Essay

The Role of Botanic Gardens in the Science and Practice of Ecological Restoration

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Abstract: *Many of the skills and resources associated with botanic gardens and arboreta, including plant taxonomy, horticulture, and seed bank management, are fundamental to ecological restoration efforts, yet few of the world's botanic gardens are involved in the science or practice of restoration. Thus, we examined the potential role of botanic gardens in these emerging fields. We believe a reorientation of certain existing*

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institutional strengths, such as plant-based research and knowledge transfer, would enable many more botanic gardens worldwide to provide effective science-based support to restoration efforts. We recommend botanic gardens widen research to include ecosystems as well as species, increase involvement in practical restoration projects and training practitioners, and serve as information hubs for data archiving and exchange.

Keywords: arboreta, botanic gardens, ecological restoration, restoration ecology, seed banks

El Papel de los Jardines Botánicos en la Ciencia y Práctica de la Restauración Ecológica

Resumen: *Muchas de las habilidades y recursos asociados con los jardines botánicos y viveros, incluyendo la taxonomía de plantas, la horticultura y el manejo de banco de semillas, son fundamentales para los esfuerzos de restauración ecológica. Por lo tanto, examinamos el papel potencial de los jardines botánicos en estos campos emergentes. Consideramos que una reorientación de ciertas potenciales institucionales existentes, como la investigación botánica y la transferencia de conocimiento permitirían que muchos jardines botánicos alrededor del mundo proporcionen un apoyo efectivo y basado en la ciencia a los esfuerzos de restauración. Recomendamos que los jardines botánicos amplíen su investigación para incluir ecosistemas y especies, incrementen la participación en proyectos de restauración práctica así como la capacitación de practicantes, y funcionen como centros de información para el almacenamiento e intercambio de datos.*

Palabras Clave: bancos de semillas, ecología de la restauración, jardines botánicos, restauración ecológica

Introduction

Restoration of degraded and imperiled ecosystems is emerging as one of the most important priorities for humanity in the 21st century. Many of the skills and resources already commonly provided by botanic gardens and arboreta to support plant conservation are also of fundamental importance to ecological restoration (sensu the Society for Ecological Restoration International 2004) and the science on which restoration efforts are based. A comprehensive overview of the potential role of botanic gardens in this emerging field is lacking. We aimed to provide a synthesis of botanic gardens' current involvement in restoration and explored opportunities that may enable many more botanic gardens and arboreta worldwide to build on existing institutional strengths to provide effective science-based support to ecosystem restoration projects.

Many of the relatively few remaining natural ecosystems in the world are at immediate risk of further degradation or complete loss, especially those that are vulnerable under current climate-change scenarios (e.g., Méndez et al. 2008). There is little prospect of the outlook improving because world population is likely to continue to expand until at least 2050 (United Nations 2007) and the global economic framework is one that encourages exploitation of natural resources rather than their conservation or sustainable use. In view of these challenges, the latest recommendations of the Global Strategy for Plant Conservation (GSPC) recognize that, in some cases, ecosystem restoration may be required to achieve the target of securing at least 15% of each of the world's ecological regions (Convention on Biological Diversity 2010).

The science and practice of ecological restoration are developing rapidly to address the challenges presented by degraded ecosystems and landscapes, as evidenced by the expanding global presence of the Society for Ecological Restoration International, emerging literature (Ormerod 2003; Young et al. 2005), and increasing private-sector activity (e.g., the Mine Closure series of international conferences) and government policy (e.g., U.S. Department of Defense and U.S. Environmental Protection Agency 2008) focused specifically on restoration activities. The Economics of Ecosystems and Biodiversity coalition, which provides a follow-up to the *Millennium Ecosystem Assessment* and the *Stern Report on the Economics of Climate Change*, cites ecological restoration as their top priority for global society (TEEB 2011). Nevertheless, the success of restoration projects often is constrained by factors such as small spatial and temporal scales (e.g., Wagner et al. 2008), insufficient biological information on target species (e.g., Lloyd & Vercoe 2002), and lack of awareness of, or inability to address, ecological processes and functioning (Bond & Lake 2003). More than ever before, there exists an immediate opportunity for biological and physical scientists to help improve on-the-ground restoration outcomes. Furthermore, there is a clear need for greater integration of restoration projects in a larger socioeconomic, political, and cultural context (Aronson et al. 2010).

