OCTOBER 2017

CURATOR THE MUSEUM JOURNAL

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60/4

OCTOBER 2017

60
4

WILEY

Volume **60** Number **4** October **2017**

ARTICLE

Plant Collection "Half-life:" Can Botanic Gardens Weather the Climate?

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Abstract Botanic gardens are organized around plant collections, and climate change will affect those collections. Land loss is expected for gardens near sea level, prompting a loss of plants from the collection. Future collection development requires planning for these losses, which in turn requires assessment of the extent and rate of collection loss. We examined collection inventory change over time using records at Montgomery Botanical Center (MBC), to formulate a plant collection half-life concept. This half-life was used to project changes in MBC's plant collection over the next 100 years within the context of sea level changes. Comparing predicted rates of collection change with projected rates of loss due to sea level rise, we expect plant collection development to keep pace with climate change. As actively curated resources, botanic garden plant collections can adapt to environmental change faster and more deliberately than natural systems.

INTRODUCTION

As "living museums" (Hohn 2004, 63), botanic gardens serve to engage and inspire. Like other museums, botanic gardens are organized around collections: we stock, study and show heritage, history and handsomeness – thus, gardens are truly (horti)cultural institutions. Furthermore, like museums, gardens must consider disaster preparedness and response in preserving their collections (Bergquist 2009). The first logistic requirement to curate and display trees is an appropriate landsite (Gratzfeld 2016, 8), and these landsites are subject to the same weather as all museums. But living collections planted outdoors are much more directly subject to environmental variance than either those items housed in buildings, or even nonliving outdoor collections (e.g. Moore or Botero, or geologic displays). As living organisms, these collections respond favorably under ideal conditions (i.e., growth and flowering) and yet may decline or even perish when conditions are unfavorable.

Bad weather and bad climate

Montgomery Botanical Center (Montgomery, MBC; Coral Gables, FL, USA) keeps

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Figure 1. Loss and damage to plants at Montgomery Botanical Center as a result of hurricanes in 2005. Photos were taken 11 months apart, at similar midday times. Compare left of (a) which shows a loss of most palms, (b) which shows a major loss of palm fronds, and (c), which shows a large live oak lost to the storms. A general thinning of the canopy is also noted throughout. Photographs: Montgomery Botanical Center. [Color figure can be viewed at wileyonlinelibrary.com]

nationally accredited collections of palms, cycads, conifers, and other trees (Noblick et al. 2008; Calonje et al. 2009; Tucker Lima and Griffith 2017), collections in development since 1932. In 2005, two major hurricanes impacted the plant collection at Montgomery; Hurricanes Katrina and Wilma caused the loss of many important specimens. Visual comparison before and after the 2005 hurricane season shows this readily (Figure 1). The losses were instructive (Griffith et al. 2008, 2013), but certainly set back the pace of collection development.

More recently, Hurricane Irma impacted the collection, passing over Miami on September 9 and 10, 2017. Storm surge of up to 6 feet was recorded, and wind damage to plants was extensive. Initial triage of the collection shows losses into the hundreds of plants, but 109 candidates for salvage and care. As of this writing (October 12), full assessment of losses is ongoing and likely to complete in 2018. Qualitatively, the damage from Hurricane Irma exceeds the losses experienced in 2005 in both breadth and specificity (Figure 2).

These comparisons show the effects of bad weather, but what about the effects of a *bad climate*? Miami-Dade County is widely recognized as particularly vulnerable to sea level rise (Hauer et al. 2016; Southeast Florida Regional Climate Change Compact 2012), and now-yearly "King Tide" events (Staletovich 2016) are a tangible illustration of our potential future. Located in that county, and with a landsite that begins at sea level, Montgomery shares these

Figure 2. The Florida Champion *Kigelia pinnata* (Sausage Tree) was severely damaged in Hurricane Irma (2017). This venerable tree was cherished by students and other visitors for its superlative size, striking purple flowers hung on long stalks, and the eponymous dachshund-sized fruits. Planted by Colonel Robert Montgomery in the 1930s, this tree was officially recognized by the Florida Forest Service as the largest and finest specimen in the state. It survived hurricanes over many decades, and is being evaluated for salvage currently. If the tree can be pruned to mitigate hazards, it may be retained in the collection as a "Champion Emeritus." [Color figure can be viewed at wileyonlinelibrary.com]

same vulnerabilities. Thus, future collections management and development planning within this context is vital to MBC's success going forward.

