Opinion

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Tropical botanical gardens: at the *in situ* ecosystem management frontier

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Tropical botanical gardens (TBGs) should have a leading role in *in situ* conservation by directly promoting several initiatives, including the reintroduction of important or valuable native species, focused habitat restoration, 'assisted migration' of species that are vulnerable to climate change, and creative local collaboration with governments, NGOs and indigenous peoples. Compared with temperate gardens, TBGs face heightened challenges for *ex situ* conservation, including greater absolute amounts of biodiversity, need for resource mobilization, risk of introducing invasive species and potential genetic introgression within living collections. Meanwhile, the ecosystems surrounding TBGs have undergone widespread and rapid conversion. Here, we provide several illustrations of the effectiveness of TBGs in achieving their mission of preserving tropical biodiversity at the frontier of *in situ* ecosystem management.

Tropical *in situ* ecosystem management: an urgent and natural agenda

The tropical regions on Earth contain most of its biodiversity [1,2]. This statement is often followed by dramatic statistics about the rapid conversion and degradation of tropical ecosystems [3,4] and dire predictions of widespread species extinction [5]. These concerns about the fate of the biodiversity on Earth are particularly disturbing when the global trends for human population growth, per capita consumption and overall condition of the natural resource base are considered [6,7]. Although most tropical countries maintain substantial protected area networks, the effectiveness and long-term viability of these parks has been questioned [8–10]. Here, we support and encourage tropical botanical gardens (TBGs) to pursue comprehensive programs of *in situ* ecosystem management, which integrate long-term monitoring, active restoration, educational outreach, agricultural extension services and policy involvement. Developing long-term management strategies at the landscape level, incorporating the entire spectrum of land use practice and history, is a robust way to conserve tropical biodiversity. TBGs, given their geographic location and fundamental integration, are natural leaders at the local and regional level and can act as a fulcrum to create major positive change.

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The Xishuangbanna Tropical Botanical Garden (XTBG; http://en.xtbg.ac.cn/) is a comprehensive botanical garden and research institute administered by the Chinese Academy of Sciences. As part of its 50th anniversary celebration in 2009, an international symposium on 'Biodiversity Conservation: Research Imperatives for Scientific Institutions' was convened. Even as botanical experts from around the world congratulated XTBG for the achievements and beauty of the garden, recent transformation of the surrounding landscape into a vast rubber plantation was impossible to ignore [11]. This pattern, where a rich living collection has become a last refuge for biodiversity harvested and cultivated from its neighboring landscape, is all too common. TBGs are poised at the frontier of *in situ* ecosystem management and restoration and have an obligation to utilize their botanical wealth, knowledge and expertise for *in situ* biodiversity conservation. As keepers of biodiversity, this is a deep responsibility.

Tropical botanical gardens: realizing their niche for biodiversity conservation

Modern botanical gardens are significant agencies for natural history collection [12], plant *ex situ* conservation [13,14], taxonomic research [15], horticultural and economic botany [16,17], public education and natural-history appreciation [18]. Historically, their main activities were horticultural and taxonomic research but the urgent need for biodiversity conservation, public education and technical outreach have become an increasingly important focus [19,20].

TBGs, many of them located within biodiversity hotspots, unfortunately represent a minority (~20%) of all botanical gardens worldwide, based on the Botanic Gardens Conservation International (BGCI) database [21]. An obvious global imbalance exists between the distribution of plant diversity and the botanical gardens that can directly manage and maintain these species in their native climate. Most of the older TBGs were established during the colonial era, as a consequence of trade and commerce [22]. These TBGs, such the Kebun Raya in Bogor, Indonesia (http://www.bogor.indo.net.id/kri/), have distinguished themselves as major historical and cultural landmarks and have a long tradition of research and training. Most TBGs, however, were established more recently, in accordance with economic development and the growing needs for

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environmental education, plant inventory and botanical research.