Many of the services and resources commonly provided by botanic gardens and arboreta are central to the study and practice of ecological restoration. The University of Wisconsin Arboretum is often considered the birthplace of the concept of ecological restoration, thanks to the pioneering work of Aldo Leopold (Jordan et al. 1987). (Hereafter, we use the phrases *botanic garden* and *garden* to include both botanic gardens and arboreta.) Disciplines essential to the practice of restoration ecology (e.g., plant taxonomy and horticulture), supporting technologies (e.g., DNA fingerprinting and geographical

Table 1. Estimated percentage of botanic gardens providing facilities and activities relevant to ecological restoration.*

Facilities and activities	*Estimated percentage of gardens (no. of gardens from subset*)*
Facilities	
computerized plant record system	38 (249)
herbarium	26 (173)
seed bank	19 (124)
micropropagation	10 (65)
Conservation work	
conservation program	26 (172)
ex situ program	25 (166)
reintroduction program	16 (107)
Research programs	
horticulture	25 (164)
conservation biology	21 (140)
ecology	19 (125)
systematics and taxonomy	18 (122)
ecosystem conservation	16 (109)
data management systems and information technology	15 (96)
restoration ecology	12 (81)
invasive species biology	11 (76)
conservation genetics	9 (61)
land restoration	9 (61)
seed/spore biology	8 (50)
pollination biology	7 (44)
Education programs	
guided tours	41 (273)
education signs	34 (222)
public lectures	33 (215)
visitor center	29 (194)
education booklets	28 (188)
education program	27 (176)
permanent public displays	24 (158)

* *Data are from Botanic Gardens Conservation International's GardenSearch database (BGCI 2010a). There are 2676 botanic gardens listed on the database, but some of them did not provide any information on their facilities or activities. Therefore the calculation of percentage of gardens providing particular resources was based on the data provided by a subset of 661 gardens that had completed the introductory text field—a preliminary survey having indicated that these gardens had generally also provided the ancillary information on their facilities. The percentage of gardens figures give an approximate indication of the relative importance of different areas of activity only and should be regarded as estimates of the overall percentage.*

information systems), practical conservation skills (e.g., seed banking), and relevant research expertise (e.g., in conservation genetics, seed science, mycology, and plant physiology) are often all represented in botanic gardens (Table 1). This breadth of knowledge, combined with a global distribution of sites, a predominant focus on wild plants as opposed to crops, an inherent service mission, and an ability to engage the public in relevant botanical and conservation discourse puts botanic gardens in a unique and germane position to integrate, apply, and deliver the best available science for the purposes of ecosystem restoration.

Despite the close match between the global need for ecological restoration and the services botanic gardens offer, comparatively few gardens worldwide engage in restoration ecology (Table 1). Enhancing the role of botanic gardens in restoration efforts offers an exciting opportunity for them to increase their service to society by helping to restore ecosystems that have been ''damaged, degraded, or destroyed'' (SERI 2004).

Opportunities to Engage in Restoration

A relatively easy step for botanic gardens is to make their wealth of information and expertise more widely available for use by restoration practitioners. In effect, scientists from botanic gardens can recast their own experience and knowledge base in horticulture, curation, species-based research, and educational display for new purposes beyond the garden. Dissemination through outreach initiatives, joint projects, and short courses puts this expertise to work. Relevance of the traditional activities of botanic gardens to practical restoration also can be increased dramatically by strategic broadening of their scope and focus (Table 2). Additionally, with a slight reorientation of mission, gardens can move into new areas of operation that build on their existing activities. Core technical disciplines can be focused and bolstered to deliver new or derivative services (Table 3). Potential areas of engagement include research into natural and managerial processes involved in ecosystem assembly and recovery, applied research to generate species- and site-specific data, project trials and demonstrations conducted onsite or locally, and storage and dissemination of data and technical information. Building on core strengths that already exist within botanic gardens can help overcome the challenges of ecological restoration.

Research in Restoration Ecology

Plant-based research has long been a standard part of the work of botanic gardens, and programs range from technologically advanced basic science (more common in larger gardens) to highly applied scientific investigations. As long as research methods meet rigorous scientific standards and the results help establish ecosystem structure and functioning at project sites, any level of garden-based research can be of value to ecological restoration, meaning all gardens, no matter how small, can contribute.

The study of single-species population ecology is a well-established activity within botanic gardens. It is also an important component of restoration ecology and a vital tool in monitoring restoration success. The relevance of such studies to ecological restoration can be increased by focusing on a greater variety of native species and

Table 2. Recommended institutional shifts for botanic gardens to pursue ecological restoration.

