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Research in the Garden: Averting the Collections Crisis

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Abstract

Botanic gardens and arboreta are a vibrant part of the natural history collections community, serving society in areas such as education, recreation, and research. Unfortunately, at the present time dwindling support and advocacy for collections-based re-

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search has placed these institutions in the midst of a collections crisis. In this review, I assess the historical importance of living plant collections in supporting research, examine why their research potential is currently unmet, and provide a series of rationales in support of collections-based research. To avert this crisis several things must occur, the most basic of which is stronger advocacy for living collections and the research derived from them. Traditional views of collections management need to be evaluated under new light and the pool of researchers expanded. Formal, on-site programs are not required for collections to be used for research, as off-site scientists can make great contributions. Toward this end, collaborative links between the garden and research communities ought to be enhanced through the pivotal role played by curators and collections managers. Investment in data-management systems are also required to increase collection value and improve the ability to disseminate information to researchers who require it. If provided the necessary leadership and support, living plant collections have great potential to meet future scientific needs.

Collections in Crisis

INTRODUCTION

Global taxonomic diversity dwindles, prompting the term biodiversity to enter the daily lexicon, affecting policy decisions as well as hypothesis generation. A sense of urgency exists to describe, characterize, and catalog biological riches before they disappear. Yet, the very segment of the scientific community that pioneered biodiversity research, the natural history museum, struggles. Despite the intrinsic value natural history collections (NHC) possess, an array of recent articles and letters to the editor (Lane, 1996; Krishtalka & Humphrey, 2000; Dalton, 2003; Miller et al., 2004; Suarez & Tsutsui, 2004) have detailed the crisis facing these institutions, some bearing alarming headlines such as "Are university natural science collections going extinct?" (Gropp, 2003). Within the academic sector, Pekarik (2003) has linked the relative decline in resources directed to NHC with the devaluing of collections, stating that "Universities across the country are threatening to abandon their natural history collections because they no longer see a vital connection between these reference collections and their teaching missions, and because they are unwilling to spend the money to maintain them."

Botanic gardens and arboreta (hereafter called gardens), a vibrant and very public part of the NHC community, have been noticeably absent from articles devoted to the modern "collection crisis" (except with regard to their affiliated herbaria). Living plant collections are central to gardens, yet collections-based garden research is not often a topic of discussion in the literature. An editorial (Nature, 2006) and feature article in *Nature* (Marris, 2006) wonderfully summarize the research activities of several of the world's most elite gardens. However, they focus little upon the specific role of living collections or research opportunities for smaller institutions. In a discussion on gardens in general, Watson et al. (1993) include a section on collections-based research. The last article of note, however, was Peter Raven's thorough review (1981) of the roles living collections play in supporting research, and he recently reiterated some of these themes (Raven, 2006). Bob Cook (2006) also describes the value of botanical collections for research, particularly with respect to studies of plant evolutionary history and functional biology. While these articles are pertinent, a thorough reexamination of living collections and research is timely, in light of the present NHC crisis.

In this paper, I examine the relationship between historic and contemporary collection development and use, reflect upon the vital role garden collections play in research, and argue that their potentials lie unmet. I outline theoretical and practical steps gardens can take to provide a framework within which they can improve collection management and enhance their research use.

AN OVERVIEW OF GARDEN COLLECTIONS AND RESEARCH

Defining Gardens, Collections, and Research

Watson et al. (1993) define a "botanic garden" or "arboretum" as "a place with an orderly, documented, labeled, collection of living plants, that is open to the general public, with collections used principally for research and education." The broader term "public garden" refers to botanic gardens and arboreta in this traditional sense as well as to those institutions whose focus may be only recreation or amenity. By their very nature, gardens contain living plants, and these can be considered displays, collections, or both (Michener, 1996). A botanical plant collection is a documented group of living plants intentionally organized according to specific criteria or themes (Lighty, 1984; DeMarie, 1996); taxonomy, phytogeography, habitat, and utility are the most common themes encountered. While a garden's entire holdings can be called *the* collection, subsets can also be referred to as distinct collections (e.g., the *Abies* collection at the Morris Arboretum, the Meso-American cloud forest collection of the San Francisco Botanical Garden at Strybing Arboretum, the herb garden collection at the U.S. National Arboretum). Collections are central to a garden's mission, particularly when the mission is related to research and education (Taylor, 1986), and can range from discretionary (short term) to obligatory (long term), depending upon the programmatic uses articulated through an institution's formal collections policy (Lighty, 1984). Many gardens maintain synoptic collections that represent the breadth of plant diversity. These are vital for a variety of research and educational purposes and are obligatory examples. Discretionary collections may last months or decades and include research plots assembled for plant evaluation or breeding studies, as well as seasonal beds used for education and interpretation.

Nevling (1984) describes three types of museum research: *summative*, *applied*, and *basic*. Essentially all gardens engage in some form of summative research, where information is compiled from previous works and presented in new formats, such as interpretive displays, pamphlets, and books. Applied research is also active in gardens and includes management research related to the preservation of the collections. Examples include plant evaluation and introduction programs, propagation studies (including those that focus upon rare plants of conservation value), and informal experiments to control invasive plants. Basic research includes contributions made to fields such as, but extending beyond, taxonomy and phylogenetics. These three categories of research are convenient in a descriptive sense, but the boundaries between them are always artificial. Each plays an important and complementary role, and as Nevling (1984) put it, "Today's basic research underpins tomorrow's applied research."

Another distinction is made between collections-based research and research that is independent of living plant collections. For example, the New York Botanical Garden and Missouri Botanical Garden are making great strides in studying biodiversity through fieldwork and herbarium collections, while other institutions such as Chicago Botanic Garden and the Morton Arboretum have established research programs that focus directly upon their living plant collections. Both types are important; however, for this paper, the emphasis is placed specifically upon research derived from and related to the living plant collections. This work can be conducted by scientists who work for the garden as well as by off-site users who visit the garden or request material (seeds, cuttings, tissue) for subsequent work.

The Historic and Contemporary Interplay between Collections and Research

Like that of a gene bank or germplasm repository, a garden's collection value is linked to its "past, present, and future uses" (Widrlechner & Burke, 2003). The earliest Western gardens began in the sixteenth century, mainly to aid in the instruction of medicine. But it was during the grand age of exploration in the eighteenth and nineteenth centuries that new institutions emerged to describe and display the world's newfound biodiversity. Societies enjoyed public access to these wonders of the world, and NHC became "city-states of knowledge" (Freedman, 2000), full of precious and curious objects from far-off places. Gardens collected plants, assigned them names, displayed them for the public's delight, and researched them with vigor.

During this era, alpha taxonomy (the naming of species new to science) became a strong focus of garden research, and coincident with the naming of species was a rise in beta taxonomy, the classification of species into ordered groups. Carl Linnaeus (1707–1778), the originator of the binomial system of nomenclature still used today, relied upon garden collections for much of his comparative work. Herbaria and living collections became essential for these taxonomic tasks, particularly for long-lived taxa that could be revisited periodically by successive generations of scientists. Great efforts were even taken to incorporate a taxonomic arrangement of plants in the layout of some gardens, many of which still persist (Medbury, 1991). Because taxonomy was traditionally based upon comparative anatomy and morphology, these disciplines also blossomed during this time. As scientists seek to understand the evolutionary trends associated with the diversification of life, gamma (or interpretive) taxonomy and phylogenetic systematics have risen in importance. The literature is replete with taxonomic studies (alpha, beta, and gamma) conducted using living collections.

Living collections are of value to research disciplines beyond taxonomy, however. As Rae (1995) put it, "taxonomic research . . . should not be regarded as the only worthwhile reason for botanic gardens to exist—there is far more to a botanic garden than this. The diversity of functions should not only be tolerated but encouraged." For instance, because of losses in biodiversity, plant conservation has become an important research activity for gardens. Ex situ collections of conservation-status plants are used for work ranging from population genetics to reproductive biology to repatriation (Rae, 1990; Thomas & Tripp, 1998; Havens et al., 2004, 2006). Plant conservation programs are often multidisciplinary, pooling together the expertise of taxonomists, ecologists, propagators, and gardeners.

During the nineteenth century, many new Western gardens were founded, and plant introduction became an institutionalized practice whereby existing or potential economic plants were brought from distant places to new environments. As a result, economic botany as a science developed: new plants led to new foods, new fibers, new chemicals, and new ornamentals. Ornamental horticulture (as well as that dedicated to fruits and vegetables) rose to become not only an art and an occupation, but also a science. Much of this was driven by research on species introduction, propagation, production, evaluation, and further enhancement (as well as the related disciplines of plant breeding, pathology, and entomology). These areas of discovery continue today, although in most gardens, horticultural collections and research tend to focus on ornamentals and not on food crops.

More recently, living collections have become useful for ecology. The University of Wisconsin Arboretum began researching prairie restoration and ecology shortly after its founding in the 1930s (Sachse, 1965) and has continued to be a site of investigation (e.g., Hendricks et al., 2000). Ever since the pioneering work of Clausen, Keck, and Heissey (1940), those studying plant adaptation and population differentiation have used common garden experiments to elucidate ecotypic variation. When the same species of different provenances are grown side by side in the garden, even if there is insufficient (or no) replication, population differences can become apparent. Hypotheses can be tested and explored by either using clones of the garden plants or returning to the original populations to assemble artificial populations.

CURRENT STATUS OF COLLECTIONS-BASED RESEARCH IN GARDENS

Are Collections Used to Their Potential?