Objective and questions

With the threat of rising seas, we wanted to determine precisely how our collection will be affected. The title of this paper puts forward an important, overall concern. To address this concern, we systematically ask a series of more direct questions that assign scope and scale to the problem. First, how far into the future should we plan? For the purposes of this assessment, given that MBC is in its 9th decade as a plant collection, and 6th decade as a botanic garden, we have chosen a 100-year planning horizon. Second: within that 100-year time frame, how much land will we lose? Third, how many plants will that land loss affect? The long timeframe also prompts questions of how the collection might develop over that period, and thus, a fourth question: will collection development keep up with sea level rise over the next 100 years? While many complex concerns surround planning for climate change, the scope of our assessment ends with that fourth question, restating our main query: will our collection weather the climate?

Table 1.
Plant collections management terminology used in this paper.

Collection/Plant Collection	The entire curated holdings of living individual plants at a botanic garden. This can include plants in a nursery, conservatory, seeds in a seedbank, pollen in cold storage, or plants planted in a landscape. In this study, we limit our analysis to the part of the collection planted on the grounds, i.e. the trees, palms and cycads planted outdoors in the landscape.
Plant	An individual, living, curated plant specimen. In botanic gardens, the term "collection" often has the same meaning, and is distinguished by its context and use. Curated plants are also known as "accessions." For clarity, and to distinguish from the entire holdings, we use the term "plant" herein for individuals curated as part of the garden's collection. In addition, most gardens have some essential botanical life occurring on the landsite that is managed but not curated, such as turfgrass, weeds, epiphytes, or native annuals, and while those are certainly plants, they are not part of the documented collection. In this paper, "plant" refers only to curated individual specimens.

METHODS

Collection data

Table 1 presents terminology used in this paper. Our assessment focuses on the plant collection and associated data at MBC. Most plants arrive to MBC as seeds, and are propagated in MBC's nursery facility before planting into the ground. All incoming plants are accessioned into a database (BG-Base, Addison, TX) upon acquisition, and records of planting are added to the database as the plantings occur. All individual plantings are mapped using GIS software (ArcGIS, Esri, Redlands, CA). Removal and deaccession from the collection occurs when plants die (from causes such as lightning, pests, herbivory, accidents, or end of life cycle), or when plants are selected for removal due to poor siting, compromised or poor form, or other management decision. These removals are logged in the database as they occur. An annual field inventory of the collection is performed, when each individual plant is manually inspected and data are logged into the database. Data on inventory, plantings and losses are summarized and archived annually. Data archives from 2015 and earlier, with complete, verified inventories, were used for most analyses, whereas 2017 database queries were used in assessments of median age, and for forward projections.

Land loss projections

Sea level rise projections were obtained from a very recent scientific study focused on Miami-Dade County (Wdowinski et al. 2016), which estimates an average of 9 mm rise per year. This factor was scaled to our 100 year timeframe to estimate 900 mm of rise, or just under 3 feet, by 2115 (cf. Craft et al. 2009). Contour elevation data (Witcher and Griffith 2011) in conjunction with a 5 m digital elevation model (DEM; FGDL 2012) were used to measure the extent of flooding due to future sea level rise. The 5 m DEM was overlaid with the contour data to evaluate and confirm accuracy. All contiguous contour lines less than or equal to 3 ft were selected and exported as the impacted area using ArcGIS. Total land loss was calculated by the overlap of the 3 ft contour and the border of the landsite.

Collection loss projections

The 3 ft sea level overlay was used to identify all plants in the rise zone. Percentage of total plants at risk was calculated as the proportion of plants growing within the adjusted sea level. The distribution of at risk plants was mapped by overlaying an Esri world imagery base map with the 3 ft sea level rise layer and locations of at risk plants.