Administrative structure and congruence of mission
Increase contributions to ecological restoration quickly and easily by making small but significant changes to mission orientations, adopting a long-term strategy to widen the scope of basic and applied research, strengthening technology transfer activities, implementing practical projects, and providing sufficient funding to initiate these activities.
Partnerships and global networking
Strengthen or develop new partnerships with other organizations that have expertise in areas that botanic gardens may lack, such as soil science and biogeochemistry, plant and animal interactions, planning, land-use law, natural resource economics.
Assess global restoration needs and priorities. Coordinate research and knowledge transfer (e.g., through Botanic Gardens Conservation International or Society for Ecological Restoration International).
Develop, expand, and link existing plant and environmental databases within botanic gardens and work with other organizations to update databases with relevant data to create a resource for restoration practitioners.
Where botanic gardens have expertise regionally or globally, work with and support partners to build the partners' capacity to undertake restoration.
Basic and applied research
Undertake long-term restoration ecology research projects, such as investigations of plant community assembly pathways, the effects of climate change on restoration outcomes and the effects of restoration on ecosystem services.
Broaden current focus on rare and endangered species to include work on entire plant communities within the ecosystems found locally or regionally or, for botanic gardens with international collections, overseas.
Identify native plant species suitable for use in restoration projects, especially for species that exhibit structural or functional traits that give them the ability to set certain ecosystem assembly and maintenance processes in motion.
In applied research programs, increase the focus on developing methods and standard protocols to produce restoration-ready plants for use in high-stress environments.
Technology transfer
Recast existing knowledge into readily available resources for restoration. Develop technology transfer services that include staffed and web-based extension services and provide, for example:
– standardized protocols, best practice guides and decision trees (e.g., for site-survey, post-restoration monitoring, seed storage, propagation, selection of genetically appropriate material);
– identification guides, interactive and illustrated keys;
– technical support of restoration efforts, from initial site surveys, through to monitoring and adaptive management; and
– assessments of changes in natural resource capital assets associated with restoration projects and programs.
Practical involvement
Undertake restorations on site (where practicable) or where garden staff have relevant expertise, to test restoration approaches and demonstrate and document best practices.
Use on-site restoration to inform and engage the public—engendering financial and political support for restoration activities.

habitats and working on larger scales. For example, garden research often prioritizes threatened, endemic, or economically important species (e.g., in the United States, the work of the Center for Plant Conservation), which, although critical, are not necessarily the most relevant areas of study for restoration of degraded ecosystems. Broadening research agendas of botanic gardens to include a focus on understanding assemblages of species that would be most effective for restoring ecosystem composition, structure, and functioning (SERI 2004) requires a calculated extension of thinking from species and populations to communities, ecosystems, and landscapes. Botanic gardens have been leaders for many years in the science and practice of single-species reintroduction, but now integration of reintroduction research more fully into the broader field of restoration ecology is overdue (Lipsey & Child 2007; Seddon et al. 2007).

Basic research is needed to improve the understanding of mechanisms controlling the establishment and persistence of plant populations, communities, and ecosystems, under what may be highly altered or changing environmental conditions. The combination of expertise in plant science and horticulture puts botanic gardens in a strong position to investigate how the performance of introduced plants is affected by their interactions with other plants, such as invasive species and mycorrhizae. Exploring the role of animal species (through mechanisms such as pollination, dispersal, herbivory, and disturbance) and soil microorganisms in plant establishment may be unfamiliar territory for garden staff and calls for new partnerships and joint initiatives. In restoration ecology, the multidisciplinary approach to conservation advocated by Falk (1990) is not only advisable, but indispensable.

Herbaria are often associated with botanic gardens (Table 1) and provide a fundamental link between plant information and restoration practice. Taxonomic expertise and herbarium resources are essential for survey and monitoring of reference and restoration sites. Rarely appreciated and even less exploited is the enormous amount of information available in herbarium collections' records (e.g., location, ecology, phenology, and biology of each taxon collected). These data are critically important in cases where a landscape is so highly degraded that no undisturbed reference ecosystems remain to be studied in the field. Data on plant distribution and trends therein also provide important information to support habitat modeling, which should be informing the process of ecological restoration in a changing climate. Information on functional traits can be used to inform the selection of native species for determining initial planting assemblages for target ecosystems (Goosem & Tucker 1995; Elliott et al. 2003) and may also be gleaned from herbarium records. Although not all botanic gardens have herbaria, recognizing their

Table 3. Existing and potential services and expertise that botanic gardens could provide to support ecological restoration.