Certainly, living plant collections are being used by on- and off-site researchers from a wide breadth of disciplines, far too many to list here. Studies on plant taxonomy, phylogeny, and biogeography often use living collections. Recent studies have described phylogenetic relationships within Rosaceae (Oh & Potter, 2005) and *Betula* (Li et al., 2005), examined the origins of endemic East Asian island *Acer* species (Pfosser et al., 2002), as well the biogeography and domestication of *Opuntia* (Griffith, 2004), and elucidated the evolution of cold-hardiness mechanisms in *Cornus* (Karlson et al., 2004). Modern tools applied to horticultural taxonomy have also been particularly useful in sorting out misidentified or uncertain cultivated genotypes (e.g., Li et al., 2002; Elias & Pooler, 2004). Plant physiologists have depended upon garden material to study whole plant-water relations (Melcher et al., 2003) as well as nitrogen fixation (Pai & Graves, 1995), while propagators have researched the regeneration of plants from seed (Reed, 2000; Dosmann, 2002), cuttings (Bojarczuk, 1982; Pooler & Dix, 2001), and tissue culture (Chan & Marquard, 1999; Cheong & Pooler, 2003; Murch, 2004). Ecological and conservation studies pertain to the genetic diversity of a rare larkspur (Koontz et al., 2001), the demography of old-growth forests (Forrester & Runkle, 2000), and the impact of nitrogen on root substrates (Hendricks, et al., 2000). Studies on the hydrophobicity of leaves (Wagner et al., 2003), the anthocyanin content in cones (Griesbach & Santamour, 2003), and medicinal products within roots (Brinker & Raskin, 2005) have also relied upon garden material. Collections have been used to study insect range expansion (Maier, 2003) and feeding behavior (Miller & Ware, 2002; Bentz & Townsend, 2004), as well as the host ranges of *Phytophthora* (Krebs & Wilson, 2002) and *Botryosphaeria* (Pooler et al., 2002).

While the brief sampling above illustrates that collections *are* being used for research, I do not believe it is to their full potential. Estimates of use have varied considerably over the past 25 years, although all values substantiate the claim that collections are underutilized. Raven (1981) noted that despite countless opportunities, too many collections are underexploited for research, and estimated that at that time only 10% of institutions actually used their living collections for this purpose. Watson et al. (1993) found that 40% of institutions in North America had designated research programs—though no distinction was made whether these were based upon living collections or herbaria, or were even collection-based at all; thus, this may be a generous value. In another survey, 27% of nonuniversity and 49% of university gardens in North America had collections used in research (Sacchi, 1991). It could be argued that having perhaps a quarter of collections used for research is a sizeable proportion; however, this may not reflect the desires of collection managers, for in a global survey conducted by Rae (1995), half of the curators thought that their collections were underutilized for research.

The American Public Gardens Association (APGA), formerly known as the American Association of Botanical Gardens and Arboreta, serves the diverse needs of a membership that comprises traditional botanic gardens and arboreta with scientific missions, as well as public gardens, parks, and other institutions that are not committed to education, collections, or research. In fact, this diversity was a factor leading to the name change in July 2005. As of July 2006, the APGA Web site listed 496 institutional members, only 46 of which identified "botanical research" as a designated program. (Note: this list is based upon garden responses to a questionnaire, not on any designation by APGA.) This value is similar to Raven's 10% estimate of over 20 years ago, suggesting a low, but perhaps stable, level of research activity. However, this percentage may underestimate the number of institutions involved in research, as some with research programs (including Chicago Botanic Garden, The Holden Arboretum, Missouri Botanical Garden, The Morton Arboretum, and U.S. National Arboretum) were omitted from the Web site listing. These omissions do not likely reflect the institutional views of the gardens and may represent errors made by uninformed individuals completing a questionnaire. But, as an observation, the omissions suggest that research might be insufficiently part of the institutional cultures to be considered important even by uninformed staff members.

Why Is the Research Potential of Living Collections Unmet?

Despite the intentions of curators, why are only a minority of garden collections being used for research? Like other NHC, garden collections may be undervalued because they are not seen as "wage earners" by society or even administrators, a perception that often reflects a shift in priority and resources away from collections to that of public service (Pekarik, 2003). Over 20 years ago, Judy Zuk (1984) posed the following question: "Are our collections underutilized because we have not been successful advocates, or because we are advocating a resource for which there is no widespread demand?" Her question remains timely and deserves to be asked again, particularly as it relates to the advocacy of collections-based research. I believe the answer is yes; gardens need to be better collection advocates, and demand for their use needs to increase.

Peter Raven (1981) challenged the International Association of Botanical Gardens (IABG) to take an active leadership role in coordinating and promoting research and collections. He seemed less than optimistic, however, when he stated, "It remains to be seen whether the IABG will accept this challenge, or some other group will assume the role of international coordination." Perhaps because of such inactivity, other groups have begun to fulfill some of these roles, at least in part. Botanic Gardens Conservation International (BGCI) advocates plant conservation and affiliated research globally (http://www.bgci.org.uk/), and within North America, the Center for Plant Conservation (CPC) has made progress in establishing networks of gardens to cultivate threatened plants (http://www.centerforplantconservation.org/). APGA coordinates the North

American Plant Collections Consortium (NAPCC), a program focused upon germplasm conservation and elevation of curatorial standards (Allenstein & Conrad, 2004). PlantNet facilitates networking among plant collection providers and users in the U.K. and Ireland and has published a collections directory toward this end (Cubey & Rae, 1999).

It remains to be seen if APGA, particularly with its new name and broader, more diffuse audience, will become the advocate for collections and research that Raven called for in 1981. *The Public Garden*, APGA's quarterly journal, devotes each issue to a special topic, and owing to the organization's diverse nature, a wide range of topical issues is to be expected. Yet in the 20 years since the publication's inception, not a single issue has dealt specifically with research (collections-based or otherwise). [Note: the July, 1991 issue (volume 6, issue 3) was devoted entirely to "botany" and included an article about research (Sacchi, 1991); an issue dedicated to ex situ conservation included two pieces (Havens et al., 2004; Raven, 2004b) related to conservation research, and two recent articles (Cook, 2006; Raven, 2006) discuss the general importance of garden research.] According to the editor, multiple attempts to publish a research issue have failed because nobody from the garden community was willing to contribute articles (S. Lee, pers. commun.). This is alarming, for if members of the garden community and its primary organization do not advocate for research, is it any surprise that collections are underutilized for that purpose?

The second part of Zuk's advocacy question relates to collection demand. Based upon the research examples listed above (in "Are Collections Used to Their Potential?"), collections are being used for a diversity of research projects, which implies some level of demand. However, the fact that their potential for use remains unmet suggests that demand is insufficient. This prompts a follow-up question: is current demand truly at capacity or does it reveal an artificial threshold reflecting the views of gardens or scientists? Collections are unlikely to have reached their maximum potential (see "Cultivating Research in the Garden," below). Instead, low demand likely reflects the perceptions by both garden administrators and researchers of how collections can be used.

Too often, collections are seen only in light of their *historical* contributions to science, rather than for their *contemporary* or *future* value. This includes narrow views of the scientific disciplines best suited to use living plant collections, as well as perspectives that the modern research community has left gardens and collections behind. On one hand, there is truth to this (e.g., there are few nineteenth century taxonomists left to review collections assembled during the nineteenth century); however one may argue that owing to nostalgia, some gardens have been reluctant to engage contemporary research users, particularly those off-site. While nostalgia is important for perspective, living for the "good old days" is a symptom of garden decline (Briggs & McDevitt, 1989). If this happens, collections can become anachronistic relics from a golden age. This need not be the case, for even when a garden's focus is purely historical, discovery and research can occur within the collection, as at Thomas Jefferson's Monticello (http://www.monticello.org/), where the active study of garden archaeology and historic plant germplasm occurs.

The Importance of Collections-based Research

Some may ask, "Why is collections-based research important?" This is a very appropriate query, particularly when budgets may be tight or missions nonresearch oriented.

Below, I argue for a series of rationales that can be applied to most, if not all, gardens. Perhaps the most basic rationale is that research is often a fundamental and crucial component of a garden's work. Steere (1969) was adamant in his support and advocacy for research, going so far as to state that "no institution is privileged to call itself a botanical garden unless it is doing research of some kind and to some degree." Because of their original missions and mandates, many gardens have an obligation to engage in research activities, using in-house staff when possible and by accommodating off-site researchers otherwise. Because the public entrusts gardens with part of its biological heritage, there is an expectation of responsible stewardship now and into the future (Raven, 1989). Should this trust be compromised, there can be significant negative reaction from the public and scientific communities (Rankin, 1955). Stewardship includes basic collection maintenance to keep the plants alive and healthy, as well as engagement activities such as research, which allow gardens to ably respond to and meet unanticipated societal needs (Widrlechner, 1997).

Gardens are inspiring and have stimulated scientists to do some of their best work (e.g., Linneaus, Charles Darwin, Gregor Mendel, Liberty Hyde Bailey, and Barbara McClintock). *Science in the Pleasure Ground* (Hay, 1995), the title of a history of the Arnold Arboretum, epitomizes the intertwined relationship among gardens, research, and inspiration. Yet it is not just the gardenesque landscape that provides motivation, but also the treasure trove of extraordinary plants within. Ricklefs (1980) wrote that "Beyond the value of museum collections as a resource for ecologists, specimens remain a source of insight and inspiration. . . . [T]he examples of taxonomic diversity and geographical variation . . . suggest . . . novel research problems or add to the context within which one thinks about ecological and evolutionary issues." Mark Chase (in Marris, 2006) describes the inspiring benefits of looking at both the molecules and the living plants, a process he calls "reciprocal illumination."

Museums have been encouraged to recognize collections as not just a core strength but a unique asset: when it comes to collections-based research, they hold a competitive edge over all other research institutions simply because they *have* collections (Winker, 2004). This does not mean that gardens should stop engaging in noncollection-based research, for those contributions may also be significant. Rather, it means that before gardens give up on their collections for other areas of research, they may wish to invest their efforts in assets that only they have. Similarly, gardens are becoming more vital as university departments in the various plant sciences shift their foci, merge, receive new names, or are dismantled altogether. This was predicted nearly 40 years ago by Steere (1969), and in time, "gardens may become the only local institutions with a specialization and knowledge of plants" (Watson et al., 1993). Threats to university gardens are particularly worrisome as they represent direct threats to the training of students. University botanical gardens "have a special obligation to try to be relevant to both research and teaching, since those are the primary reasons that a university would have any facility" (P. Raven, pers. commun.).

One can rationalize and justify collections and research using a dollars-and-cents argument. By applying a cost-benefit analysis, Suarez and Tsutsui (2004) argue that "collections confer economic benefits by serving as centralized locations for information processing and storage, saving other institutions, and taxpayers, hundreds of millions of dollars per year." Similar to the USDA National Plant Germplasm System (NPGS), garden collections can serve as valuable repositories of plants, providing material (typically free of charge) to an array of scientists around the world who lack the resources to cultivate the plants themselves (Mann, 1997). Finally, the broader the community of collection users (researchers, educators, visitors), the stronger the justification that can be made for collection support during fund-raising and grant-writing (Stern & Eriksson, 1996).