Collection capacity

Total capacity for plants on MBC's landsite was determined by comparing and scaling master planning assessments (Hibbard 1992, 9) with archived inventory data. The 1992 Master Plan only directly assessed space needs for palms and cycads, but acknowledged the space needs of other trees on the landsite. To scale the rigorous 1992 capacity assessment to include all plants, a ratio of palms and cycads to the entire 2017 collection was calculated, and this factor was used to transform the 1992 capacity number to include trees. A logarithmic regression was fit to the time series of inventory data, and the time horizon to reach the rescaled capacity was calculated.

Half-life of collection

Archived collection data with complete records (2015 and earlier) were reviewed to provide a yearly sequence of total number of live plants, number of new plants added, and number of plants removed. Variance between year-over-year inventory numbers and net gains and losses was compared. Losses each year were totaled, working backward from the most recent fully inventoried year (2015), to measure the time it would take to lose and replace half of the current inventory, i.e. the "half-life" of the total collection. The plant collection half-life, then, represents the amount of time for half of the existing plants in a collection, in a given year, to be lost and replaced. To compare and confirm this half-life value, the collection was assayed to find (1) the median planting year of the current living collection, and (2) the proportion of the collection planted prior to or after the current year minus the half-life. The planting year for each plant is equal to the year accessioned, with a post-hoc adjustment based on time plants typically spend in the nursery between accession and planting. To estimate nursery time, we transformed actual planting dates and accession numbers into four-digit years using Python (www.python.org), calculated the difference between accession date and planting date for each plant since 2002 (n = 9,602 records), and used the median value. Thus, to strengthen confidence in our assessment, the half-life of the collection was evaluated by multiple means: (1) via cumulative losses over time, (2) via median age of the collection, and (3) via the portion of collection planted prior to and after an a priori date.

Collection change projections

Using the three calculated half-life values, we estimated the percentage of the 2017 collection remaining in 2117. These values were considered in the context of the existing collection.

RESULTS

Land loss projections

Figure 3 presents how change in sea level over the next century may affect Montgomery. Currently, MBC has 6.3 acres of water surface at sea level, as tidal lakes. With sea level at the 3 foot contour line, the water surface will expand to 49.4 acres, newly inundating 43 acres.

Collection loss projections

Figure 3 also shows existing plants at MBC that are predicted to be below sea level in 2117. This includes 1,268 plants, or 8% of the collection. The vast majority of these inundated plants are palms (n = 1,169).

Collection capacity

Via comparison of master plan assessments and current inventory, ultimate capacity for MBC was determined as 17,250 plants. Logarithmic regression of past inventory data ($inventory = (646{,}403 \times \ln year) - 4{,}903{,}092$; $r^2 = 0.90$) predicts that Montgomery will reach its planned collection capacity around 2025, well before the 100 year assessment horizon.

Half-life of collection

The plant collection half-life was determined to be 13 years in three separate analyses. First, the documented losses throughout 2003–2015 (13 years of records) totaled 6,759 plants, or 49% of the 2015 collection of 13,873 plants (Table 2; Figure 4). Second, the median accession date in the 2017 collection was 2001, and the median age at planting was 4 years; thus half of the collection was planted in 2005 through 2017 (13 years). Finally, 54% of the 2017 collection was planted in 2004 or earlier, and 46% of the 2017 collection was planted in 2005 or later (13 years). Thus, in a 13 year period, Montgomery retained 50—54% of its collection.

Collections change projections

According to the various replacement rates determined above, and assuming those rates are constant (see below), the MBC collection will retain no more than 0.8% of its current plants 100 years later, even if the total inventory number continues to increase (Figure 5). Thus, an estimated 120 plants present in 2017 will survive until 2117.