Area, discipline, derivative function	*Existing service or expertise*	*Potential service* or expertise with current resources*	*Potential service* or expertise with expanded resources*
Core technical discipline			
systematics	plant inventory and identification	publish life-history handbooks, with increased focus on seedlings	standardize genetic inventory (provenance) methods for restoration
autecology	identify native plants that are suitable for use as founder species on restoration sites (e.g., stress tolerant, prolific)	characterize ex situ demographic performance of life history stages	standardize evaluation of physiological tolerance limits; develop predictions of site-specific survivorship and fecundity for use in restoration designs
reintroduction biology	establish or enhance plant populations in natural habitats	optimize survival and reproduction of founding propagules	develop criteria and methodologies for assessing successful population establishment
community ecology	compile complete species checklists for natural habitats	suggest functional groupings of plants suitable for use in restorations (e.g., pioneers, nitrogen fixers, shade producers); identify and collate pollinator, disperser, and mycorrhizal requirements	characterize and develop plant community assembly pathways for habitats and regions; assess role of plant–animal interactions in restoration success; assess role of restored sites as corridors or barriers for animal dispersal
plant–soil biology interactions	identify symbiont-dependent plants	identify plant species for further research; characterize soil microbes in situ	elucidate mechanism of plant-soil biology interactions essential for successful establishment and growth of founders; make site-specific innocula available for restoration projects
conservation genetics	characterize known patterns of genetic variation, mating systems, and population genetic structure	determine propagule locations (provenance)	assess effect of restoration on gene flow and genetic diversity
Public outreach and education			
disseminate restoration knowledge	provide restoration-themed tours, interpretation, volunteer services, education programs	conduct training for other gardens and restoration groups	conduct training and public outreach for a broad spectrum of end users and the general public
Technologies			
seed collection, banking and provision	make collections for restoration purposes; expand databases on long-term germination and storage	develop seed quality and longevity databases; conduct training for other gardens and restoration groups; develop methodologies for bulking up seed supplies	make custom, high-quality seed lots available for restoration projects
propagule source conservation	identify source populations with high genetic diversity	inventory existing ex situ collections for diversity linked to specific sources	protect source populations with high genetic diversity
propagation	publish propagation protocols on widely accessible databases	improve production scheduling methods; develop acclimation protocols for outplanting founders; develop protocols for mass production	develop field-sowing technologies; make custom, high-quality plant lots available for restoration projects
plant–soil nutrition	record soil nutrient, pH, and structural requirements for plants used in restoration	provide soil amendment prescriptions	provide an array of soil amendments for use in restoration; outsource expertise for soil management systems

continued

Table 3 (continued).

Area, discipline, derivative function	*Existing service or expertise*	*Potential service* or expertise*	
		with current resources	*with expanded resources*
Derivative skills/disciplines			
restoration design	survey ecological attributes of remnant habitats (reference sites) to guide planning and evaluation of specific restoration projects	assist in or carry out research to develop standard lists of species for founding assemblages for target ecosystems; identify network of reference sites to serve as regional models for planning and evaluating restoration efforts	use assembly pathways to guide construction sequencing and timing; work with fauna specialists to build in ecosystem functions (e.g., in pollination and seed dispersal)
GIS systems	standardize GIS protocol for accessions to living collections	identify and use relevant GIS analytical methods to target restoration sites/ opportunities	apply GIS analytical methods and modeling to assist in design and monitoring small- and large-scale restoration projects
CADD systems			develop design documents to support small- and large-scale restoration projects
Management of site operations			
site management	verify identification of plant materials prior to installation; identify and characterize the behavior of weedy invasive species	identify appropriate provenances for plant materials; develop site-specific, integrated weed control prescriptions and adaptive management strategies; develop design templates for on-site nursery operations	implement integrated weed control prescriptions and adaptive management strategies as demonstration projects; establish and manage plant/propagule salvage operations prior to site disturbance; design and build on-site nurseries to support small and large scale restoration projects; assess condition of plant materials and supervise their installation
Evaluation and accountability			
success indicators	review literature and collate approaches to articulation of project targets, standards, and success criteria	create and consolidate project targets, standards, and success criteria generally and by ecosystem type	develop site-specific project targets, standards, and success criteria to support small- and large-scale restoration projects
monitoring protocols	review literature and collate approaches to monitoring for compliance and to support adaptive management		archive monitoring data for long-term evaluation
Derivative activities			
assessments of natural capital/resources	identify products, ecosystem services, and values for local plants or community types	incorporate local and indigenous knowledge into restoration planning and management	initiate demonstration projects that showcase and provide ecological services and socioeconomic values; carry out and support cost-benefit analyses of carbon sequestration in restoration sites versus reference or unrestored control sites
adaptive management for climate change	identify species broadly tolerant of anticipated changes in climate change	develop selection regimes for species broadly tolerant of anticipated changes in climate	design and build projects that anticipate climate change

**Some potential services could be provided by refocusing current institutional resources (e.g., staff, funding, facilities), whereas others would require expanded resources.*

importance in ecological restoration provides another argument in support of their continued maintenance and development.