The very nature of the objects maintained in a garden, the plants, provides yet another rationale for research. In the art world, there is but one *Mona Lisa*, a lone masterpiece that can be duplicated only by forgery—and then not exactly. Because of its solitary and fragile nature, the potential for physical research on the painting is obviously constrained. However, gardens are distinct from art collections and other NHC in that living plant accessions often can be cloned, allowing for the replication and perpetuation of unique material, material that can also be given, not just loaned, to researchers for study. Because of this intrinsic characteristic, gardens have the potential to extract a great deal more information from any given accession than their peers can. And if appropriate methods for clonal propagation have not been discovered for specific plants, that opens up opportunities for new research. Gardens are germplasm repositories that, with proper planning and management, can represent a near limitless supply of material for contemporary and future use.

The management of the plant collection can improve with research. When an accession is targeted for study, general practice dictates that it is accessed by a member of the curatorial or horticultural staff, its condition is evaluated, and if necessary, appropriate measures can be taken to improve its health or to repropagate it. At this time, new information can be added to the individual accession records and previous data entries reviewed, allowing for errors to be detected and corrected. Plant acquisition can also be affected by research, with new plants often being donated to the garden by collaborating researchers.

Similarly, research use prevents collections from becoming obsolete. As Miller (1963) noted, "when research ceases, the facility, of whatever kind, retains only historical and curiosity value, and all concerned tend to look backward only. The backward look is essential for enrichment and the understanding to be derived, but, without the ability to look and move forward through active research, we make no progress." Universities encourage faculties to engage in original research and discovery throughout their tenure as a means of maintaining relevance and ensuring they are up-to-date with contemporary ideas. Gardens are similar, in that they maintain relevance and the ability to react to future needs by engaging their collections through research. Land-grant universities in the United States are committed to a three-part mission of extension/outreach, teaching, and research. This analogy also extends to gardens, where research (in many forms) not only allows gardens to keep pace with contemporary issues but also can advance and improve educational and outreach efforts.

Cultivating Research in the Garden

I have described the collections crisis facing gardens, pinpointed reasons it has arisen, and provided rationales for supporting collections-based research. For the remainder of this article, I focus on actions gardens can take to enhance their collections and collections-based research. These include: a shift in paradigm toward collections and research advocacy; anticipating future research needs, including the unexpected; strengthening collaborative efforts; building and strengthening the relationship between users and providers; and substantially investing in information management and technology.

PARADIGMATIC SHIFT IN COLLECTIONS ADVOCACY AND MANAGEMENT

In order to have an effective collections-based research program, a garden must first have an effective collection. If they have not already, curators and garden administrators must take full stock of their collections and determine how they fit into the institutional goals and missions. As DeMarie (1996) stated, "Lack of sufficient interest or awareness of a collection's contents and purpose often means that the collection is not used effectively, which results in diminished efforts to advocate for the collection. Thus a downward spiral begins, resulting in the loss of valuable collections of plant genotypes." Gardens cannot risk a decline in collection interest and advocacy, or worse, the accompanying loss of germplasm.

Central to collections development and maintenance is a clearly defined collections policy. This living document stems from the institutional mission statement and serves as a rule and guide, regardless if the collections are cultivated for amenity or for educational or research purposes (which are not mutually exclusive). It affects plant acquisition, collection development and use, as well as subsequent collection review, modification, and deaccessioning.

Every accession should meet at least one collection need—if an accession has no collection value, why should resources be allocated toward its cultivation? This does not mean that accessions in a garden lacking a clear purpose should be immediately deaccessioned. Rather, it suggests that those very accessions should be reviewed, their value determined, and purpose delineated. Amazingly, when pressed to justify individual plants, gardens can be very creative and come up with novel and legitimate rationales to maintain them. A "collections evaluation matrix," akin to the one described by Waddington (1997) for assessing a geologic collection, could be adapted for reviewing garden collections. Routine review may be less an issue for obligatory than for discretionary collections. For example, if a plant in a specific research collection has lived beyond the end of the research project, it ought to be reviewed and a decision made as to whether it should remain in the garden. Similarly, in a collection of plants grown *only* for their ornamental attributes, deaccessioning can be justified if those plants fail to achieve specific display effects because of poor health or genetic inferiority.

Operationally, a collection is merely an intellectual construct that allows an object to be better managed. Traditional categories (e.g., taxonomic, phytogeographic, physiognomic, habitat, use) have served gardens well and will continue to do so, yet other designations can be also flexibly applied (e.g., conservation status, expedition, collector, cultural significance, research project, location in the garden). Gardens contain an array of realized and unrealized collections that span their entire holdings, with individual plants falling into multiple collections. For example, a single katsura tree (*Cercidiphyllum japonicum*) may occupy a place in a garden's various taxonomic (Cercidiphyllaceae), geographic (Eastern Asia), conservation (threatened), ecological (disturbance-induced stem sprouting), collector (E. H. Wilson), horticultural (trees with outstanding autumn color), educational (specimens included in the monthly tree walk), and research (dimorphic leaf project) collections.

Collections shift over time, and new collections arise as societal or scientific needs change. Sometimes, like the plants in the garden, collections appear spontaneously. Heywood (1995) used the term "serendipitous collectionism" to refer to the fact that many gardens now have conservation collections that were originally assembled without "any conservation ethic in mind." At the Royal Botanic Garden Edinburgh, there exist a number of accessions with conservation value yet no placement in a specific conservation collection. Radford et al. (2003) surveyed a subset of these and found that they often slipped through the curatorial cracks because of a lack of awareness or any clear management scheme (i.e., they were not part of a designated conservation collection). Following this review, these previously disjointed accessions were placed under the umbrella of ad hoc ex situ conservation collections and an improved management program.

Assessing collection value requires a perspective that extends beyond the garden walls. Dosmann and Del Tredici (2003, 2005) examined accessions from multiple institutions derived from a historically important collecting trip to China: the 1980 Sino-American Botanical Expedition (SABE). When viewed as individual garden accessions, their unique value was not so apparent. It was only when they were examined collectively (within and among gardens) as the SABE Collection that their individual value and rarity could be determined. This study of a relatively recent expedition also demonstrated that gardens ought not to lose sight of their responsibility to acquire new plants. A collection should not be given the static stigma of being "complete," for when a garden stops acquiring new objects, a notion can arise that there is nothing new under the sun to obtain, and nothing more to research (Prather et al., 2004). However, future acquisition must be directed and deliberate, for gardens cannot afford to randomly acquire new plants in an ad hoc manner. Gardens that are mere stamp collections have difficulty meeting programmatic goals, whether these are amenity, education, or research. A well-conceived collections policy should be applied during the acquisition process, as it guides the enrichment and development of specific collections.

In addition to their intellectual management, garden collections deserve the highest quality horticultural care possible. Except when specific experimental treatments are imposed (e.g., drought stress, poor nutrition, herbivory), plants grown in field plots and greenhouses for experimental purposes require optimum growing conditions. Living collections require the same for optimal research use. Gardens employ some of the most skilled horticulturists in the world, and effective utilization of their talents is required to provide the hale and hearty plants needed for research. Healthy collections are also essential for amenity purposes, impacting public visitation and appreciation.

SOWING SEEDS FOR FUTURE RESEARCH NEEDS

As original participants in the collection, description, and evaluation of botanical biodiversity, gardens have been research players for the last several centuries, and they still have much to contribute (Marris, 2006). Also, when considering research possibilities and agendas, gardens ought to contest views that collection-based research may be too applied or perhaps inferior to basic research. As Havens et al. (2004) recommend, the emphasis should be on distinguishing between good and bad science, not between basic and applied categories. By recognizing their scientific value to society and raising their self esteem, gardens can better justify long-term commitments to collections and research, and even improve the competition for funding from governmental agencies (Ertter, 2000). Institutional pride also benefits those who work in research collections by improving staff morale, performance, and career recognition (Lyal & Weitzman, 2004).

If tradition dictates (Sacchi, 1991; Rae, 1995), large university and government-funded gardens are most likely to have their collections used for research. However, to exclude gardens whose primary focus may be display or education from participating in research is misguided; there should not be any sort of litmus test. *Any* institution with a desire to engage its collection for research should be encouraged to do so and supported in its efforts. In fact, similar to local and small herbaria (Ertter, 2000; Prather et al., 2004), regional or specialized gardens can contain unique collections of germplasm, have exceptional cultural histories, or grow plants under unique environmental conditions. Whether their goal is the development of collections or research agendas, the most logical route for gardens to follow is to *tell their own story*, to build upon their unique collection strengths and assets.

Just as there should be no litmus test restricting research to gardens whose collections are "researchworthy," there should not be restrictions (real or perceived) with respect to the researcher pool. Some gardens employ their own researchers and can direct the nature of research accordingly. However, no garden can employ enough staff to investigate every potential facet of their entire living collection. Thus, gardens should not only encourage research use by off-site scientists but actively market themselves to these audiences. No longer can there be an expectation that simply having a collection is sufficient to attract outside users.

The Modern Research Garden

Some garden administrators and curators lament that their collections are not used to their potential because of a lack of users. In part, this appears true if one considers historical or traditional users only. But being wedded solely or too closely to a limited array of research foci can restrict what future users (scientists, students, visitors) will find available and valuable in the collection (Bryant, 1983). To maximize broad collection use, gardens will have to avail themselves to users in fields including and beyond the traditional, from ecology and natural resources to molecular biology, even including nonbiological sciences.

While it seems as if there are fewer practitioners of taxonomy now than in the past, in truth there are more—they just happen to be exploring other reaches in the biodiversity stream (Raven, 2004a). The total number of plant species on the planet, including those yet to be discovered, is estimated to be around 300,000, yet there is an estimated (and perhaps conservatively so) 10 million organisms on the planet, the majority of which are unnamed (Wilson, 2003). Thus, it is understandable that underfunded global taxonomic efforts have been redirected to nonplant taxa. Challenges such as those made by Wheeler et al. (2004) have called for an expansion in systematics research, and hopefully in the near future they will be heeded and accompanied by further description of biodiversity and elucidation of its phylogenetic relationships.