Since the 1980s, a core mission of botanical gardens has been the *ex situ* conservation of plant diversity, especially of rare and endangered species. Numerous significant achievements, although not all satisfactory, have been made by the botanical garden community in this respect. The BGCI database documents collections from >700 botanic gardens worldwide, indicating ~150 000 taxa listed in botanic gardens, among which are >12 000 threatened species (*sensu* IUCN). Nine species, categorized as 'extinct in the wild', have been preserved in the living collections of European botanical gardens [23]. Efforts to expand the species diversity of vulnerable and valuable species in seed banks and living collections, such as those of The Center for Plant Conservation in the USA (http://www.centerforplantconservation.org/) and the Millennium Seed Bank at the Royal Botanic Gardens, Kew (http://www.kew.org/msbp/index.htm), have established ambitious targets and have already achieved great success. Eight major Chinese botanical gardens [i.e. XTBG; South China BG (http://www.scib.ac.cn); Wuhan BG (http://www.whiob.ac.cn/); Beijing BG (North: http://garden.ibcas.ac.cn); Guilin BG; Nanjing BG; Fairy Lake BG in Shengzhen and Turpan Eremophytes BG] affiliated to the Chinese Academy of Science have preserved ~40 000 taxa, including 18 000 native species (~65% of the total floristic diversity of China; data collected by the authors, 2008). Nonetheless, compared to gardens located in temperate regions, where most internationally known and active botanical gardens are found, TBGs have their own unique set of challenges and opportunities (Table 1).

Challenges and opportunities for TBGs

First, tropical flora remains poorly known. Monographic treatments are available for only a small proportion of tropical families and geographic regions. Major regional flora, such as the Flora Malesiana project, are rare and progress is slow, primarily because of the scope of the project. In Xishuangbanna, Markku Häkkinen, a banana taxonomist from the University of Helsinki Botanical Garden, working with XTBG staff, recently discovered 12 new species in the genus *Musa* [24–26] during a brief four-month survey. Häkkinen achieved this remarkable effort despite the fact that Xishuangbanna is relatively well studied and >4500 higher plant species have already been recorded [27]. Unfortunately, given the rapid rate of land-use change and forest conversion throughout the tropics, particularly in Xishuangbanna [28,29] and the slow pace of taxonomic revision, it is unlikely that the floristic diversity in the tropics will be documented and described before many of the species become extinct or at least extremely rare.

Second, to establish and maintain viable *ex situ* populations for even a small fraction of the overall plant diversity would demand enormous resources, in terms of land area, financial budget and human expertise. Traditional guidelines for *ex situ* conservation, for example, recommend that 10–50 individual plants from five natural populations are necessary to have genetically diverse and representative living collections [30,31]. Meeting these guidelines would be impossible in the tropics. Even the development of seed banks, which have been shown to be efficient for temperate flora, cannot be easily adapted by TBGs, because the seeds of many tropical plant species either germinate immediately and cannot be stored or are recalcitrant even under the best conditions. However, the development of cryopreservation technology might be a solution to current problems of storage of recalcitrant tropical seeds [32,33].

Third, most tropical countries have lower per capita wealth and weaker infrastructure compared with temperate countries. This disparity means that many tropical countries do not maintain a botanical garden and the financial support, both public and private, is often limited in those countries with a botanical garden. XTBG is relatively unique among TBGs, as the Chinese Academy of Sciences supports a large and international research institute, focused on both basic and applied science, in parallel with the normal activities and responsibilities of a TBG. Meanwhile, both the National Science Foundation of China and the Chinese Academy of Sciences have set up grants to support taxonomic research. This system ensures that a relatively high profile and dynamic community of scientists remain active within the garden, utilizing its collections and promoting its science.

Fourth, the potential for genetic pollution or introgression among closely related species in a living collection has been recently recognized as important risk for *ex situ* conservation [34–37]. This risk is common to all gardens but might be greater for TBGs for several reasons. Tropical plant families often have tens to even hundreds of congeneric species within a single biogeographic region and each species can be endemic to a specific geographic location [38,39]. Living collections are often organized taxonomically, meaning that introduced species, including rare endemics, would be in close contact. This secondary contact among normally geographically isolated taxa could lead to genetic introgression and the potential breakdown of important genetic variation. This risk also exists at the species level. For example, 220 accessions of breadfruit (*Artocarpus*, Moraceae) from 18 Pacific islands, the Philippines, the Seychelles, Indonesia and Honduras have been established in the National Tropical Botanical Garden (http://www.ntbg.org/) in Hawaii [40]. Although relatively

