope of this assessment to interpret population-level representation of ex situ collection sites, Fig. 5 suggests that botanic gardens may offer unique population samples (and genotypes) not represented in crop gene banks.

DISCUSSION

The CWRs maintained in botanic gardens represent significant capacity for preservation of CWR plant genetic resources, particularly for CWRs native to the United States. The Royal Botanical Garden, Kew's Millennium Seed Bank, as a partner with the Crop Trust in the "Adapting Agriculture to Climate Change" project, is an exceptional example of a botanic garden providing focused support for CWR preservation (Table 3). Whether intentionally or serendipitously, botanic gardens maintain collections useful for crop preservation, breeding, and research. The plant conservation missions central to many botanic gardens today could be leveraged to further secure priority, underrepresented, and threatened CWRs.

The two germplasm types for botanic garden holdings that were tracked for this assessment were plants and seeds, which each have their unique costs and benefits for ex situ conservation (Kramer et al., 2011), and depending on

Table 2. Number of global and US priority crop wild relative taxa per botanic garden collection type, including the number of taxa not represented in crop gene banks. Based on priority crop wild relative lists from Castañeda-Álvarez et al. (2016) and Khoury et al. (2013), crop gene bank accessions reported by Genesys (2019), and botanic garden collections data reported to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

Type of botanic garden holding	No. of global priority crop wild relative taxa (and no. of taxa *not* represented in crop gene banks)	No. of US priority crop wild relative taxa (and no. of taxa *not* represented in crop gene banks)
Seed bank holdings only	24 (0)	56 (37)
Seed bank and living plant holdings	177 (4)	76 (44)
Living plant holdings only	114 (18)	43 (27)
All holdings combined	315 (22)	Globally: 175 (108)

Table 3. Top 10 most taxonomically diverse botanic garden collections of (a) global priority crop wild relatives and (b) priority crop wild relatives native to the United States. Based on priority crop wild relative lists from Castañeda-Álvarez et al. (2016) and Khoury et al. (2013), and botanic garden collections data reported to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

Botanic garden collection name	No. of crop wild relative taxa	Location
(a) Global priority crop wild relative taxa		
1. Millennium Seed Bank	176	UK
2. Royal Botanic Gardens, Kew (plant holdings)	128	UK
3. Natural History Museum of Denmark	112	Denmark
4. Eden Project	107	UK
5. New Botanic Garden of Göttingen University	102	Germany
6. Botanic Garden Meise	94	Belgium
7. Technischen University Dresden Garden	91	Germany
8. Botanical Garden, University of Bonn	89	Germany
9. Main Botanical Garden, Russian Academy of Sciences	89	Russia
10. Jardin des Plantes de Paris et Arboretum	85	France
(b) US priority crop wild relative taxa		
1. Rancho Santa Ana Botanic Garden Seed Bank	40	CA, USA
2. Regional Parks Botanic Garden	29	CA, USA
3. National Tropical Botanical Garden	24	HI, USA
4. Millennium Seed Bank	23	UK
5. Santa Barbara Botanic Garden	22	CA, USA
6. Lyon Arboretum Seed Conservation Laboratory	21	HI, USA
7. Huntington Botanical Gardens	21	CA, USA
8. Arboretum at University of California Santa Cruz	19	CA, USA
9. Honolulu Botanical Gardens	19	HI, USA
10. United States Botanic Garden	18	DC, USA

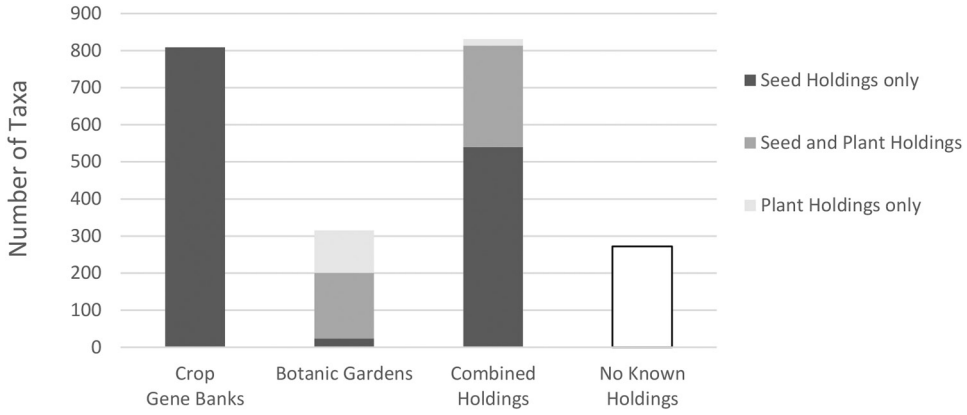

Fig. 3. Global priority crop wild relative taxa maintained in botanic garden and crop gene bank collections worldwide. Based on the priority crop wild relative list from Castañeda-Álvarez et al. (2016), crop gene bank accessions recorded in Genesys (2019) and botanic garden collections data reported to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