Furthering this, the comparative methods and approaches practiced by taxonomists will be applied and extended using molecular, developmental, morphological, and chemical characters. As botanical science seeks to apply the lessons gleaned from *Arabidopsis thaliana* (and other model systems) to the diversity of the plant kingdom, gardens will find they are well positioned because of the wealth of genetic and molecular diversity they maintain. Just imagine the typical ornamental border: a polyploid circus of cuticular waxes, pigment combinations, bizarre leaf and floral morphologies, contorted habits, atypical growth rates, and unusual tolerances to environmental stresses. Like serendipitous conservation collections, gardens will find that many of their ornamental mutants will become serendipitous collections to be exploited for genomics.

In the future, as ecology becomes more central and important to the study of plant biology (Bazzaz, 2001), garden collections can be used as sources of genetic material for off- and on-site investigations. One of the future challenges will be the integration of community with ecosystem ecology (Loreau et al., 2001), and despite (or perhaps because of) their artificial nature, gardens may contribute to an improved understanding of ecosystem processes, particularly urban ecosystems. Studies in plant conservation will certainly increase, driven by global environmental changes and challenges. Threatened plants will need to be rescued, reared, studied, and returned to ameliorated habitats; deteriorated landscapes will need to be restored. Horticultural research will also increase, driven by the need to improve the palette of ornamentals and methods to cultivate them. The science of horticulture is also intrinsic to the conservation (i.e., culture) of living collections and constitutes the bulk of management research in gardens. Even researchers in the psychological sciences find gardens valuable as they seek to understand the interaction between plants and human behavior (Kuo & Sullivan, 2001; Rappe & Kivelä, 2005).

Responding to and Meeting Unanticipated Needs

Not all future research can be predicted, which presents a significant challenge for gardens: how to prepare for *unanticipated* research needs. Luckily, new technologies and new research interests have a way of shedding light on old, anachronistic collections. Because collections comprise "objects [that] serve as a body of data against which a myriad of . . . assumptions [can] be tested" (Mori & Mori, 1972), they can be "regarded as 'scientific data in waiting' " (Pettitt, 1994).

Archeologists and anthropologists have often relied upon new analytical techniques and novel questions when justifying the maintenance of their collections (Stankowski, 1998). For instance, innovations such as magnetic resonance imaging have resurrected archeological collections thought to have been fully characterized (Irving & Ambers, 2002). The potential yields generated from molecular data are staggering and revolutionizing, as shown by Larson et al. (2005), who used a combination of living and preserved museum specimens to paint a global picture of swine domestication.

New light can be shed on collections when they are studied by nontraditional users. Caravaggio's beautiful paintings, extensively studied and appreciated by artists and historians for their detailed realism, when studied by a horticulturist provide in unanticipated fashion a unique glimpse of the crop diversity, pests, and diseases present in the late sixteenth and early seventeenth centuries (Janick, 2004). Most NHC specimens were collected with taxonomy in mind, and yet many have been used by nontaxonomists in studies ranging from environmental pollution to epidemiology (see examples in Suarez & Tsutsui, 2004; Winker, 2004). Stern and Eriksson (1996) present additional examples of herbarium collections used by nontraditional users, including ecologists, entomologists, and conservation biologists.

Living plant collections have also been assembled for one purpose and used for another. Sometimes the unanticipated use is the result of unfortunate events, leading to the application of the adage "When life gives you lemons, make lemonade." Ongoing research at the Arnold Arboretum on the hemlock wooly adelgid, an introduced insect decimating hemlock forests in eastern North America, ranges from studies on forest floor regeneration to the identification of replacement hemlock species. When famed plant explorer E. H. Wilson collected *Tsuga chinensis* from Asia a century ago for the Arnold Arboretum, there was no anticipation that those accessions would play a role in studying the insect (Del Tredici & Kitajima, 2004). Harrison Flint (1974) predicted plant collections would be useful for studying phenology, and recently they have been—not to examine genecology as he suggested but to study climate change (Primack et al., 2004; Wolfe et al., 2005). Researchers can also look beyond intentionally planted accessions, for gardens are ideal for studying spontaneous flora and invasion biology (Dosmann & Del Tredici, 2003; Jefferson et al., 2004; Mack, 2005).

Gardens, as intact ecosystems, present countless opportunities for discovery. Below-ground fungal diversity, expressed as a function of both environment and host-plant diversity, has been explored at Dawyck Botanic Garden, a satellite garden of the Royal Botanic Gardens Edinburgh (Krivtsov et al., 2003). And garden collections, in the broadest sense, have even been used by researchers to study the growth and development of wild rabbits (Marchandeau et al., 1995) and the conservation biology of pond turtles (Spinks et al., 2003).

Unanticipated research opportunities will always arise, and gardens must be ready to respond. In particular, management research that relates directly to the preservation, maintenance, and curation of collections is critical. An a posteriori analysis of distribution patterns allowed curators to better anticipate and plan for future germplasm demand and use (Widrlechner & Burke, 2003). Case studies can improve the management of conservation-status taxa (Maunder et al., 2001; Radford et al., 2003) as well as improve the execution and follow-up practices of plant-collecting expeditions (Dosmann & Del Tredici, 2005). Management research can also be directed to collection threats such as pathogens (Hibben & Franzen, 1989) and invasive species (Levy, 2005).

Zoos and aquaria have been challenged to vigilantly monitor new and emerging areas of science to maximize the use and application of their own collections (World Association of Zoos and Aquaria, 2005). Similarly, the future of collections-based research in gardens is not bleak, provided gardens are willing to engage a wider research audience. Gardens will find that expanding the number and breadth of users will help guarantee collection survival by generating a wider array of data accumulated and a broader base of advocates within the scientific community (Stern & Eriksson, 1996; Widrlechner, 1997; Heyning, 2004).

ENHANCED COLLECTION USE THROUGH COLLABORATION

Michener (1996) used the term "collection envy" to describe internal struggles between collections and displays, yet I would extend this term to apply to intergarden competition as well. Too frequently, gardens compare the number of accessions, quantity of taxa, or percentage of wild-collected versus garden-origin accessions they hold. While these descriptive statistics have meaning, the comparative mentality is counterproductive, taking attention away from the intrinsic value collections have regardless of their size or composition. As Lane (1996) articulated for herbaria: "No longer should the goal be to demonstrate that Kew has more specimens than Paris, the American Museum more than Berlin, my own herbarium in Kansas more than Oklahoma's or Colorado's; in short to demonstrate that: 'mine is bigger than yours.' "

Fortunately, gardens already collaborate in a number of ways to improve collections management and research. In North America, NAPCC works to improve germplasm conservation and elevate curatorial standards (Allenstein & Conrad, 2004), and the North America China Plant Exploration Consortium mounts collaborative expeditions to China to collect herbarium specimens and germplasm for long-term research goals. The International Conifer Conservation Programme, based at the Royal Botanic Garden Edinburgh, is a multi-institutional, multinational, and multiscale network that focuses on plant conservation and research (Thomas & Tripp, 1998). Similarly, gardens in North America, in collaboration with the CPC, have succeeded in ex situ conservation efforts (Kennedy, 2004).

Because of their ability to inspire, gardens are ideally suited to become research centers for collaborating on- and off-site users. In fact, collaboration might be an alternative for gardens trying to conduct research on their own (particularly noncollection-based) in competition with institutions that are better suited (Mann, 1997). When seeking external collaboration partners, gardens should not limit themselves to scientists housed only in large universities or those housed in plant science departments, for departments of biology in regional and community colleges, as well as the private sector, contain talented researchers.

THE USER-PROVIDER RELATIONSHIP AND THE ROLE OF THE CURATOR

Even when a garden employs collections-based scientists, often the research department remains an island unto itself, creating a separation between the users (scientists) and the providers (horticulture staff); this division is exacerbated in institutions that have no research staff on-site and all investigation is carried out by external users. Gardeners may not realize why the plants are important for research, while scientists report they have little control over what or how plants are grown (Rae, 1990). A collection's value depends not only upon its quality and organization, but its accessibility to researchers (Pekarik, 2003). Because collections frequently contain eclectic groups of specimens and rare curiosities that have value apparent only to specialists (Bryant, 1983), their utilization hinges upon those specialist users knowing what the providers have, and the providers knowing what users need. Scientists from nontraditional disciplines who do not use living collections find it difficult to determine what plants are grown in gardens or assume that the material that they desire is unavailable. Some are unaware that most gardens maintain databases containing detailed records and that many of these can be accessed online. This further illustrates the disjunct between gardens and potential user pools, and that gardens can do better in marketing their resources.

The curator or collections manager is key to this conversation. In gardens, curatorial duties can be administered by a single individual or a team of specific garden collection (e.g., woody plants, tropicals, herbaceous plants, rose garden) curators. The latter has been noted to improve collections management by maximizing curator knowledge bases, particularly when a highly diverse group of taxa is maintained at a single site (Widrlechner, 1997). Regarding curatorial duties, the question arises: should curators be custodians of collections (Walker, 1963), or should they be researchers (Miller, 1963)? Both are essential. As custodian, the curator is entrusted with ensuring the safety, development, and long-term care of the collection. In many, though not all, gardens, curators manage the horticultural and gardening staff as well. If there is a separate administrator for these staff, it is imperative that the curator have this individual's ear and can affect gardening policy appropriately. As a researcher, the curator should be expected to extract information from the collection, including that related to its efficient conservation (i.e., management research). As Miller (1963) noted, not only is the research-curator inspired by the collections but his or her "research leadership will inspire others and, by thus leading, draw more investigators." However, the custodial and stewardship roles of the curator must be the first priority, for if the collection languishes or falls into disrepair, all further research is threatened.

The curator, as the plant collection's primary advocate, is to engage outside researchers directly (Lighty, 1984). Raven (1981) described a separate "garden utilization officer," whose job it is to promote living collections for research. Because of the rapidly changing face of science, this position of collection advocate requires familiarity with a broad array of disciplines as well as a willingness to seek out new researchers.