Table 1. Comparison of criteria for tropical botanical gardens versus temperate gardens

Criteria	Temperate gardens	Tropical gardens	Refs
Area	Small–intermediate	Intermediate–large	[21]
Year of establishment	Some are very old (>300 years)	Most <200 years	[21][a]
Species richness	Rich	Intermediate–poor	[21]
Capacity in *ex situ* conservation	High	Many are poor	[20,21]
Risk in plant invasion	Low	Presumably high	[42]
Genetic pollution in collection	Little known	Little known, presumably high	[34–37]

[a]http://www.bgci.org/

little evidence exists about the level of genetic introgression expected in these situations and its subsequent impact, simply because of the greater diversity of congeneric and closely related species in the tropics, TBGs should pay particular attention to this situation and develop research programs to properly understand this threat.

Finally, the maintenance of exotic species in the living collections of TBGs poses a greater risk of naturalization and ultimate invasion than in temperate regions [41]. A recent survey determined that 31 invasive species were probably introduced by botanic gardens [42]. Dawson *et al.* (2008) assessed the risk of plant invasions in the Amani Botanical Garden in Tanzania. Of the 214 alien plant species surviving from the original plantings in the early 20th century, 38 had locally naturalized while 16 had spread widely in the botanical garden. Additionally, in contrast to temperate gardens, which must protect their tropical plant collections in greenhouses, living collections in TBGs are maintained outdoors, enhancing the risk of escape and invasion and genetic pollution. Although data about plant invasions in other TBGs are inadequate for a proper evaluation, traditional approaches to *ex situ* conservation would place TBGs at a higher risk of introducing invasive species. The inadequate information also impedes the process of institutional framework. For example, the major Chinese BGs do not have a clear accession collection policy to minimize the risk of invasion.

We suggest that TBGs must develop and pursue their own unique strategies for both *ex situ* and *in situ* conservation programs. We would like to see a shift in emphasis towards *in situ* conservation, given the numerous challenges outlined above for *ex situ* conservation. TBGs, with their traditional expertise in horticulture and applied research, can fill a unique niche in the management of ecosystems and landscapes. Protected areas are a cornerstone of biodiversity conservation but given the continued degradation of the forests surrounding them and the slow erosion within them, an integrated approach, linking conservation efforts across the entire spectrum of land-use practice and forest condition is necessary. TBGs are naturally positioned to have a key role in facilitating these activities.

Success stories of TBGs working for *in situ* ecosystem management

Most well-funded TBGs with scientific staff have successfully put into practice a holistic approach towards *in situ* ecosystem management. Examples include the Rio de Janeiro Botanic Garden in Brazil, the National Botanic Gardens of Cuba, the Bogota Botanic Garden in Colombia, the Singapore Botanic Garden (http://www.sbg.org.sg/), and the Queen Sirikit Botanic Garden in Thailand (http://www.qsbg.org/). The XTBG currently has a key role in the development of an international project that coordinates management and conservation activities across six countries (Cambodia, China, Laos, Myanmar, Thailand and Viet Nam) in the Greater Mekong Subregion (GMS). The Biodiversity Conservation Corridors Initiative (BCI) aims to conserve habitats for wildlife along with migration corridors; conserve and enhance ecological services, such as water supply and flood protection; and improve local