In recent years the added dimension of conservation collection and archiving has brought gardens into the realm of conservation genetics research, seed banking, and reintroduction technologies (Table 1). To maximize the capture and persistence of variation in plant species, gardens (and seed banks in particular) adapt their propagule sourcing to account for local adaptation, hybridization, and the need to work with small populations. Although some guidance on these issues is available (e.g., CPC 2009; Offord & Meagher 2009), botanic gardens worldwide are in a strong position to build on existing available resources by using their own research techniques and experience to develop globally applicable best-practice guidelines for propagule sourcing for restoration.

Most gardens employ technical personnel, particularly in nurseries and seed banks, that routinely carry out trials on a broad spectrum of wild species to address site- and species-specific practical problems in areas such as seed handling and plant propagation. Trials are often conducted with large numbers of replicates and multiple genotypes under varied conditions for growth and reproduction. When such research is undertaken with robust scientific methods, it provides reliable baseline information that is needed by those practicing, promoting, or teaching restoration. This research is of great intrinsic value to ecological restoration and supports and complements the more conceptual work of restoration ecology, population biology, and ecological genetics. The aim is to get application and theory working together to ultimately benefit the species in situ, as discussed by Pavlik (1996) and Hobbs and Harris (2001).

Even the smallest botanic garden can develop best-practice guidance and protocols for generating plant material for restoration (e.g., Steele 2007). Botanic Gardens Conservation International estimates that over 104,000 plant species are in cultivation in botanic gardens worldwide (perhaps one-third of known species) (BGCI 2010*b*). The development of propagation protocols has included studies of germination, soil conditions, and establishment, and has been the stock-in-trade of many botanic gardens for centuries. Invaluable knowledge is often locked in the heads and rote procedures of good horticulturalists, and a concerted, well-designed, collaborative effort may be required to bring this knowledge to publication and use.

One proviso is that protocols should be tailored to produce hardy, restoration-ready plants rather than the tender or nutrient-reliant individuals more commonly used for display or sale. In the protected environments of botanic gardens, horticultural staff members do not have to account for many of the environmental stressors (e.g., grazing, unsustainable harvest, site water balance) that occur outside the garden walls, so standard horticultural techniques may need to be modified for application in a restoration context. In some cases, the traditional activities of a botanic garden may need scaling up to be directly transferable to landscape-level restorations. For example, site preparation, weed control, and irrigation in gardens are often implemented manually rather than mechanistically, whereas agricultural- or construction-scale techniques and equipment will often be required in a restoration project.

Practical Ecosystem Restoration

Many gardens were themselves founded on or include degraded sites, for example Kings Park and Botanic Garden in Perth, Australia (Erickson 2009). Consequently, they develop a special, local expertise and capacity to transform landscapes for specific purposes. Drawing from this experience, gardens immediately can enter the realm of restoration by translating their own successes into approaches that can be used in off-site projects. Such experience and expertise are beyond the capabilities of most consultancies, academies, and government agencies.

In addition to on-site restoration, botanic gardens can build their practical experience in many aspects of the restoration process through joint projects with local partners. For example, scientists from the University of Washington Botanic Gardens have worked with a private-sector design and technical team to restore 24 ha of a riverine ecosystem at the university's campus in Bothell, Washington. Garden staff advised the team on plant propagation methods, site preparation, and how to calculate hydraulic characteristics for the relocation of the channel system and construction of microtopographic features (e.g., large wood structures, floodplain depressions, and mounds). Botanic gardens with international collections and expertise may also take an active role in restoration through collaboration with partners overseas. For example, through its Center for Conservation and Sustainable Development, the Missouri Botanical Garden contributes research and training to restoration projects in Peru, Ecuador, and Madagascar.

Both on-site and local restorations provide opportunities for interpretation and education. Botanic gardens are known widely as places to see and understand plants and plant biology, and they attract over 150 million visitors globally each year (Wyse-Jackson & Sutherland 2000). The basic elements of signage, interpretation, volunteer-led tours, master-gardening programs, and informal education are directed at both committed plant lovers and casual visitors. Both groups can be inspired by offering compelling demonstrations of implementation methods, post-restoration sustainable management and use, and the ecological and socioeconomic benefits of restoration, and may thus provide a constituency and political support for local restoration projects and possibly even carry out restoration on their own land.