DISCUSSION

Insights from this analysis

Land lost and land preserved: We project 43 acres of currently dry land will be inundated in 100 years. While this projection floods over one third (36%) of the total landsite (120 acres), the inundated area contains only 8% of the current plant collection. Historic and site-specific factors have limited the number of plantings in the lower lying areas of the garden. Most obvious of these factors is the presence of lakes. Another

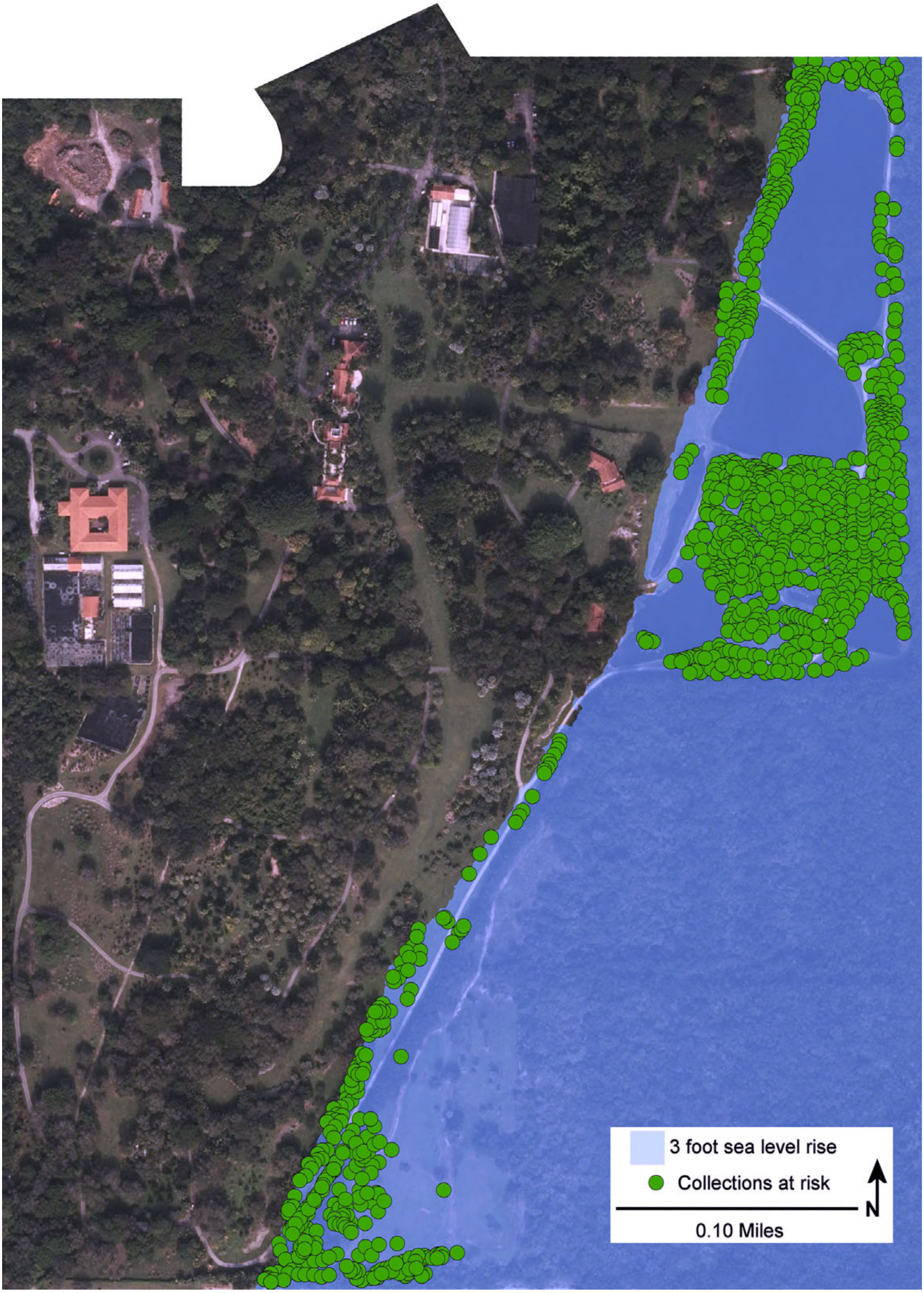

Figure 3. Plants at risk due to sea level rise, 2017–2117. A 3 foot (900 mm) rise in sea level would newly inundate 43 acres of the MBC landsite. Plants on the inundated areas represent 8% of the total plant collection. Tree canopy cover in the southeast area of the garden is native mangrove habitat, with other tree species, and is not included in the collection. [Color figure can be viewed at wileyonlinelibrary.com]

Table 2.
Collections inventory by year, 2001–2015.