What Gardens Provide Researchers

As stated, collection use (or lack thereof) hinges upon the premise that providers need to know what users need, and users need to know what providers have. In this relationship, gardens can inform researchers about the range of germplasm, information, and resources they are able to provide. Fortunately, many gardens now have searchable inventories on their Web sites to facilitate this. Access to the plants (or tissues/propagules) should be provided as soon as is feasible for all requests deemed legitimate by the garden. Additionally, researchers should receive all of the accession's associated information: the records that make them valuable (see "What Information Is Valuable" for a discussion on plant records). Often, there are affiliated collections, such as herbarium specimens, images, and collection notes that are of use to researchers. With respect to these ancillary collections, Rae (1995) stated, "it is the combination of these very resources that make botanic gardens unique and useful research institutions and it is inconceivable that much useful research could be done without all of them."

Not to be overlooked is the expertise of the horticultural staff, which includes knowledge of cultivation practices and propagation techniques, as well as an understanding of unique garden plant variation. Raven (1981) was keenly aware of this asset, writing of "the special but underutilized and often unrecognized potential of the working garden staff of botanical gardens in contribution to our fund of knowledge about plants." Providing a researcher with access to staff is rewarding for all involved—users learn more about the plants they are studying and gardeners learn more about how the collection can be used.

Gardens that cannot hire full-time research staff owing to limited budgets can investigate relatively economical tactics for bringing off-site researchers to the collection. Financial assistance in the form of grants or fellowships can be provided to support collections research and are particularly valuable to visiting scholars and graduate students. In-kind support, such as office, greenhouse, or laboratory space, and in some cases, even on-site housing can be provided (e.g., Montgomery Botanical Center, Coral Gables, Florida). Recognizing a researcher with formal institutional affiliation, even without remuneration, can further elicit a sense of collaboration and strengthen the user-provider relationship. Regardless of the level of support gardens can allocate to visiting scientists, what is important is that researchers are made to feel welcome and given access to the primary garden resources: the plants, their records, and staff.

What Researchers Provide Gardens

In any successful relationship, there is a degree of reciprocity. Sixty percent of gardens ask researchers to complete some sort of material-use form that records the type of research being conducted, information about the user, and a listing of accessions used

Table I
Documentation of research use and requests made of researchers by North American gardens[a]

Gardens indicating that frequency of collection use for research . . .	
. . . could at least be estimated:	83%
. . . was known exactly:	11%
Gardens indicating that documentation of collection use occurred . . .	
. . . at least some of the time:	63%
. . . all of the time:	40%
Gardens indicating that material use forms were used to track collection use . . .	
. . . at least some of the time:	60%
. . . all of the time:	46%
Gardens indicating that collection use was recorded in a database . . .	
. . . at least some of the time:	37%
. . . all of the time:	29%
Gardens requesting acknowledgments in publications:	69%
Gardens receiving acknowledgments in publications:[b]	29%
Gardens requesting reprints of published work:	51%
Gardens receiving reprints of published work:[b]	37%
Gardens requesting proper accession citation:	14%

[a] Percentages based solely upon questionnaire respondents who indicated that their living collections were used for research (n = 35). Forty percent of these institutions were affiliated with universities and 86% had a research mission (which included the supply of material to outside users).

[b] Includes responses from gardens that did not make any requests for acknowledgments or reprints.

(Table I). These records are necessary to allow the garden to document (and publicize) usage, justify maintenance of collections, and facilitate planning. In some cases, gardens can even resupply information lost by the researchers during or after the project work.

When gardens provide researchers with the plant material and records, they should ask that (1) the institution be acknowledged as the source of the material; (2) all accession information be properly referenced in publications; and (3) reprints of the work be sent to the garden when published. A majority of gardens request acknowledgment; however fewer than a third report that researchers actually follow through (Table I). And while researchers may acknowledge the source of specimens, too often they fail to provide any information about the unique specimens examined (Ruedas et al., 2000). This may be less a problem in taxonomic studies, where vouchers are conventionally cited, but it is not uncommon to read articles from other disciplines where this information is neglected. Gardens rarely point out the value of directly referencing the accessions used (Table I), and to some gardens and researchers, this request may seem trivial. However, failure to reference accession numbers in a publication hamstrings a future researcher's ability to repeat the experiment. It also makes it impossible to reconcile ambiguous or anomalous results due to a specific genotype, misidentification, or environment the plant may have been growing in. Like the vouchering of herbarium specimens, this form of documentation can increase the individual study's credibility and long-term significance, separating "valuable research" from mere "short stories" (Barkworth & Jacobs, 2001).

Upon completion of the work, researchers should supply the garden with reprints (or electronic files) of all published work, which seems to occur about a third of the time (Table I). This allows the garden to append individual accession records to reflect the plant's use in published work, and also makes it easier for the garden to document collection use to the general public, staff, board, and funding sources. Gardens may wish to use follow-up reports similar to those used at the USDA North Central Regional Plant Introduction Station in Ames, Iowa, where curators ask germplasm users to complete periodic Accession Performance Reports, which allow curators to evaluate usage and better characterize the collection (M. Widrlechner, pers. commun.). All of these requests of researchers are far from extreme and are the least that can be done in exchange for (typically) free access to the collections.

As mentioned earlier, scientists can expand the holdings of a collection by donating plant material. It is not unusual for researchers to assemble their own core collections for in-depth study and evaluation off site. Frequently, these repositories become the most comprehensive of their kind and represent pools of novel germplasm that can enter the garden gate for short- to long-term purposes. Most scientists are eager to share material, particularly if they know it will be able to outlive their own programs.

Researchers familiar with the collection can also be placed on garden advisory boards and committees. This provides the garden with scientists' perspectives and helps ensure research is part of institutional planning. It also fosters the dialogue between users and providers. At Cornell Plantations (the botanic garden, arboretum, and natural areas of Cornell University), the Collections and Design Committee is composed of Plantations' horticulture and administrative staff as well as researchers from various academic departments in the university.

COMMUNICATING AND DOCUMENTING THE RESEARCH VALUE OF COLLECTIONS

Gardens can better educate members of the scientific community and the general public about the sheer breadth of their contributions to science. In particular, nontraditional and off-site researchers may be unaware how they can make use of living plant collections, placing the onus on gardens to inform and illustrate collection value. For example, a physiological ecologist may rely on wild-origin plant material to conduct studies on ecotypic variation. Yet first considerable time and resources must be invested to amass the required germplasm, either by collecting the material directly or working through collaborators. Gardens can step in to make this job easier by supplementing a researcher's collection with clonal material of their own. For example, the Urban Horticulture Institute at Cornell University has established research collections of several genera (*Acer* and *Koelreuteria*) by obtaining material from gardens.

Taylor (1987) observed that university gardens, active sites for research, are "too often . . . better known outside than inside the university community. It is the old problem of not appreciating one's own backyard." Richard Howard (quoted in Raven, 1979) attributed part of this problem to semantics, suggesting that the names "garden" and "arboretum" were misunderstood as being simply displays of living plants, not as institutions of active discovery. Museums often struggle with a lack of public understanding, particularly when so much of the research occurs behind closed doors. Nevling (1984) encouraged museums to tell the public their full story, to impress upon them the unique and special responsibilities that NHC have for society. In fact, it has been proposed that the failure of the NHC community to communicate the unique value of collections has contributed to the current collection crisis (Heyning, 2004).

Fortunately, gardening remains a popular public pastime, providing gardens an opportunity to use ornamental plants and horticulture to teach the public about plant diversity, the natural sciences, as well as behind-the-scenes research. The public itself can even be involved in the research process. Scientists at Cornell University's Laboratory of Ornithology conduct research projects spanning large geographic areas with the help of thousands of volunteer birders, an approach known as Citizen Science (Bhattacharjee, 2005). By following a similar model, gardens can conduct original research as well as educate the public about timely research topics (e.g., phenology, invasion biology, plant evaluation, plant adaptation) by enlisting them as volunteer data collectors. In fact, the National Phenology Network uses this type of program to monitor climate change (http://www.uwm.edu/Dept/Geography/npn/shrubs.html).

When defending a collection in crisis, better documentation and monitoring of use is required. Documentation of these activities is generally insufficient (Table I), and, as Pettitt (1994) succinctly put it, "If you don't write it down it didn't happen!" Most garden curators can estimate collection usage, but only a minority track each use using some sort of documentation system; fewer than a third consistently record use in the individual accession files of the database (Table I). [Note: upon responding to the questionnaire cited in Table I, a number of institutions decided to change their policy and now track collection use.]

Publicizing collection availability or use is not always regarded as positive, however. To some, this can foster unwanted interest, increase security concerns, and even create situations where demands are placed on gardens that cannot be met. I was once told by the former director of a university garden that he chose not to make public the garden's supply of tissue and germplasm to researchers for fear that the university would force the garden to refrain from distribution completely or charge for the services. While I empathize with the reality of this director's plight, I cannot disagree with the action more. If gardens fail to document the value and use of their collections while it occurs, how can they ever hope to justify their importance once they are threatened or gone completely?

IMPROVING RECORDS TO IMPROVE RESEARCH

A collection's value is proportional to the information it contains and can provide others (Pekarik, 2003); collections are not just collections of *objects* but associations of *objects* and *information*. Widrlechner and Burke (2003) reported that "users request germplasm based upon knowledge gained about specific accessions through personal experience and by examining the collective results of past evaluation and characterization work." Research collections with a history of characterization serve as benchmarks against which future results can be compared. As gardens strive to enhance the research use of their living collections, they will find that improving the quality of collections-based information and access to it will help them reach this goal. By viewing their specimens as "biological filter paper" (Winker, 2004), gardens can assemble their stored (and increasing) taxonomic, ecological, physiological, and genetic data to further research needs.

Metaphorically speaking, collections are icebergs: the living plants represent the proverbial tip, while the vast array of records, previously collected data, reports, and evaluations represent the submerged portion of the iceberg. And as new information is added, the iceberg increases in size and value, becoming more appealing to future researchers, provided they can easily access and manipulate these data and connect them back to specific accessions. The cycle of information mining and generation can potentially continue ad infinitum.

What Information Is Valuable?

