Preface

The mission and function of a botanical garden are plant living collections, botanical research, and public education. Over the past 500 years, as specialized research institutions of botany, the botanical gardens have always played a key role in basic biological research, collections, evaluation, exploration and sustainable utilization of plant resources, especially in assembling and maintaining living collections and discovering sustainable uses of plants for human society. These research activities are the soul of botanical gardens and the backbone of botanical garden development. The trajectory of scientific research of the world's botanical gardens over the past 500 years is not only a microcosm of the whole history of biological sciences, but also an unremitting pursuit of mankind's exploration and utilization of plant resources to benefit the development of economy and human society.

Scientific research in botanical gardens

The research and discovery based on plant living collections have played a prominent role in the evolution of botanical sciences. Botanical research is the core and soul of botanical gardens. Botanical gardens are generally characterized as "common gardens" for various research purposes. Many plant taxa (species, genera and families) are cultivated and managed in a relatively consistent protocol under similar environmental conditions, which inspired many great scientists towards numerous theoretical and scientific discoveries and epochal change of early studies of plant classification, taxonomy, floristic studies, flora compilation, biogeography, etc. (see Chapter 1 for details).

As the origin of plant taxonomy research, botany had a long historic origin that stemmed out from ancient Greece. Known as the Father of Botany, Theóphrastos (371 BC–287 BC), ancient Greek philosopher and scientist, established the original concept of botany. However, modern plant taxonomy is a product of the European Renaissance. In the early days of modern botanical research, the botanical gardens played a crucial role. For example, Luca Ghini (1490–1556), a famous naturalist and botanist, invented the specimens that were made from live plants and was credited with establishing the first herbarium in the world as the first director of Pisa Botanical Garden in 1544. Carl Linnaeus, the director of Uppsala Botanical Garden from 1741 to 1778, introduced the binomial nomenclature in 1753 in his *Species Plantarum*, which is recognized as the beginning of modern plant systematic nomenclature, and created a unified biological nomenclature and made original disordered cognition of the plant world in order. Botanical gardens in the 18th–19th centuries landmarked many events. A group of botanical garden directors and well-known botanists made great contributions to plant taxonomy and published many important monographs on families, genera and Flora. For example, the Swedish botanist Augustin Pyramus de Candolle (1778–1841), director of Montpellier Botanical Garden in France, established a natural classification system of hundreds of plant families, and created the word "Taxonomy". He was also the founder of natural classification system of "class" rank. The milestone of botanical gardens' contribution in plant taxonomy is the Engler system founded by Adolf Engler (1844–1930) in Berlin Botanical Garden, Germany, which is still widely used in many herbaria around the world, known as the "plant taxonomy system from botanical gardens".

As innovative research platforms of basic biology, botanical gardens have made indelible contributions to scientific discoveries of biology and the establishment of theoretical systems since 18th century. For example, Augustin Pyramus de Candolle developed the concept of circadian rhythm or "biological clock", and the concept of "natural war" for bio-origin and evolution. John Stevens Henslow (1796–1861) of Cambridge University, the supervisor and mentor of Darwin, designed the Cambridge Botanical Garden for both scientific verification and botanical teaching of biological hypothesis. During Darwin's studying at Cambridge University, he was called the "shadow" of Prof. Henslow. They often walked together on campus discussing scientific questions. It was Henslow who recommended the young Darwin to take the global expedition of Beagle, and with Henslow's thoughts of speciation, Darwin boarded the Beagle and made the five-year scientific expedition. There is no doubt that Henslow's enlightenment and subsequent guidance were crucial to Darwin's evolution theory during his stay in Cambridge Botanical Garden. Joseph Dalton Hooker (1817–1911), one of the pioneers of the global botanical expeditions, launched botanical expeditions and collections in Antarctica, South Pacific, Himalayas, Indian subcontinent, southern Asia and Palestine, North Africa-Morocco and the western United States, which led to the discovery of many new species and made important contributions to the garden plants introduction to Europe. He also contributed greatly to floras of many other countries and regions, such as the epoch-making works *Flora of British India*, *Flora of Antarctica*, *Handbook of New Zealand Flora*, *Niger Flora*, *Student's Flora of the British Isles*, and *Handbook to the Ceylon Flora*, etc. He and Bentham edited *Handbook of the British Flora* which established the formulation and standard of compiling flora that was used for more than 100 years. Lourens Baas Becking (1895–1963), famous Dutch botanist, microbiologist, director of Leiden Botanical Garden in the Netherlands, and director of Bogor Botanical Garden in Indonesia, originated the Baas-Becking hypothesis (1934) that "everything is everywhere, but the environment selects", which so far has been still widely cited by many microbiologists.