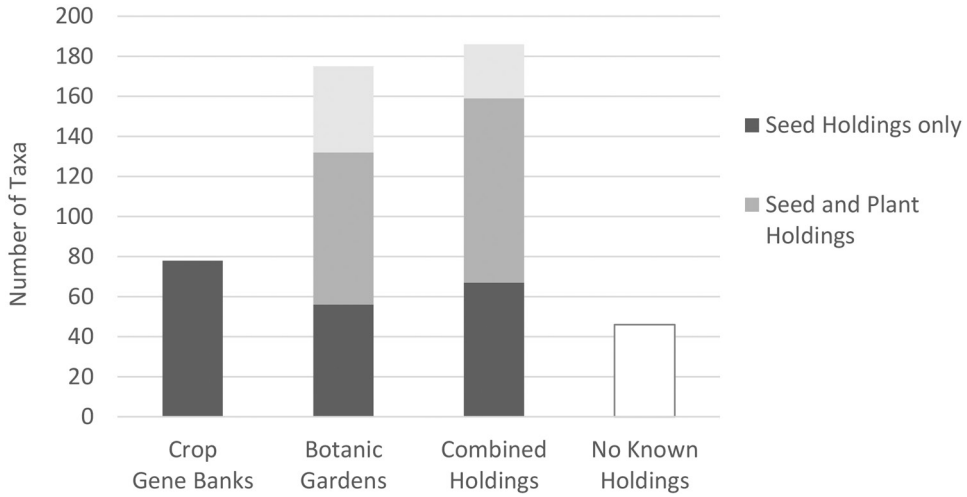

Fig. 4. US priority crop wild relative taxa maintained in botanic garden and crop gene bank collections. Based on a priority crop wild relative list from Khoury et al. (2013), crop gene bank accessions recorded in Genesys (2019), and botanic garden collections data reported to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

the goals specific to each species and accession. As most CWRs are thought to produce orthodox seed (Vincent et al., 2013), it is not surprising to see more taxa in botanic garden seed bank holdings than in living plant holdings. The seed collections identified likely represent greater genetic diversity than living plant specimens (Kramer et al., 2011) and are readily accessible and used for CWR conservation, breeding, and research applications via institutional websites and published collection inventories. The most common priority CWR taxa in botanic gardens (Table 1) are almost all relatively long-lived, ornamental, woody species, which likely reflects a common cultivated plant focus of botanic gardens, but are often represented with wild-origin material valuable for CWR conservation and research. Further, most of the botanic gardens maintaining priority CWRs reported them as part of living plant collections (Table 2). The CWRs in botanic garden plant holdings are very valuable for preserving species that cannot be seed banked, documenting cultural and adaptive traits, breeding, and for education and outreach to botanic garden visitors about CWRs and topics surrounding food and agriculture (Krishnan and Novy, 2016; Moreau and Novy, 2018).

Geographic trends might be useful for future collecting, management, and capacity building efforts. The botanic gardens with highest species diversity of global and US priority CWRs are located in the northern hemisphere. In addition to the geographic bias of the US CWR list used in this study, this likely also reflects the northern-focused distribution of botanic gardens worldwide (Mounce et al., 2017). The high number of Californian and Hawaiian botanic gardens with US priority CWRs probably also mirrors the high CWR species richness in biodiverse regions of the United States.

Our findings also suggest that botanic garden holdings complement and fill taxonomic gaps in crop gene bank holdings. Tables 2 and 4 and Fig. 4 and 5 highlight taxa and accessions that botanic gardens maintain which are not represented in crop gene banks. The accessions survey demonstrates the presence of documented, wild

provenance CWR collections in botanic gardens, which may represent important genetic diversity no longer extant in the wild, or not collected or stored by any other organizations. It is worth noting that accessions in crop gene banks mostly represent seeds (though not always), whereas botanic garden accessions can represent seeds, or one or more living plant specimens that may be clonal seed siblings from the same maternal line, or progeny of separate maternal lines from the same wild population. The utility of each botanic garden accession depends on the original intent when the collection was first made.