Within NHC, typically there are three general categories of data used to document collections: (1) *biodiversity* (taxonomic identity and associated data pertaining to the specimen's natural history); (2) *geography* (the locality and habitat from which the specimen was collected, as well as its present location); and (3) *time* (the date on which the collection or evaluation was made) (Graham et al., 2004; Winker, 2004). Within the U.S. NPGS and other germplasm repositories, collections are documented according to three similar categories: (1) *passport data* (geography and locality data, collection/expedition, donor); (2) *taxonomic/characterization data* (generally highly heritable traits); and (3) *evaluation data* (traits and characters that are plastic and markedly respond to environment) (Engels & Visser, 2003; M. Widrlechner, pers. commun.). Both of these documentation systems can be applied to garden collections, but there are some shortcomings and difficulties in extending their use completely. Thus, it might be best to hybridize both systems to create a structure ideal for gardens and the collections they house. These three garden categories are: (1) *genotypic biodiversity*; (2) *environment and source history*; and (3) *phenotypic biodiversity*. These data coalesce to represent the object's collective record, and, provided there are enough of them, can reveal valuable patterns at a level above an individual accession.

Genotypic biodiversity data reflect the accession's taxonomy, including at subspecific and population levels (if known). These represent the NHC biodiversity category and the NPGS taxonomic/characterization category. Notes pertaining to the accession's verification status (Michener, 1991) as well as any information related to its use in previous taxonomic research (including citations in databases such as GenBank) also can be incorporated here.

The second category, *environment and source history*, represents all geographical references to the accession's original provenance, as well as its current location in the garden. These are the NHC geography and the NPGS passport data categories. Those plants derived from the wild, assuming they retain accurate passport or provenance data, provide a link to the original populations, and in some cases become "frozen glimpses of the past" due to the loss of unique populations or entire species (Winker, 2004). These passport data include georeferences (latitude, longitude, elevation), habitat descriptors, associated species, and other collection notes (Steiner & Greene, 1996). The information associated with the act of collecting (the collector's name, the collection number, purpose of the collection) should always be included, not only for its utility in repatriating lost information (Dosmann & Del Tredici, 2003) but also for its social-history value (Walley, 1997). Most records that indicate that the accession is of wild origin yet lack any further provenance information are of limited value. The primordial vegetation of the garden often represents wild-origin material, yet is frequently overlooked; attempts can be made to accession these collections. For material not of wild origin, these data are still important and the record should indicate if the plant came from another garden (including their accession number and sources), or commercial nursery, or even if it arose spontaneously. Spontaneous flora should be recorded, and if left intact, formally integrated into the collection, as it can be useful in studying hybridization events (Del Tredici & Li, 2002).

Not to be discounted is the information related to a plant's current (or even historical) location in the garden. Many gardens georeference plants to create accurate maps and improve stock-checking activities. These data also provide a foundation upon which to append a wide array of other statistics, such as soil analyses, meteorological records, or even maintenance reports. Dataloggers and wireless sensor networks (Porter et al., 2005) can be used to document a range of environmental data, over time creating a comprehensive spatial and temporal record of keen interest to scientists. Cultural and land-use history information related to the site are valuable, too, as the garden's noteworthy historical layers and cultural artifacts can be constructive in interpreting research stories (Schulhof, 1996). For instance, a researcher may be interested in assessing the impact of landscape legacies such as logging, grazing, plowing, or flooding on a garden's current collection, even if such events occurred long before the garden was established.

Phenotypic biodiversity, the final category, can be viewed as the observable manifestation of the other two, or as the genotype × environment interaction. This category includes some of the NHC biodiversity as well as the NPGS evaluation data. These data sets relate to plant growth and performance in both the wild and the novel garden environments, and may also include research results. Unfortunately most garden-performance data are recorded with subjective, qualitative scales (e.g., excellent, fair, poor) that have limited use owing to strong observer bias. A marked improvement to this standard rating system would be the use of objective and standardized scales more meaningful over the long term. Other measurements, such as plant size, growth rates, phenological and physiological data, as well as digital images, are particularly valuable, especially if gathered at routine intervals. Subjective descriptions and notes, while not always useful as data points, can still be constructively used in interpreting and generating hypotheses.

While NHC maintain a separate temporal category, in reality time is ubiquitous to all three of the garden categories and might best be considered as simply an accompanying, yet essential, information tag. Date is simply an accessory to all other events in an accession's life (e.g., time of collection, planting, repropagation, relocation, evaluations, and observations).

Managing and Disseminating Information

To best study these "biological libraries" (Suarez & Tsutsui, 2004), NHC have begun to rely upon technological tools (e.g., bar-coding of specimens, relational databases, geographical information system), described broadly by Graham et al. (2004) as natural history collection informatics. One impediment to garden collections' management and research use is the lack of information sharing among institutions (Taylor, 1986; Watson et al., 1993; Dosmann & Del Tredici, 2003). Raven (1981) postulated, "If all of the holdings of botanical gardens worldwide were known and accessible to the scientists who needed their material, . . . collective justification [of gardens] would probably be a simple matter." He recently wrote, "As matters stand now, it is impossible to determine who has which plants in cultivation and where they are being grown. That situation is intolerable, and it means that most of the living accessions in botanical gardens will be generally ignored." (Raven, 2006). A previous attempt to establish a plant collection data center by the American Horticulture Society had potential yet failed in promoting collections among researchers (Zuk, 1984), most likely because of poor publicity of the service and insufficient technology at the time to make it function efficiently. Thankfully, the technology has arrived, and distributed networks are revolutionizing collection-based science by linking biological collections (and their data) from multiple institutions (Lane, 1996; Graham et al., 2004; Wheeler et al., 2004; Marshall, 2005). The importance of these extends beyond collections, as journals such as *Plant Physiology* have created a section dedicated specifically to the development and promotion of plant databases for research (Rhee & Crosby, 2005). These networks can provide for efficient information exchange among different gardens, and between them and researchers, the lack of which remains a noted problem (Raven, 2004a; Dosmann & Del Tredici, 2005). While some institutions may view data sharing with skepticism, such parochial attitudes severely limit access to collections and restrict the very type of biodiversity research for which collections may have been originally assembled (Krishtalka & Humphrey, 2000). An example of a fully accessible collection is the on-line database The Fairchild Guide to Palms of Fairchild Tropical Botanic Garden (http://www.fairchildgarden.org/palmguide/index.php), which makes accessible information on their living, dried, and DNA collections of palms, including images.

Data sharing across collections not only improves the research process but also can serve as a curatorial auditing system. With increased collection use and information exchange, it is more likely that errors in the record will be detected and corrected (Hijmans et al., 1999; Heyning, 2004), and specimen uniqueness determined (Dosmann & Del Tredici, 2003; Radford et al., 2003). Examples of online databases that extract collection information from multiple garden collections include: BGCI's Plant Search (http://www.bgci.org.uk/conservation/plant_search.html), Quarryhill Botanic Garden's Database of Asian Plants in Cultivation (http://www.quarryhillbg.org/DAPC/DAPC.htm), the Multisite BG-BASE Database hosted by the Royal Botanic Garden Edinburgh (http://rbg-web2.rbge.org.uk/forms/multisite2.html), and the USDA Germplasm Resource Information Network (GRIN) (http://www.ars-grin.gov/npgs/searchgrin.html). What is still needed, however, is satisfaction of Raven's initial call for a master clearinghouse of collections worldwide, a metacollection. Over 30 years ago, the International Species Information System was established to serve this exact purpose for zoos and aquaria. At present, over 600 institutions worldwide include their collections as part of a database (Zoological Information Management System) that tracks the fate of nearly 2 million animals across 10,000 taxa (World Association of Zoos and Aquaria, 2005). A new endeavor, still in the planning stages at the time of publication, is a distributed information retrieval system for gardens called PlantCollections. This venture, being developed by the Chicago Botanic Garden, APGA, and 15 other institutions, may in time become the valuable tool necessary to improve global collections management and aid research (Tankersley, 2006).

Conclusions

Like other museums, gardens comprise a plethora of objects, information, and expertise of value to a broad array of researchers. Unfortunately, like other NHC, these living plant collections face a crisis of underutilization. If gardens fail to engage collections for research activity, they risk losing their long-standing societal commitment to collections-based science and relevance within the research community. As some of the original describers of biodiversity, gardens owe it to their founders, as well as to present-day and future society and supporters, to reinvest in collections-based research.

There are many missed opportunities for gardens to engage in the act of scientific discovery, as collections-based research can take different forms (summational, applied, and basic), cover a range of disciplines, and be executed by gardens of varying size. One misconception is that a garden must have a formal research program for its collection to be used for research, yet in reality the researcher pool contains an assortment of both on- and off-site users. Difficult as it may seem, gardens must be ready to meet the research needs of the future, many of which may be unanticipated. One key component to this process is the role played by the research-curator, an individual who not only safeguards and studies the collection, but works to improve the dialogue between providers and users. Collaboration is also born out of this relationship, which extends beyond garden-researcher connections to garden-garden interactions. Because of its relationship to collection value, information management has become another important requirement for better research use. To accomplish this, gardens will need to advance their ability to document collection use, develop more meaningful methods of evaluating plant performance, integrate these various data sets into easily extractable forms, and disseminate this knowledge to global audiences. Luckily, the tools of the information age make these tasks easier.

But first, gardens must become clear advocates for their collections and the research derived from them. While Taylor (1987) was blunt when he wrote, "Any public garden worth its salt should develop an active and effective research program," his advocacy cannot be questioned. Similarly, Tom Elias (1991) challenged the garden community to "never compromise the quality of our collections, the importance of educational opportunities and the value of research and conservation efforts, even if they are not as cost effective as more popular but nonbotanical and peripheral activities designed to increase attendance and admission fees." While not all gardens have research missions and goals, I urge those that *do* maintain collections for science (and have invested significant resources to manage them to this end) to make every effort to emphasize their use; we cannot afford further compromise. With strong advocacy and leadership, broadened research audiences, and improved management of our living collections, gardens can avert the crisis and elevate their value to science and society.

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Literature Cited

Allenstein, P. & K. Conrad. 2004. National Plant Germplasm System and North American Plant Collections Consortium: a decade of collaboration. Public Gard. 19(3): 14–16, 37.

Barkworth, M.E. & S.W.L. Jacobs. 2001. Valuable research or short stories: what makes the difference? Hereditas 135(2–3): 263–270.