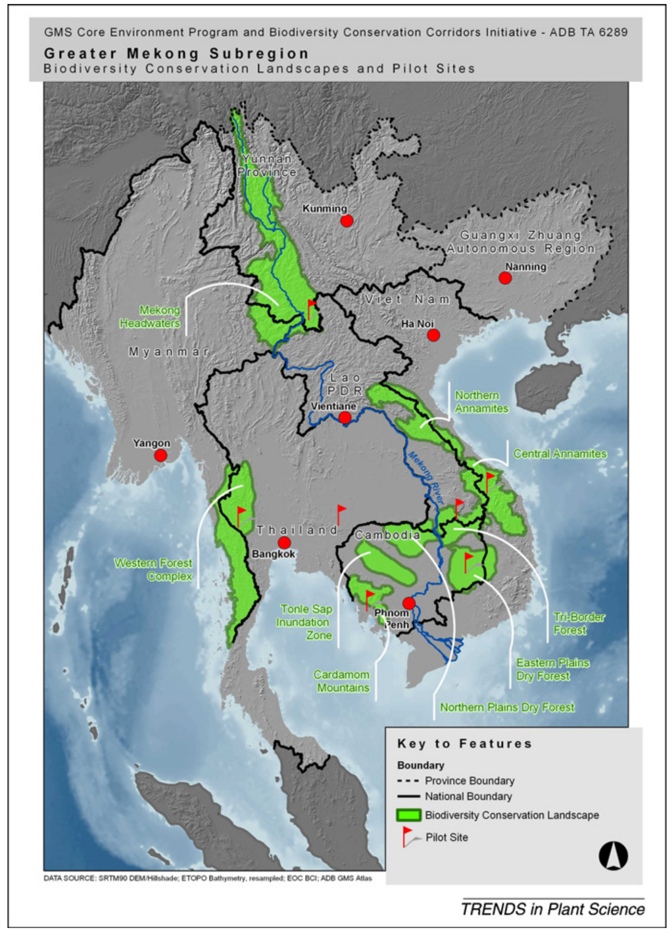

Figure 1. Biodiversity conservation landscapes and pilot sites in the Greater Mekong Subregion (Asian Development Bank TA 6289 GMS Biodiversity Conservation Corridor Initiatives). The XTBG is one of the partners and focal points for China's part in the Biodiversity Conservation Corridors Initiative. Reproduced with permission from Lothar Linde.

community welfare through sustainable use of natural resources. It is a flagship component of the GMS core environment program executed by the Asian Development Bank (ADB) (Figure 1).

The Xishuangbanna BCI project area is one of five sites in the GMS. The project will connect reserves through a series of corridors within the Xishuangbanna conservation complex, a unique formation of tropical and subtropical forests in southern Yunnan Province. During Phase One (2006–2009), two corridors were selected to test the conservation and development strategies. The objectives of the pilot BCI project were to accelerate regional sustainable development while enhancing the ecological integrity of the National Nature Reserves in Xishuangbanna through improved management of biodiversity conservation of corridors and core areas. According to project design, 15 relevant activities under four major components (poverty reduction, land use planning and management, restoring ecosystem connectivity and capacity building) were undertaken.

During the course of project implementation, XTBG researchers worked closely with local agencies and villagers, and delineated the corridor boundaries after ground and village surveys. After consultative workshops interacting with local government officials and conservation professionals, the People's Government of Xishuangbanna

Figure 2. Examples of TBGs involving in *in situ* conservation programs. **(a)** A piece of unique tropical rainforest [43] has been proposed by XTBG scientists and accepted by local government to be preserved as a protected area, increasing the total protected area in Xishuangbanna from 14 to 16%. **(b)** Scientists and horticulturists from Fairchild Tropical Garden performing a successful reintroduction program. Within the past two decades, the garden has conducted 32 reintroductions of 11 species, in collaboration with land managers at its partner agencies. **(c)** With the help of technical and financial support from the Kadoorie Farm and Botanic Garden, the ecosystem and species status of the Hainan gibbon (*Nomascus hainanus*), the world's rarest ape, both significantly improved. Reproduced with permission from Hua Zhu (a) and Qing Chen (c).

Dai Autonomous Prefecture approved, in principle, the boundaries of the proposed corridors. Forest restoration, awareness building and training, and a village-level revolving loan mechanism were performed within and outside the pilot corridor areas.

As part of the BCI project, XTBG scientists convinced the Xishuangbanna Government to create a new nature reserve along the China–Myanmar border, known as the Bulong Nature Reserve [43], which was established by the Governor in December 2008 (Figure 2a). Policy framework for the future management of these corridors and new nature reserves is under preparation and discussion. After review and evaluation by external experts, the Environment Operation Center of the ADB invited delegates from other countries in the GMS to visit the Xishuangbanna project area, and developed plans for expanding the project throughout the region.