Year	Total plants on January 1[a]	Plants added[b]	Plants lost[b]	Net change by additions and losses	Net change by inventory, year over year	Variance in net change
2001	9,254	1,166	362	804	968	-164
2002	10,222	972	362	610	198	412
2003	10,420	958	332	626	439	187
2004	10,859	800	881	-81	-50	-31
2005	10,809	370	859	-489	-489	0
2006	10,320[c]	703	535	168	61	107
2007	10,381	682	441	241	225	16
2008	10,606	653	383	270	212	58
2009	10,818	1,348	479	869	837	32
2010	11,655	1,141	505	636	595	41
2011	12,250	689	514	175	348	-173
2012	12,598	973	364	609	540	69
2013	13,138	909	570	339	320	19
2014	13,458	816	502	314	415	-101
2015	13,873	472	394	78		

[a]Numbers from field inventory.
[b]Numbers from database records.
[c]Inventory for 2006 was determined retroactively from addition and loss records in the database, as a field inventory was not possible in 2005 due to Hurricane Katrina and Hurricane Wilma.

limitation is county and state regulations that restrict the alteration of areas with established mangrove plants (Edelman and Griffith 2010). While 8% of the current collection is on land expected to be lost in a century, because the collection is not static in time (as shown above and discussed below), most of those 8% will have cycled out of the collection over the same period. While these impacts to the collection are significant, perhaps more significant is the cultural loss represented by flooding that portion of the landscape. The lowland areas – and their connection to upland vistas – are part of master planning and development dating to the 1930s (Anderson and Griffith, 2011), and thus comprise decades of careful architecture and stewardship. The visitor experience will be greatly diminished through the land loss.

Change in capacity: Master planning in 1992 evaluated space requirements for the plant collection, circulation, habitats, vistas, and other uses at Montgomery (Hibbard 1992, 9). The 1992 capacity projections planned for 13,800 palms and cycads, without accounting for other plant types. With 12,208 palms and cycads in 2017, MBC holds close to 90% of its planned capacity. As shown above, we expect peak capacity (17,250 plants of all types) to be reached in 2025, well before the 100 year sea level planning horizon. On the reduced 2115 landsite, we can expect an 8—36% reduction in this capacity due to sea level rise, based on current plants and acres (low value = plants; high value = acres) inundated in the future landscape. This sets our 2115 collection capacity as low as 11,000 plants – nearly equivalent to our 2009 collection, but more densely spaced.

No strong bias towards older collections: Large, old trees hold a special cultural value (Lewington 2013, 9), and command specialized