Bazzaz, F.A. 2001. Plant biology in the future. Proc. Natl. Acad. Sci. U.S.A. 98(10): 5441–5445.

Bentz, J. & A.M. Townsend. 2004. Spatial and temporal patterns of abundance of the potato leafhopper among red maples. Ann. Appl. Biol. 145(2): 157–164.

Bhattacharjee, Y. 2005. Citizen scientists supplement work of Cornell researchers. Science 308: 1402–1403.

Bojarczuk, K. 1982. Propagation of magnolias by softwood cuttings using different substrates for stimulation of rooting. Arbor. Kórnickie 27: 169–185.

Briggs, G. & W. McDevitt. 1989. Dream a little before you pick up that shovel. . . . Public Gard. 4(1): 16–19.

Brinker, A.M. & I. Raskin. 2005. Determination of triptolide in root extracts of *Tripterygium wilfordii* by solid-phase extraction and reverse-phase high-performance liquid chromatography. J. Chromatogr. 1070(1–2): 65–70.

Bryant, J.M. 1983. Biological collections: legacy or liability? Curator 26(3): 203–218.

Chan, C.R. & R.D. Marquard. 1999. Accelerated propagation of *Chionanthus virginicus* via embryo culture. HortScience 34(1): 140–141.

Cheong, E. & M.R. Pooler. 2003. Micropropagation of Chinese redbud (*Cercis yunnanensis*) through axillary bud breaking and induction of adventitious shoots from leaf pieces. In Vitro Cell. Developmental Biol., Plant 39(5): 455–458.

Clausen, J., D.D. Keck & W.M. Hiesey. 1940. Experimental studies on the nature of species. I. The effects of varied environments on North American Plants. Carnegie Institute of Washington Publication Number 520, Washington, D.C.

Cook, R.E. 2006. Botanical collections as a resource for research. Public Gard. 21(1): 18–21.

Cubey, R. & D. Rae. 1999. PlantNet directory of botanical collections in Britain and Ireland. PlantNet, Cambridge, UK.

Dalton, R. 2003. Natural history collections in crisis as funding is slashed. Nature 423(6940): 575.

Del Tredici, P. & A. Kitajima. 2004. Introduction and cultivation of Chinese hemlock (*Tsuga chinensis*) and its resistance to hemlock woolly adelgid (*Adelges tsugae*). J. Aboric. 30(5): 282–286.

——— **& J. Li.** 2002. *Stewartia* 'Scarlet Sentinel'. HortScience 37(2): 412–414.

DeMarie, E.T., III. 1996. The value of plant collections. Public Gard. 11(2): 7, 31.

Dosmann, M.S. 2002. Stratification improves and is likely required for germination of *Aconitum sinomontanum*. HortTechnol. 12(3): 423–425.

——— **& P. Del Tredici.** 2003. Plant introduction, distribution, and survival: a case study of the 1980 Sino-American Botanical Expedition. BioScience 53(6): 588–597.

——— **&** ———. 2005. The Sino-American Botanical Expedition of 1980: a retrospective analysis of success. HortScience 40(2): 302–303.

Elias, T.S. 1991. About this issue. Public Gard. 6(3): 6.

——— **& M.R. Pooler.** 2004. The identity of the African firebush (*Hamelia*) in the ornamental nursery trade. HortScience 39(6): 1224–1226.

Engels, J.M.M. & L. Visser. 2003. Genebank management procedures. Pp. 60–79 *in* J.M.M. Engels and L. Visser (eds.), A guide to effective management of germplasm collections. IPGRI Handbooks for Genebanks No. 6. International Plant Genetic Resources Institute, Rome.

Ertter, B. 2000. Our undiscovered heritage: past and future prospects for species-level botanical inventory. Madroño 47: 237–252.

Flint, H.L. 1974. Phenology and genecology of woody plants. Pp. 83–97 *in* H. Leith (ed.), Phenology and seasonality modeling. Springer-Verlag, New York.

Forrester, J.A. & J.R. Runkle. 2000. Mortality and replacement patterns of an old-growth *Acer-Fagus* woods in the Holden Arboretum, northeastern Ohio. Amer. Midl. Naturalist 144(2): 227–242.

Freedman, G. 2000. The changing nature of museums. Curator 43(4): 295–306.

Graham, C.H., S. Ferrier, F. Huettman, C. Moritz & A.T. Peterson. 2004. New developments in museum-based informatics and applications in biodiversity analysis. Trends Ecol. Evol. 19(9): 497–503.

Griesbach, R.J. & F.S. Santamour. 2003. Anthocyanins in cones of *Abies, Picea, Pinus, Pseudotsuga* and *Tsuga* (Pinaceae). Biochem. Syst. Ecol. 31(3): 261–268.

Griffith, M.P. 2004. The origins of an important cactus crop, *Opuntia ficus-indica* (Cactaceae): new molecular evidence. Amer. J. Bot. 91(11): 1915–1921.

Gropp, R.E. 2003. Are university natural science collections going extinct? BioScience 53(6): 550.

Havens, K., E.O. Guerrant Jr., P. Vitt & M. Maunder. 2004. Conservation research and public gardens. Public Gard. 19(3): 40–43.

———, P. Vitt, M. Maunder, E.O. Guerrant Jr. & K. Dixon. 2006. Ex situ plant conservation and beyond. BioScience 56: 525–531.

Hay, I. 1995. Science in the pleasure ground: a history of the Arnold Arboretum. Northeastern Univ. Press, Boston.

Hendricks, J.J., J.D. Aber, K.J. Nadelhoffer & R.D. Hallett. 2000. Nitrogen controls on fine root substrate quality in temperate forest ecosystems. Ecosystems 3(1): 57–69.

Heyning, J.E. 2004. The future of natural history collections. Collections 1(1): 6–9.

Heywood, V.H. 1995. A global strategy for the conservation of plant diversity. Grana 34(6): 363–366.

Hibben, C.R. & L.M. Franzen. 1989. Susceptibility of lilacs to mycoplasmalike organisms. J. Environm. Hort. 7(4): 163–167.

Hijmans, R.J., M. Schreuder, J. De la Cruz & L. Guarino. 1999. Using GIS to check co-ordinates of genebank accessions. Genet. Resources Crop Evol. 46(3): 291–296.

Irving, A. & J. Ambers. 2002. Hidden treasure from the Royal Cemetery at Ur: technology sheds new light on the ancient Near East. Near E. Archaeol. 65(3): 206–213.

Janick, J. 2004. Caravaggio's fruit: a mirror on Baroque horticulture. Chron. Hort. 44(4): 9–15.

Jefferson, L., K. Havens & J. Ault. 2004. Implementing invasive screening procedures: the Chicago Botanic Garden model. Weed Technol. 18: 1434–1440.

Karlson, D.T., Q.-Y. Xiang, V.E. Stirm, A.M. Shirazi & E.N. Ashworth. 2004. Phylogenetic analyses in *Cornus* substantiate ancestry of xylem supercooling freezing behavior and reveal lineage of desiccation related proteins. Pl. Physiol. 135: 1654–1665.

Kennedy, K. 2004. Twenty years of ex situ plant conservation. Public Gard. 19(3): 17.

Koontz, J.A., P.S. Soltis & S.J. Brunsfeld. 2001. Genetic diversity and tests of the hybrid origin of the endangered yellow larkspur. Conservation Biol. 15(6): 1608–1618.

Krebs, S.-L. & M.-D. Wilson. 2002. Resistance to *Phytophthora* root rot in contemporary rhododendron cultivars. HortScience 37(5): 790–792.

Krishtalka, L. & P.S. Humphrey. 2000. Can natural history museums capture the future? BioScience 50: 611–617.

Krivtsov, V., R. Watling, S. Walker, D. Knott, J. Palfreyman & H. Staines. 2003. Analysis of fungal fruiting patterns at the Dawyck Botanic Garden. Ecol. Modelling 170(2–3): 393–406.

Kuo, F.E. & W.C. Sullivan. 2001. Environment and crime in the inner city—does vegetation reduce crime? Environm. Behav. 33(3): 343–367.

Lane, M.A. 1996. Roles of natural history collections. Ann. Missouri Bot. Gard. 83(4): 536–545.

Larson, G., K. Dobney, U. Albarella, M. Fang, E. Matisoo-Smith, J. Robins, S. Lowden, H. Finlayson, T. Brand, E. Willerslev, P. Rowley-Conwy, L. Andersson & A. Cooper. 2005. Worldwide phylogeography of wild boar reveals multiple centers of pig domestication. Science 307(5715): 1618–1621.

Levy, D. 2005. Controlling garlic mustard: an integrated approach. Cornell Plantations Notes 83: 3–4.

Li, J.H., M.S. Dosmann, P. Del Tredici & S. Andrews. 2002. Systematic relationship of weeping katsura based on nuclear ribosomal DNA sequences. HortScience 37(3): 595–598.

———, S. Shoup & Z.D. Chen. 2005. Phylogenetics of *Betula* (Betulaceae) inferred from sequences of nuclear ribosomal DNA. Rhodora 107(929): 69–86.

Lighty, R.W. 1984. Toward a more rational approach to plant collections. Longwood Program Seminars 16: 5–9.

Loreau, M., S. Naeem, P. Inchausti, J. Bengtsson, J.P. Grime, A. Hector, D.U. Hooper, M.A. Huston, D. Raffaelli, B. Schmid, D. Tilman & D.A. Wardle. 2001. Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294(5543): 804–808.

Lyal, C. H. C. & A. L. Weitzman. 2004. Taxonomy: exploring the impediment. Science 305: 1106.

Mack, R. N. 2005. Predicting the identity of plant invaders: future contributions from horticulture. HortScience 40(5): 1168–1174.

Maier, C. T. 2003. Distribution, hosts, abundance, and seasonal flight activity of the exotic leafroller, *Archips fuscocupreanus* Walsingham (Lepidoptera: Tortricidae), in the northeastern United States. Ann. Entomol. Soc. Amer. 96(5): 660–666.

Mann, D. 1997. The economics of botanical collections. Pp. 68–82 *in* J. R. Nudds and C. W. Pettitt (eds.), The value and valuation of natural science collections, Manchester, 1995. The Geological Society, London.