As the center of plant introduction, botanical gardens activated crop plants introduction, re-domestication and utilization across continents, regions and countries, which profoundly changed the world economic and social pattern and affected the rise and fall of many countries. Since the end of the 15th century, botanical gardens have played a major role in the introduction and domestication of crop plants. Botanical gardens, first established in Mediterranean coastal countries, are key to the introduction of major food plants and various crops into Europe. For example, Padua Botanical Garden, established in 1545, Italy, began to collect plants on a large scale since 1546, with 1800 species recorded at that time, including maize, potato, tomato, pepper, sunflower, green beans and many other plants from South America. These first botanical gardens were important bases for the introduction and re-domestication of food and crop plants in Europe. In the 16th–18th centuries, the introduction and re-domestication of crop plants in Mediterranean countries led to evolutionary changes of agricultural pattern and natural vegetation, and even changed agricultural, ecological and cultural landscape in southern Europe. In >200 years before the European industrial revolution in the 18th century, introduction and re-domestication of crop plants in Mediterranean countries had a profound impact on modern European civilization. From exploration and collection of plants to establishment of modern plant taxonomy and other disciplines, from the curiosity of exotic plants to changes of large-scale plantations and agricultural production, from changes of food crops production to changes of diet culture, introduced plants had completely changed the economy, social and cultural history of Europe. It's hard to imagine a European meal nowadays without tomatoes and potatoes. Moreover, expansion of European colonialism in the 18th century gave birth to the rise of botanical gardens in Northern and Western Europe, and plant introduction and collection gradually became a mainstream, further promoting the collection of plants and botanical discovery in America, Africa and Asia. A large number of new plants have been introduced into Europe, while botany has become an independent discipline. For example, Royal Botanical Garden—Kew and Edinburgh and James Veitch & Sons sent or funded a large number of botanists to carry out expeditions and collections, such as David Douglas (1799–1834) hunted Douglas fir (*Pseudotsuga menziesii*) in North America; Robert Fortune (1812–1880) hunted Chinese tea; Joseph Dalton Hooker (1817–1911) hunted Rhododendrons in Himalayan mountains; and Ernest Henry Wilson (1876–1930) hunted *Davidia involucrata* and *Meconopsis* in China. Furthermore, collecting activities of western plant hunters also made botanical gardens as windows for horticultural display, which in turn stimulated the development of European horticultural and nursery industries.

As the center of plant *ex situ* conservation and biodiversity research, the advantage of numerous plant species cultivated in the botanical garden is obvious. The botanical garden has become an ideal place and platform for biological research coping to global climate changes. Botanical gardens will still play a vital role in macro- and micro-plant biology research, as well as many other areas in the mega data era. First, in macrobiological fields of plant science, as the origin and focal point of plant taxonomy, botanical gardens have incomparable advantages for comparative or contrastive studies. For example, nowadays comparative floristic geography, comparative phylogeny, comparative functional physiology, and comparative adaptive evolution can still be focuses of research deployment in botanical gardens. The wide spectra of cross-genera, cross-flora and cross-habitat collections of living plants and controllable cultivation owned by botanical gardens provide special convenience for researches in biology, secondary metabolism biology, phytochemistry, epigenetics and other frontier disciplines. Most importantly, botanical gardens played and will be playing a leading role in the global plant inventory, cataloguing, documenting and diversity research. They will also be important research base for *ex situ* plant conservation and restoration/recovery of threatened and endangered plants. Second, in microbiological fields of plant science, many microbiological researches that rely on the real-time sampling and dynamic analyses of living materials can be effectively supported in botanical gardens. For example, chromosome research in cytogenetics usually needs real-time sampling to do the real-time analysis of mitosis and dynamic changes of chromosomes. Advantages of botanical gardens become more obvious especially in large-scale cross-family and across-genus comparative studies of chromosome behaviors of different plant taxa, and in embryology, cytology, population genomics, metabolomics and other related studies. Third, mega data and omics are becoming focuses and trends. Botanical gardens, as hub of basic biological data accumulated in the long term and research center of basic botany, will create a digitalized world of their living collections and herbaria. It can be foreseen that the construction of today's botanical garden's mega data platforms will promote the development of botanical research towards "Integrative Biology". Multilevel data mining platform in genes, functions, patterns, processes, mechanisms and other comprehensive researches will break through existing cognitive limitations, contribute to the global online database and basic data sharing, and simultaneously support the data mining of mega data platforms for various macro- and microbiological researches, thus showing broad prospects and great vitality. Finally, against the background of global climate change, opportunities and challenges facing biosciences involve many research hotspots and scientific questions. Botanical gardens are not only an important part of global plant diversity conservation, but also important germplasm resources for human understanding of nature, exploring resources and sustainable utilization in responses to global climate changes, such as phenology, restoration ecology, plant migration and geobotany, alien invasive plants, etc.