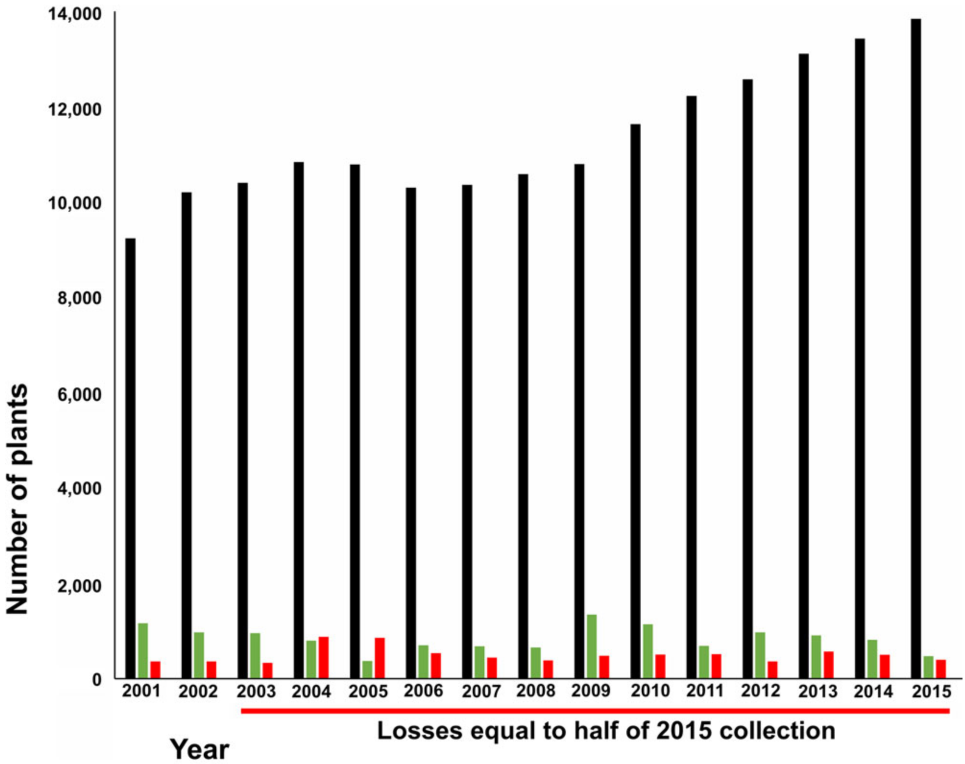

Figure 4. Collection replacement over time, 2001–2015 (compare to Table 1). First bars = total number of living plants in inventory on January 1. Second bars = number of plants added that year. Third bars = number of plants removed that year. Data prior to 2001 are not shown on this graph for brevity, and are available via correspondence. [Color figure can be viewed at wileyonlinelibrary.com]

management at botanic gardens (Meilleur and Raddick 2014). Often called Heritage Trees (Jim 2004), these individuals are revered with honorific official or folk titles, including "ancient, beautiful, big, champion, elite, famous, heritage, historic, old, outstanding, remarkable, specimen, [or] veteran trees (ibid.)" (Figures 2 and 6). Prior to the half-life analysis, we expected that most recorded losses in our collection were from younger, newly-planted plants. We hypothesized that the half-life calculations might demonstrate that when half the collection was replaced, turnover would be concentrated among newly-planted plants, leaving a majority of established, mature individuals on the landscape. Our findings only weakly support this prediction. First, the median tenure of plants on the landscape (13 years) matched the half-life determined by loss and replacement over time. The difference of 54% plants older than 13 years, versus 46% younger than 13 years, suggests only a slight bias in losses toward younger collections. The very small predicted number of 100-year or older trees in 2117 (120 trees or less) highlights the rarity of such Heritage Trees, reflecting the low frequency of our oldest plants. At Montgomery, our oldest plants date back to the establishment of the collection in 1932 (Montgomery 1939, 222). Eighty-five years later, only 73 of these original plants survive. At Montgomery, the increasing rarity of older plants over time

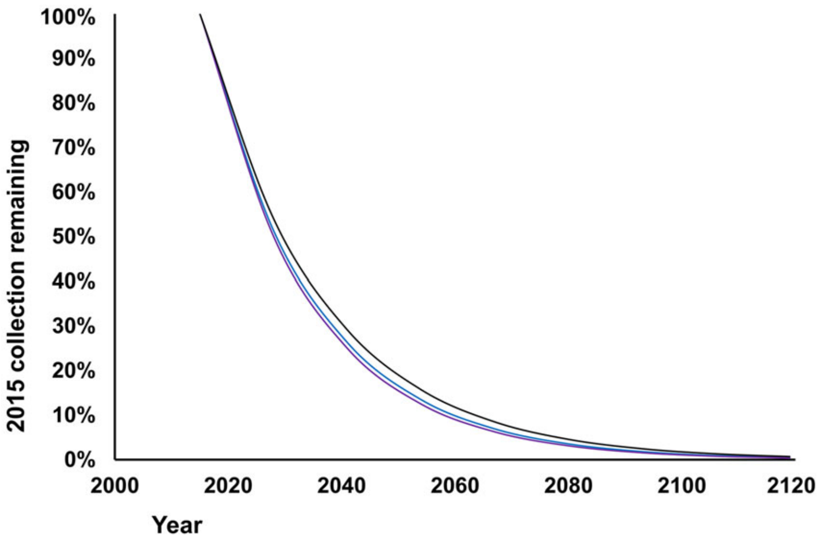

Figure 5. Collection replacement projections. Every thirteen years, 50% (bottom line), 51% (middle line), or 54% (top line) of the remaining 2017 collection is expected to remain (see text for calculations). Thus, in 2117, no more than 0.8% of plants from 2017 are expected to survive, even as total inventory numbers continue to increase to capacity. [Color figure can be viewed at wileyonlinelibrary.com]