Our ability to georeference wild-collection locations was facilitated by the critical plant records data shared by botanic gardens participating in our survey. The *J. hindsii* map assessment demonstrates the potential value of ex situ geographic gap analysis.

Although assessing ex situ genetic representativeness of each species' remaining wild populations is outside the scope of this study, the number of accessions reported in botanic garden holdings are often lower than recommended levels for maximum gene capture (Hoban, 2019; Khoury et al., 2019; Whitlock et al., 2016). By combining complimentary crop gene bank and botanic garden holdings as metacollections, sample size will increase, and possibly gene capture as well (Griffith et al., 2019).

With the current information and tools available, the plant genetic resources community is poised to adopt an integrated collections development approach to collaboratively support research and conservation (Meyer, 2018). Many botanic gardens make their collection inventories available through their institution's website and provide valuable access to their collections for research and conservation. Much like the gene bank data portals GRIN-Global (USDA-ARS-NPGS, 2018a) and Genesys database (Genesys, 2019) in the crop gene bank community, PlantSearch offers a centralized repository of botanic garden collection information. A closer alignment of these digital resources might encourage better alignment between the botanic garden and crop gene bank communities. Although PlantSearch provides a passive request function to connect users to collection managers, and many botanic gardens publish their collection inventories via their websites, there is a need to network and increase accessibility of information about botanic garden accessions.

Building on existing collaborations between the crop preservation and botanic garden communities is an important step toward ex situ preservation of CWRs. Coordination around plant taxa or geographic region may be a way to establish more connectivity between the botanic garden and crop gene bank communities (Krishnan et al., 2019). For example, Denver Botanic Gardens provides critical expertise and support for coffee species conservation (see Bramel et al., 2017).

Table 4. Ten US priority crop wild relative species surveyed in botanic gardens, with number and provenance type of accession records reported. Based on a priority crop wild relative list from Khoury et al. (2013), crop gene bank accessions recorded in Genesys (2019), and botanic garden collections data reported to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018).

Crop wild relative species	Family	Growth habit	US distribution	Associated crop	Crop use	Relationship to crop	No. of crop gene bank accessions	Total botanic gardens	No. of reported botanic garden accessions and provenance types†
Asimina tetramera	Annonaceae	shrub	Florida	pawpaw	Food	Unknown	7	6	15W, 1G, 7U
Eugenia koolauensis	Myrtaceae	shrub/tree	Hawaii	Suriname cherry	Food	Unknown	0	4	484W
Juglans hindsii	Juglandaceae	tree	California	walnut	Food, nut	Close	16	26	8W, 4G, 20U
Manihot walkerae	Euphorbiaceae	forb/herb	Texas	cassava	Food	Distant	0	2	2W
Prunus geniculata	Rosaceae	shrub	Florida	almond, cherry, peach, etc.	Food	Distant	2	1	1W
Prunus havardii	Rosaceae	shrub	Texas	almond, cherry, peach, etc.	Food	Close	0	2	1W
Ribes binominatum	Grossulariaceae	shrub	California, Oregon	currant	Food, fruit	Close	3	1	0
Ribes erythrocarpum	Grossulariaceae	shrub	Oregon	currant	Food, fruit	Assume distant	19	1	0
Rubus hawaiensis	Rosaceae	subshrub	Hawaii	raspberry, blackberry	Food, fruit	Unknown	15	2	5W
Santalum ellipticum	Santalaceae	shrub/tree	Hawaii	n/a	Wood, material	Wild utilized species	0	7	4W

† W, wild; G, cultivated; U, unknown.

Fig. 5. Geographic comparison of recorded wild collection sites of crop gene bank and botanic garden accessions near the historic natural range of *Juglans hindsii* (Jeps.) R. E. Sm. *Juglans hindsii* is a priority crop wild relative due to the threatened status of remaining wild populations in California and its use as rootstock for the English walnut industry worldwide (Khoury et al., 2013). Based on crop gene bank accessions reported to Genesys (2019), botanic garden collections data reported to the Botanic Gardens Conservation International (BGCI) PlantSearch database (BGCI, 2018), and information on the historic natural range of *Juglans hindsii* provided by Bartosh (personal communication, 2018).

Overall, we recognize the urgent need to preserve CWR plant genetic resources. To accomplish this with greater efficiency and success, coordination between botanic gardens and crop gene banks offers promising synergy. The combined strengths and expertise within the crop gene bank and botanic garden communities make the ex situ preservation of all CWRs a goal that is within reach.

Conflict of Interest

The authors declare that there is no conflict of interest.

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