Botanic gardens could expose visitors to a wider range of concepts, broadening the offer from plants to ecosystems and landscapes and from gardening to restoration (Hobbs 2007). Many gardens already are moving away from the traditional layout of lawns and flower beds to showcase natural habitats (e.g., Royal Botanic Garden, Jordan; Oman Botanic Garden, Muscat [Maunder 2008]). Displaying active restoration efforts could be the next step—one already taken by the University of Washington Botanic Gardens in their Union Bay Natural Area, where visitors can witness this former landfill site being restored to a diverse system of meadows, woods, and wetlands.

Botanic gardens could build capacity and expertise among visitors and the local community by offering short courses and demonstrations of solutions that mitigate local or regional environmental problems, and providing technical handbooks. The emphasis could be applied and local, rather than theoretical and universal, as at the Botanic Gardens and Parks Authority of Perth, Australia, which has an active extension program to disseminate information arising from their practical experience of restoring bushland on the Bold Park and Kings Park sites. This initiative includes an annual Bold Park Restoration Research Workshop aimed at the local community, government departments, and universities.

Dissemination of Information

Botanic gardens tend to be long-lived. Some have operated as independent, science-based institutions for centuries, such as the Royal Botanic Gardens, Kew, which celebrated its 250th anniversary in 2009. Gardens have earned reputations as objective and reliable sources of information and often have ties to government, academic, and commercial sectors. Correspondingly, restoration is a long-term endeavor that requires integration of scientific, technical, administrative, regulatory, and socioeconomic domains. Gardens are thus well suited to serve as information hubs that facilitate data archiving and exchange to maintain essential linkages among science, education, public, and business communities. A good model is provided by Kew's Millennium Seed Bank Partnership, which works with over 100 partners to facilitate access to information and transfer of best practice in seed conservation, including optimal germination protocols for wild plant species. Establishing a hub provides a botanic garden with an outlet for information generated by its own work, making information such as plant identification keys or propagation and restoration protocols more readily available. As another example, the Australian National Botanic Gardens provides the Growing Native Plants database, which is updated by botanical interns as part of their training (Australian National Botanic Gardens 2010). In addition to including all the traditional components of a botanic garden, they could expand by adding a fully operational information center with reference tools such as GIS-based project registries and libraries of design and monitoring reports (Pavlik 1997).

Such hubs could also serve as repositories for data that enable application and testing of the principles and practices of adaptive management. One way this can be done is through the approach developed by *Conservation Evidence*, a peer-reviewed online journal dedicated to reporting successes and failures in conservation management. Over time, each information center could become a regional resource for restoration practitioners seeking a record of past successes and failures for a given set of ecosystems. As such, hubs could provide practical solutions for solving restoration problems faced by industry, government, and conservation organizations. As gardens increase research capacity in restoration ecology by building links with other institutions, web-based tools could be used increasingly to link and integrate research results and make them more accessible.

The world-wide distribution of botanic gardens is another key feature that positions them as information centers. There are over 2600 botanic gardens in 169 countries throughout the world (BGCI 2010*a*). Although gardens are concentrated in Europe and North America, those practicing restoration ecology are dispersed across the globe (Fig. 1) and most biomes are, or could be, represented by at least one garden that could serve as an information hub. Many of the larger western botanic gardens are also centers of excellence for certain overseas ecosystems and can thus become part of a community to support restoration efforts in those countries. Some organizations have made great progress in collating botanical information at the national level, for example, the Australian Network for Plant Conservation and the Center for Plant Conservation in the United States. Implementing and running information networks at the international level would be facilitated greatly by involvement of an umbrella organization, such as Botanical Gardens Conservation International or the Society for Ecological Restoration International.

Nontraditional Activities

Issues surrounding cost-benefit analyses and development of widely applicable metrics of ecosystem functioning or restoration success could be addressed worldwide and over the long-term by botanic gardens. These issues include, for example, the environmental and economic benefits of sequestering carbon in vegetation and soils through restoration. The large and rapidly growing international markets in natural resources (e.g., carbon trading, biodiversity offsets, payments for ecosystem services) could potentially fund large-scale restoration over

*Figure 1. Global distribution of botanic gardens practicing restoration ecology, 2010. Includes all gardens recorded in Botanic Gardens Conservation International's GardenSearch database as practicing restoration ecology (*n *= 99) (BGCI 2010*a*). This map was created by BGCI using ArcEditor 10.0 (ESRI).*

millions of hectares and represent a major opportunity for restoration practitioners. Nevertheless, the barriers to entry into these markets (including large transaction costs, data archiving over many decades, and expertise in ecosystem-carbon accounting) are considerable. Botanic gardens could provide an institutional base for overcoming such barriers. Crucially, botanical gardens are well equipped to undertake long-term monitoring of the restoration process. After restoration they should become engaged in the development of viable protocols for monitoring and subsequent better management of stocks of natural capital (i.e., natural ecosystems and native biodiversity [Aronson et al. 2007] and associated flows of ecosystem goods and services [Millennium Ecosystem Assessment 2005]).