Another world-renowned garden, the Fairchild Tropical Garden (FTG; http://www.fairchildgarden.org/), has an important role in the conservation of the endangered plants of South Florida through its research with rare plant introductions. FTG has several necessary elements to perform these reintroductions: adequate horticultural facilities, a large base of volunteer labor and scientific expertise. Within the past two decades, FTG has performed 32 reintroductions of 11 species, in collaboration with land managers at its partner agencies (http://www.fairchildgarden.org/centerfortropicalplantconservation) (Figure 2b).

Kadoorie Farm and Botanic Garden (KFBG; http://www.kfbg.org.hk/), a tropical garden in Hong Kong, China, with active involvement in local biodiversity inventory and conservation, initiated an *in situ* conservation program for the world's rarest ape, the Hainan Gibbon (*Nomascus hainanus*), at Bawangling National Nature Reserve, Hainan Island, in 2003 (Figure 2c). The program included patrolling, threat evaluation, staff capacity-building, promoting public awareness and landscape-scale forest restoration [44]. Adopting an animal as a flagship species is a truly original approach for a TBG. This conservation approach, spanning taxonomic kingdoms, enabled KFBG to incorporate its botanical knowledge and expertise into a comprehensive program to promote ecosystem restoration.

Conclusion: adapting the actions of TBGs to a rapidly changing world

The overwhelming threats to biodiversity worldwide require a long-term integrative approach to conservation and sustainable management, with its heart and mind focused on entire ecosystems and landscapes [45]. Because these threats range from small-scale conversion to global climate change, TBGs must pay attention to local grass-roots programs, aimed at educating rural farmers and urban consumers, while also providing technical guidance and influence to regional and national governments in the development of natural resource policies with a sound ecological and botanical basis. For example, climate change will have a major impact on biodiversity and plant extinction [46,47] and a profound effect on the living collections found in botanical gardens themselves.

TBGs can provide direct evidence for the consequences of climate change through the accumulation of data about long-term flowering patterns for a diversity of plants [48], providing an irreplaceable contribution to climate-change research [49]. Another possible major contribution by TBGs to the overall response to climate change would be the 'assisted migration' of plants highly sensitive to local climatic conditions into areas that have only recently become appropriate. Assisted migration has been proposed to reduce the risk of species extinction owing to climate change, but the suggestion has generated much debate [50–52]. With proper horticultural management and carefully monitoring, TBGs can provide the best mechanism for managed relocation or 'assisted migration' to minimize the risk of creating invasive species [53].

The most effective conservation programs generally involve institutions with long-term commitment to a particular region [54], becoming increasingly well adapted to the constraints of local cultural and political environment. TBGs, with their natural long-term commitment to the maintenance of living collections and overall plant diversity, have an institutional mandate for stability and conservation. By linking *ex situ* species conservation to *in situ* ecosystem management with the help of the worldwide botanical garden community under the mechanism of 'South–North' cooperation in capacity building [23], TBGs can help create the best conditions for tropical systems to survive both land-use and climate change, through the creation of regional networks of corridors, close technical integration with rural farmers, and educational and policy outreach to the general public and government officials (Box 1).

Box 1. Recommendations for TBGs involvement in *in situ* ecosystem management

- Strengthen skills and knowledge on restoration ecology and develop local habitat recovery programs
- Promote research on the potential effects of 'genetic pollution' or introgression within living collections and surrounding natural populations
- Investigate the mechanisms and conditions that facilitate and promote the invasiveness of exotic plant species
- Incorporate and preserve indigenous knowledge on ecosystem management and conservation
- Study the market-oriented mechanisms for biomass and biodiversity conservation and take advantage of emerging opportunities
- Seek the latest and most effective technologies, including bioinformatics, GIS, internet resources and genomics, and develop the necessary expertise to effectively utilize them
- Promote 'South–North' cooperation within the botanical garden communities to maximize overall conservation efforts
- Develop close and reciprocal ties with government officials, from local to national levels
- Cooperate and collaborate directly with large-scale industries, from energy to agriculture to tourism, that affect natural resource use
- Provide leadership in climate change research and education and explore the feasibility of managed relocation of species most vulnerable to extinction owing to climate change

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