parallels and highlights the great cultural value these individuals hold (Figure 7). Thus, while maintaining a robust inventory of plants is important, it is equally important to provide special curatorial attention to those oldest plants in the collection, given the vital connections those plants make with the visitor, the stories they hold, and the way these plants anchor the landscape.

Collection dynamics: Even though trees (and especially palms; Tomlinson and Huggett 2012) are known for long life cycles, both the time series of losses (Figure 4) and the future projections (Figure 5) highlight how rapidly a plant collection can cycle within a span of decades. This demonstrates that a botanic garden collection can never quite be completed per se; collection development must continue indefinitely, and must equal or exceed the rate of collection loss, in order to maintain breadth. Given the conservation role of modern gardens (BGCI 2016), continuous and directed collection development is thereby also essential to safeguard against loss of genetic diversity (Cibrian Jaramillo et al. 2013; Griffith et al. 2015, 2017). The fleeting nature of plants shows the importance of fully leveraging present-day collections via propagation, exchange and distribution. Distribution between gardens is especially important for those species which are extinct or highly threatened in the wild. Equally important is their active use for research; individual plants in a collection are ephemeral, but the knowledge gained from them can persist.

Limitations of this analysis

Validity of extrapolations: This analysis makes some assumptions about future conditions. First, it assumes sea level rise will be constant and continuous over the next 100 years, and that no engineering solution to sea level rise will be effective (Lenk et al. 2017). The actual rate of sea level rise may indeed deviate from

Figure 6. The Florida Champion *Cananga odorata* (Ylang-Ylang Tree) was lost in Hurricane Irma. This tree is known for its unique fragrance, used in the famous Chanel No. 5 perfume. This individual was the largest one in Florida, and was planted by Nell Montgomery to enjoy near her home. Because of its history and use, this tree was featured on tours. It also provided students an example of primitive flower morphology. [Color figure can be viewed at wileyonlinelibrary.com]

current estimates used for Miami-Dade County (Wdowinski et al. 2016), or perhaps infrastructure projects may mitigate flooding (Hinkel et al. 2014). Second, it assumes that MBC's collections development operation will continue in the same manner at the same volume as in the recent past. Long-term stability in mission, leadership and resources marked the past two

Figure 7. The Florida Champion *Microcycas calocoma* is a treasured plant at Montgomery. Obtained in 1932, it has endured many hurricanes. Hurricane Irma (2017) left it unscathed; note damage to trees in the background and foreground. This male plant is the father or grandfather of virtually every other *Microcycas* in the US, and seedlings have also been shared with botanic gardens around the world. The robust history of this individual (Kay et al. 2011) makes it irreplaceable. [Color figure can be viewed at wileyonlinelibrary.com]

decades at MBC (Haynes 2015; Zuckerman 1997), and such stability will be required to continue these trends. In addition, some variation in salt tolerance and root zone saturation has been observed for palms (Perry and Williams 1996). Our current observations at Montgomery suggest that more palms are likely tolerant of salt water than is currently assumed, but this variable is outside the scope of the current study.

Collection emphasis: Living plant collections at different gardens may be broad or narrow in scope, or variously focused on different taxonomic groups, geographic regions, forms, or display purposes (Gratzfeld 2016, 50). The current study, focused on a collection of primarily palms and cycads, with a focus on genetic and geographic diversity (Tucker Lima 2017), may not apply to all types of botanic gardens. Plants with shorter life cycles, such as annuals or short-lived perennials, will likely affect the half-life value of collections they are included in. However, the methods presented here can be of use as a starting point to evaluate the collection dynamics for any garden. As a tool for visualizing turnover, the half-life analysis developed here is readily transferable to other living collections. But, there may be limitations in application, given the great variation in plant life histories and the diversity of interests in other curated collections. Differences in topography among gardens can also limit the way in which land loss projections can manifest. Thus, when comparing climate change projections to collection dynamics, care must be taken to relate these to specific circumstances.