World garden flora and living collections

There are 2118 botanical gardens in the world, widely across different climatic zones and floristic regions. Most importantly they provide habitats for >100,000 vascular plants in *ex situ* cultivation, accounting for about a third of known world plant species, including many economically important taxa or groups. This *ex situ* cultivated flora contains an enormous amount of plant diversity in many well documented living collections in different botanical gardens and plays a critical role in the security of plant diversity, and in conservation, sustainable agriculture and other related bio-industries. Overall, Europe has 678 botanical gardens, North America 506 botanical gardens, Asia 499 botanical gardens, South America 173 botanical gardens, Africa 131 botanical gardens, and Oceania 131 botanical gardens, respectively accounting for 32.30%, 23.79%, 23.46%, 8.13%, 6.16% and 6.16% of the total number of botanical gardens in the world. The United States, China, and Australia have more than 100 botanic gardens. The top 10 counties have 56.6% of the total in the world, including the United States, China, Australia, France, India, Italy, Germany, Japan, Russia and Canada.

In Africa, there are 131 botanical gardens in 41 countries or regions. African countries with the largest number of botanical gardens are South Africa (22 botanical gardens), Nigeria (18 botanical gardens), but 15 countries have no botanical gardens. Apparently, the lack of capacity of botanical gardens devoted to *ex situ* flora in Africa and biased distribution of African botanical gardens will hamper *ex situ* conservation ability to cope with the high risk of rapid loss of plant diversity, especially in many hotspots of plant diversity in Africa.

In Asia, there are a total of 499 botanic gardens in 37 countries or regions. Asian countries with the greatest number of botanical gardens are China (161 botanical gardens), India (90 botanical gardens) and Japan (78 botanical gardens). The number of botanical gardens in Asia is impressive, but the disproportionate distribution across Asian countries is still problematic. Many Asian countries with rich plant diversity and a large number of threatened and endangered species are behind of capacity for *ex situ* conservation and efforts in restoration and recovery initiatives.

In Europe, a total of 678 botanical gardens are found in 41 countries. The European countries with the greatest number of botanical gardens are France (90 botanical gardens), Italy (86 botanical gardens), Germany (82 botanical gardens) and Russia (60 botanical gardens). European counties have a long history of botanical garden heritage and well-established capacity in plant conservation, botanical research and plant exploration. In addition, many leading botanical institutions are in Europe, such as Royal Botanical Gardens at Kew and Edinburgh, playing an important role in *ex situ* conservation worldwide.

North America is a continent with the largest number of botanical gardens. A total of 506 botanic gardens are distributed in 25 countries or regions. The United States has the greatest number of botanical gardens (363), followed by Canada (45 botanical gardens) and Mexico (37 botanical gardens). The distribution of botanical gardens in North America reflects the socioeconomic development, instead of rationales of *ex situ* conservation and capacity for containing the current risk of rapid loss of plant diversity. Given that endemic threatened species should be held *ex situ* within their original countries and available for ecological or species restoration, the number of botanical gardens in Mexico would be greatly increased, in addition to many plants with crucial solutions to our future agriculture, horticulture and forestry, etc.

In South America, there are a total of 173 botanical gardens in 18 countries or regions. Brazil, Argentina and Columbia have the greatest number of botanic gardens, which are 46, 30 and 26 respectively. The number of botanical gardens and conservation capacity are largely under-distributed, particularly in tropic regions with the highest plant diversity and risks of loss of a large number of important species. Many regional hotspots lack active *ex situ* conservation efforts to rescue threatened and endangered plants, primarily due to socioeconomic situations.

In Oceania, Australia has 102 out of 131 botanical gardens in Oceania, followed by New Zealand with 10 botanical gardens. The unique position of botanical gardens in Australia and New Zealand with a great number of endemic plant species in the continent is still undervalued and needs to be re-recognized as a priority of the *ex situ* conservation as the botanical gardens are the main institutions in this regard.