Realities of Restoration Policy, Science, and Practice

A move toward more restoration-focused activities may be constrained by internal factors, such as staff perceptions that their talents or training are not relevant, institutional missions that are tangential or conflicting, funding sources that are not conservation oriented, and governing bodies that lack awareness of legitimate support from industry clients and emerging natural resource markets. We suggest that with minimal but crucial changes to the mission of most botanic gardens, they can build quickly and easily on existing strengths in efficient and meaningful ways. To accomplish reorientation and expansion, botanic garden leaders need to create and support a blend of policy and management systems that encourage integration of basic and applied science with technology transfer activities and implementation of practical projects. This must include start-up (core) and cooperative funding from many different sources. At the University of Wisconsin Madison's Arboretum, advances in the restoration and management of restored areas have been facilitated by a strong institutional focus on restoration, embodied in its stated mission, "...to conserve and restore Arboretum lands, advance restoration ecology, and foster the land ethic" (University of Wisconsin Madison's Arboretum 2010).

Once a botanic garden enters the field of ecological restoration, integration of an ecosystem science and restoration services division or close collaboration with local institutions with restoration expertise (universities or conservation research institutes) is an appropriate step. For most gardens, interdisciplinary partnerships likely offer the best way forward. On the scientific side, alliances will need to be formed with specialists in complementary fields such as animal ecology and soil science, as described above. When becoming involved in restoration projects, input will be required from cross discipline staff qualified in operational specialties, such as hydrogeology, civil engineering, sustainable development and land-use law, drawn from a network of regional agencies. Such teams would require relatively little overhead costs to sustain because they could assemble and disband on demand. In time, practical involvement in restoration projects will provide on-the-job experience for botanic garden staff, enabling them to strengthen and extend their own expertise.

Involvement in all phases of the project (from planning through implementation and monitoring) would enable the botanic garden team to ensure best practice and fidelity to the overall restoration goals. It would also facilitate an adaptive-management component, which the team could plan and operate through data maintenance. In this way, botanic gardens could facilitate the application of scientific principles and methods to improve restoration success incrementally as managers learn from experience and as new scientific findings emerge.

There is an increasing need for botanic gardens to be both ambitious and creative with regard to the science and practice of ecological restoration. Embracing restoration ecology as a sister discipline among botanic gardens' core scientific programs will result in new and meaningful initiatives that meet service, scientific, and sustainable mandates. Ultimately, these will maintain the relevance of botanic gardens and arboreta by addressing the challenges posed by global change.

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Literature Cited

Aronson, J., S. J. Milton, and J. N. Blignaut, editors. 2007. Restoring natural capital: science, business and practice. Island Press, Washington, D.C.

Aronson, J., et al. 2010. Are socioeconomic benefits of restoration adequately quantified? A meta-analysis of recent papers (2000–2008) in *Restoration Ecology* and 12 other scientific journals. Restoration Ecology **18**:143–154.

Australian National Botanic Gardens. 2010. Growing Native Plants database. www.anbg.gov.au/gnp/index.html (accessed January 2010).

BGCI (Botanic Gardens Conservation International). 2010*a*. GardenSearch database as of June 2010. BGCI, Richmond, Surrey, United Kingdom.

BGCI (Botanic Gardens Conservation International). 2010*b*. PlantSearch database as of June 2010. BGCI, Richmond, Surrey, United Kingdom.

Bond, N. R., and P. S. Lake. 2003. Local habitat restoration in streams: constraints on the effectiveness of restoration for stream biota. Ecological Management & Restoration **4**:193–198.

CPC (Center for Plant Conservation). 2009. Genetic considerations in ecological restoration: an annotated bibliography. CPC, Missouri Botanical Garden, St. Louis, Missouri. Available from http://www.centerforplantconservation.org/Education.html (accessed December 2009).

Convention on Biological Diversity (CBD). 2010. Draft decisions for the tenth meeting of the Conference of the Parties to the Convention on Biological Diversity: the global strategy for plant conservation. Pages 60–66 in UNEP/CBD/COP/10/1/Add.2.CBD, Montreal. Available from http://www.cbd.int/cop10/doc/ (accessed September 2010).

Elliott, S., P. Navakitbumrung, C. Kuarak, S. Zangkum, V. Anusarnsunthorn, and D. Blakesley. 2003. Selecting framework tree species for restoring seasonally dry tropical forests in northern Thailand based on field performances. Forest Ecology and Management **184**:177–191.