Variance in inventory: Table 2. reveals some variance in the inventory, between numbers censused in the field and totals calculated by planting and removal records. Review of the timing and processes involved suggests the variance is due to three factors. First, the scale of the inventory, accomplished in person and by hand, requires a multi-week or months-long effort by multiple staff. Thus, the inventory process verifies a number that is changing while it is being counted. This contrasts with plantings and removals which are tallied from records accumulated by December 31 of each year. Second, review of this variance noted that some records of translocation may have been incorrectly recorded. Finally, we assume some user and data entry error. The variance is insignificant, representing 0.3% of all records in 15 years, and only exceeding 1% in 4 of those years.

Catastrophic losses: This paper began by relating the effects of hurricanes on the collection. Table 2 depicts two years when removals exceeded plantings, 2004 and 2005. In each of those two years, MBC lost 8% of its collection due to hurricanes (Frances, Katrina and Wilma). In that era, the frequency of hurricanes was predicted to increase (e.g. Emmanuel 2005), but the frequency since 2005 was in fact slower than expected (Hall and Hereid 2015). Nevertheless, the half-life model used here includes two years out of 13 with hurricane-related losses, and 11 years without, which provides a balanced and realistic model for future projections. Since establishment, hurricanes have struck Montgomery in 1935, 1941, 1945, 1950, 1960, 1964, 1965, 1979, 1992, 2004, 2005, and 2017, a rate of around one hurricane every 7 years. These infrequent but intense events are very likely over the next hundred years, and will affect the collection in similar ways. Predictions of higher frequency and more intense storms (Bodman et al. 2006) can alter the rate of collections loss. As the impact of Hurricane Irma is fully assessed, comparing its impact with the impacts of past storms can help refine the half-life model further.

Editorial

Climate change and collections: Comprising living organisms that interact directly with the environment, botanic garden collections will certainly be affected, directly and indirectly, by a changing climate. However, while natural ecosystems face extinction challenges from environmental changes, our opinion is that a garden collection can adapt to these changes rapidly and effectively. First, losses that occur in a garden are documented, and these records can be assessed for what does well under changing conditions, and what does not. Second, inputs into a garden are curated, and this provides the opportunity to change the trajectory of the developing collection. Given the speed at which a plant collection changes (shown above), it is essential for the curators to keep up with this speed and adapt their desiderata to changes in the environment. An emphasis on setting priorities, having firm intellectual control of the collection, and using this information for adaptive management will allow gardens to effectively plan for climate change (Dosmann 2012).

Will gardens weather the climate? Based on the above analyses, our answer to this question is *yes, they already are*. The rapid speed at which botanic garden losses can accumulate also illuminates the clear path forward: curators must be proactive in collection development. Faced with a changing landscape and changing environment, botanic garden leaders must adapt their collection to the circumstances. An admired but apocryphal quote perfectly highlights this urgency, and the fleeting, temporal nature of the plant collection: *The garden exists between the expedition and mulch pile, only by the intensive input of specialized resources.* END

ACKNOWLEDGMENTS

We thank Dakota Moore, Sandra Rigotti-Santos, Jessica Sparks, Arantza Strader, and Alex Whitworth, for data gathering and processing. We thank the American Public Gardens Association for hosting our 2016 panel *Collections and Climate Change* in Miami, where this research was first presented, and we thank Dr. Nicole Cavender for facilitating that discussion. We also thank the Institute of Museum and Library Services and the National Science Foundation for supporting collections stewardship, planning, and security (MA-05-12-0336-12, MA-30-14-0123-14, MG-30-16-0085-16, DBI 1203242 and DBI 1561346), and especially for rescue of living collections after Hurricane Irma (DBI 1762781).

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