Marchandeau, S., M. Guenezan & J. Chantal. 1995. Weight increase as a criterion of age in young wild rabbits (*Oryctolagus cuniculus*). Gibier Faune Sauvage 12(4): 289–302.

Marris, E. 2006. Gardens in full bloom. Nature 440: 860–863.

Marshall, E. 2005. Will DNA bar codes breathe life into classification? Science 307: 1037.

Maunder, M., S. Higgens & A. Culham. 2001. The effectiveness of botanic garden collections in supporting plant conservation: a European case study. Biodivers. & Conservation 10(3): 383–401.

Medbury, S. 1991. Taxonomy and garden design: a successful marriage? Public Gard. 6(3): 29–32, 42–43.

Melcher, P. J., M. A. Zwieniecki & N. M. Holbrook. 2003. Vulnerability of xylem vessels to cavitation in sugar maple. Scaling from individual vessels to whole branches. Pl. Physiol. 131: 1775–1780.

Michener, D. 1996. Collections as a tool, not a purpose. Public Gard. 11(2): 6, 30.

———. 1991. The hows and whys of verifying a living collection. Public Gard. 6(3): 14–16.

Miller, A. H. 1963. The curator as a research worker. Curator 6(4): 282–286.

Miller, F. & G. Ware. 2002. Suitability and feeding preference of selected North American, European, and Asian elm (*Ulmus* spp.) biotypes to elm leaf beetle (Coleoptera: Chrysomelidae). J. Environm. Hort. 20(3): 148–154.

Miller, S. E., W. J. Kress & K. Samper. 2004. Crisis for biodiversity collections. Science 303(5656): 310b.

Mori, J. L. & J. I. Mori. 1972. Revising our conceptions of museum research. Curator 15(3): 189–199.

Murch, S. J. 2004. In vitro conservation of endangered plants in Hawaii. Biodiversity 5(1): 10–12.

Nature. 2006. The constant gardeners. Nature 440: 845.

Nevling, L. I., Jr. 1984. On public understanding of museum research. Curator 27(3): 189–193.

Oh, S. H. & D. Potter. 2005. Molecular phylogenetic systematics and biogeography of tribe neillieae (Rosaceae) using DNA sequences of cpDNA, rDNA, and LEAFY. Amer. J. Bot. 92(1): 179–192.

Pai, J. G. B. & W. R. Graves. 1995. Seed source affects seedling development and nitrogen fixation of *Maackia amurensis*. J. Environm. Hort. 13(3): 142–146.

Pekarik, A. J. 2003. Long-term thinking: what about the stuff? Curator 46(4): 367–370.

Pettitt, C. 1994. Using natural history collections. Pp. 144–166 *in* G. Stansfield, J. Mathias & G. Reid (eds.), Manual of natural history curatorship. HMSO, London.

Pfosser, M. F., J. Guzy-Wróbelska, B.-Y. Sun, T. F. Stuessy, T. Sugawara & N. Fujii. 2002. The origin of species of *Acer* (Sapindaceae) endemic to Ullung Island, Korea. Syst. Bot. 27(2): 351–367.

Pooler, M. R. & R. L. Dix. 2001. Screening of *Cercis* (redbud) taxa for ability to root from cuttings. J. Environm. Hort. 19(3): 137–139.

———, K. A. Jacobs & M. Kramer. 2002. Differential resistance to *Botryosphaeria ribis* among *Cercis* taxa. Pl. Dis. 86(8): 880–882.

Porter, J., P. Arzberger, H.-W. Braun, P. Bryant, S. Gage, T. Hansen, P. Hanson, C.-C. Lin, F.-P. Lin, T. Kratz, W. Michener, S. Shapiro & T. Williams. 2005. Wireless sensor networks for ecology. BioScience 55(7): 561–572.

Prather, L. A., O. Alvarez-Fuentes, M. H. Mayfield & C. J. Ferguson. 2004. Implications of the decline in plant collecting for systematic and floristic research. Syst. Bot. 29(1): 216–220.

Primack, D., C. Imbres, R. B. Primack, A. J. Miller-Rushing & P. Del Tredici. 2004. Herbarium specimens demonstrate earlier flowering times in response to warming in Boston. Amer. J. Bot. 91(8): 1260–1264.

Radford, L., M. Dossman (sic) & D. Rae. 2003. The management of 'ad hoc' ex situ conservation status species at the Royal Botanic Garden Edinburgh. Sibbaldia 1(1): 43–80.

Rae, D. A. H. 1990. What conservation role for botanic gardens? Profess. Hort. 4: 3–10.

———. 1995. Botanic gardens and their live plant collections: present and future roles. Ph. D. diss., Univ. of Edinburgh.

Rankin, T. V. 1955. Arnold Arboretum controversy. Science 121(3154): 835–836.

Rappe, E. & S. L. Kivelä. 2005. Effects of garden visits on long-term care residents as related to depression. HortTechnol. 15(2): 298–303.

Raven, P. H. 1979. Research programs in botanic gardens. Longwood Program Seminars 11: 13–19.

———. 1981. Research in botanical gardens. Bot. Jahrb. 102: 53–72.

———. 1989. The value of living collections. Arnoldia 49(1): 5–6.

———. 2004a. Botanical gardens and the 21st Century. Proc. Calif. Acad. Sci. 55(Suppl. 1, Article 12): 275–282.

———. 2004b. Ex situ conservation. Public Gard. 19(3): 7.

———. 2006. Research in botanical gardens. Public Gard. 21(1): 16–17.

Reed, S. M. 2000. Development of an in ovolo embryo culture procedure for *Hydrangea*. J. Environm. Hort. 18(1): 34–39.

Rhee, S. Y. & B. Crosby. 2005. Biological databases for plant research. Pl. Physiol. 138: 1–3.

Ricklefs, R. F. 1980. Old specimens and new directions: the museum tradition in contemporary ornithology. Auk 97: 206–208.

Ruedas, L. A., J. Salazar-Bravo, J. W. Dragoo & T. L. Yates. 2000. The importance of being earnest: what, if anything, constitutes a "specimen examined?" Molec. Phylogen. Evol. 17(1): 129–132.

Sacchi, C. F. 1991. The role and nature of research at botanical gardens. Public Gard. 6(3): 33–35.

Sachse, N. D. 1965. A thousand ages: the University of Wisconsin Arboretum. Regents of the University of Wisconsin, Madison.

Schulhof, R. 1996. Public garden landscapes: new stories to tell. Public Gard. 11(1): 12–15.

Spinks, P. Q., G. B. Pauly, J. J. Crayon & H. B. Shaffer. 2003. Survival of the western pond turtle (*Emys marmorata*) in an urban California environment. Biol. Conservation 113(2): 257–267.

Stankowski, C. 1998. The curation crisis: can we afford the future? (4 February 2005; http://www.sfsu.edu/~museumst/minerva/stankow.html).

Steere, W. C. 1969. Research as a function of a botanical garden. Longwood Program Seminars 1: 43–47.

Steiner, J. J. & S. L. Greene. 1996. Proposed ecological descriptors and their utility for plant germplasm collections. Crop Sci. 36(2): 439–451.

Stern, M. J. & T. Eriksson. 1996. Symbioses in herbaria: recommendations for more positive interactions between plant systematists and ecologists. Taxon 45(1): 49–58.

Suarez, A. V. & N. D. Tsutsui. 2004. The value of museum collections for research and society. BioScience 54(1): 66–74.

Tankersley, B. 2006. Plant databases linked for botanists and gardeners. Nature 441: 574.

Taylor, R. L. 1986. Defining and distinguishing the research and education roles of botanical gardens and arboreta from those of other institutions and organizations. Pp. 12–24 *in* M. J. Balick (ed.), Botanical gardens and arboreta: future directions. New York Botanical Garden/American Association of Botanical Gardens and Arboreta, Swarthmore, PA.

———. 1987. Research at public gardens: community benefits. Longwood Program Seminars 19: 13–18.

Thomas, P. & K. Tripp. 1998. Ex situ conservation of conifers: a collaborative model for biodiversity preservation. Public Gard. 13(3): 5–9.

Waddington, J. 1997. Evaluating the earth sciences collections at the Royal Ontario Museum. Pp. 117–122 *in* J. R. Nudds & C. W. Pettitt (eds.), The value and valuation of natural science collections, Manchester, 1995. The Geological Society, London.

Wagner, P., R. Furstner, W. Barthlott & C. Neinhuis. 2003. Quantitative assessment to the structural basis of water repellency in natural and technical surfaces. J. Exp. Bot. 54(385): 1295–1303.

Walker, B. W. 1963. The curator as a custodian of collections. Curator 6(4): 292–295.

Walley, G. 1997. The social history value of natural history collections. Pp. 44–60 *in* J. R. Nudds & C. W. Pettitt (eds.), The value and valuation of natural science collections, Manchester, 1995. The Geological Society, London.

Watson, G. W., V. Heywood & W. Crowley. 1993. North American botanic gardens. Hort. Rev. 15(1): 1–62.

Wheeler, Q. D., P. H. Raven & E. O. Wilson. 2004. Taxonomy: impediment or expedient? Science 303: 285.

Widrlechner, M. P. 1997. Managerial tools for seed regeneration. Pl. Var. Seeds 10: 185–193.

——— **& L. A. Burke.** 2003. Analysis of germplasm distribution patterns for collections held at the North Central Regional Plant Introduction Station, Ames, Iowa, USA. Genet. Resources Crop Evol. 50(3): 329–337.

Wilson, E. O. 2003. The encyclopedia of life. Trends Ecol. Evol. 18(2): 77–80.

Winker, K. 2004. Natural history museums in a postbiodiversity era. Bioscience 54(5): 455–459.

Wolfe, D. W., M. D. Schwartz, A. N. Lakso, Y. Otsuki, R. M. Pool & N. J. Shaulis. 2005. Climate change and shifts in spring phenology of three horticultural woody perennials in northeastern USA. Int. J. Biometeorol. 49(5): 303–309.

World Association of Zoos and Aquariums. 2005. The world zoo and aquarium conservation strategy: building a future for wildlife. WAZA, Bern, Switzerland.

Zuk, J. D. 1984. Confessions of a collections advocate. Longwood Program Seminars 16: 21–26.