Erickson, D. 2009. A joy forever: the story of Kings Park & Botanic Garden. Botanic Gardens and Parks Authority, West Perth.

Falk, D. A. 1990. Integrated strategies for conserving plant genetic diversity. Annals of the Missouri Botanical Garden **77**:38–47.

Goosem, S. P., and N.I.J. Tucker. 1995. Repairing the rainforest – theory and practice of rainforest re-establishment in North Queensland's wet tropics. Wet Tropics Management Authority, Cairns, Queensland, Australia.

Hobbs, R. J. 2007. Managing plant populations in fragmented landscapes: restoration or gardening? Australian Journal of Botany **55**:371–374.

Hobbs, R. J., and J. A. Harris. 2001. Repairing the earth's ecosystems in the new millennium. Restoration Ecology **9**:239–246.

Jordan, W. R. III, M. E. Gilpin, and J. D. Aber. 1987. Restoration ecology: ecological restoration as a technique for basic research. Pages 3–21 in W. R. Jordan III, M. E. Gilpin, and J. D. Aber, editors. Restoration ecology: a synthetic approach to ecological research. Cambridge University Press, Cambridge, United Kingdom.

Lipsey, M. K., and M. F. Child. 2007. Combining the fields of reintroduction biology and restoration ecology. Conservation Biology **21**:1387–1390.

Lloyd, M. V., and T. K. Vercoe. 2002. Floradata: developing a national database for effective utilization of Australian native seed. Pages 3–7 in S. W. Adkins, S. M. Bellairs, and L. C. Bell, editors. Proceedings of the Fourth Australian workshop on native seed biology for revegetation. Australian Centre for Mining Environmental Research, Pinjarra Hills, Brisbane.

Maunder, M. 2008. Beyond the greenhouse. Nature **455**:596–597

Méndez, M., D. García, F. T. Maestre, and A. Escudero. 2008. More ecology is needed to restore Mediterranean ecosystems: a reply to Valladares and Gianoli. Restoration Ecology **16**:210–216.

Millennium Ecosystem Assessment. 2005. Ecosystems and human wellbeing: multiscale assessments. Volume 4. Synthesis report series. Island Press, Washington, D.C.

Offord, C. A., and P. F. Meagher, editors. 2009. Plant germplasm conservation in Australia. Australian Network for Plant Conservation, Canberra, Australia in Partnership with Australian Seed Conservation and Research (AuSCaR), Perth, Australia.

Ormerod, S. J. 2003. Restoration in applied ecology: editor's introduction. Journal of Applied Ecology **40**:44–50.

Pavlik, B. M. 1996. Defining and measuring success. Pages 127–155 in D. A. Falk, C. I. Millar and M. Olwell, editors. Restoring diversity: strategies for reintroduction of endangered plants. Island Press, Washington, D.C.

Pavlik, B. M. 1997. Perspectives, tools and institutions for conserving rare plants. The Southwest Naturalist **42**:375–383.

Seddon, P. J., D. P. Armstrong, and R. F. Maloney. 2007. Developing the science of reintroduction biology. Conservation Biology **21**:303–312.

Society for Ecological Restoration International (SERI). 2004. The SER International primer on ecological restoration. SERI, Tucson, Arizona.

Steele, W. K. 2007. Propagation protocol for ram's head lady's slipper (*Cypripedium arietinum*). Native Plants Journal **8**:58–64.

TEEB (The Economics of Ecosystems and Biodiversity). 2011. The Economics of Ecosystems and Biodiversity in National and International Policy Making. P. ten Brink, editor. Earthscan, London and Washington.

U.S. Department of Defense and U.S. Environmental Protection Agency. 2008. U.S. Code of Federal Regulations. Title 33,parts 325 and 332, and title 40,part 230. U.S. Government Printing Office, Washington, D.C.

United Nations. 2007. World population prospects: the 2006 revision, executive summary. UN, New York.

University of Wisconsin Madison's Arboretum. 2010. Arboretum mission. University of Wisconsin, Madison. Available from http://uwarboretum.org/about/mission_vision/ (accessed June 2010).

Wagner, K. I., S. K. Gallagher, M. Hayes, B. A. Lawrence, and J. B. Zedler. 2008. Wetland restoration in the new millennium: Do research efforts match opportunities? Restoration Ecology **16**:367–372.

Wyse Jackson, P. S., and L. A. Sutherland. 2000. International agenda for botanic gardens in conservation. Botanic Gardens Conservation International, Richmond, Surrey.

Young, T. P., D. A. Petersen, and J. J. Clary. 2005. The ecology of restoration: historical links, emerging issues and unexplored realms. Ecology Letters **8**:662–673.