The geographic distribution of the botanical gardens worldwide revealed gaps and challenges of the unevenly distributed garden flora. Recent studies revealed that 91% of recorded accessions and 93% of recorded species are documented from *ex situ* collections in the Northern Hemisphere, suggesting the bias is largely due to the geographical distribution of botanical gardens and species richness in botanical gardens, including socioeconomic factors and metropolitan population size. The biased bio-geographical distribution of the world botanical gardens will hamper global conservation goals. A recent analysis showed substantial bio-geographic gaps in the representation of living collections, with 93% of species held in the Northern Hemisphere and an estimated 76% of species absent from living collections are tropical in origin.

The mass extinction of plant species at present is the greatest challenge to humankind. Living collections *ex situ* in botanical gardens featured world garden flora not only provide security of rapid loss of plant diversity in the wild but also a comprehensive experimental base for research of specific plant groups. Inventory of world garden flora revealed that gymnosperms are highest covered in garden *ex situ* cultivation, and 90 out of 93 genera have been brought into *ex situ* conservation in botanical gardens, accounting for approximately 97% of total genera within gymnosperms. Only a few species of Araucariaceae, Cupressaceae and Podocarpaceae are absent from the botanical gardens. This is consistent with the traditional holding of tree species, particularly conifers in the history of botanical garden cultivation. Meanwhile, inventorying world garden flora in Angiosperms revealed that a total of 15,487 genera and 388 families have been brought into botanical garden *ex situ* cultivation, accounting for 75.3% of the total number of genera documented. However, there are as many as 26,892 species were missing from the botanical gardens of the world, although 8726 or 32.4% of the missing species are yet unresolved. A large number of unresolved angiosperm plants confront taxonomic dilemmas and *ex situ* conservation efforts. Currently, the large number of taxonomically unresolved species presents challenges to plant conservation both *in situ* and *ex situ*. Inclusion of all species of plant groups into botanical garden conservation should be encouraged for both taxonomic research and purposes of conservation to impede rapid loss of plant species in facing current Earth's sixth mass extinction.

Pteridophytes in the world garden flora are not as much coverage as that of angiosperms, with a total of 538 genera and 47 families held in botanical gardens, accounting for 69.3% of total genera within pteridophytes. One problem facing pteridophytes *ex situ* conservation in botanical gardens is that a high percentage of unsolved species involved, which made uncertainty for the conservation status of approximately 2000 species. Bryophytes were not historically attention for botanical garden collections, mostly because of not adequate research information and cultivation techniques available except taxonomic documentation. Therefore only 17.4% of known genera of bryophytes are presented in botanical gardens' *ex situ* conservation.

Obviously, in centuries of botanical garden development, the purposes and capacity built within the world botanical garden community have not quite fitted into current conservation needs to rescue the rapid disappearance of plant diversity. Traditional skills within the botanical garden community are mostly towards high vascular plants. It has been badly behind of cultivation skills for non-vascular, such as moss and lichen. Furthermore, botanic gardens should be more aggressively responding to the threat of species extinctions because of currently housing at least 13,218 species at risk of extinction, equating to just over 41% of the world's known threatened flora.

Ex situ Flora of China

There are 161 botanical gardens in China (Figure 1), holding ca. 20,000 species in China. *Ex situ Flora of China* is a new initiative for the garden cultivated flora to address plant diversity conservation and germplasm discovery for sustainable agriculture and the bio-industries. Initiated in 2012, the project aims to catalogue and document the mega-diversity of plants that are currently cultivated in Chinese botanical gardens.

The concept of *Ex situ Flora of China* is to build a brand new formulation for species found in living collections, rely on botanical garden cultivated individuals and populations to obtain better morphological descriptions, and provide multi-purpose applicability and a fundamental data service. *Ex situ Flora of China* emphasizes integrative information accurately collected from living collection across different botanical Chinese gardens, on biology, phenology, cultivation requirements and uses of plant germplasm, which are normally not available from traditional floras based on herbarium specimens. So in this way, the *ex situ* flora will provide better information coverage for taxonomy, biological and introduction and collection data, and color photos of the stem, leave, flower, fruit and seed, as well as useful information of cultivating protocols and main uses of each plant.

In practice, the *Ex situ Flora of China* will provide significant support to botanical research and plant germplasm discovery and sustainable use. ① It will enhance taxonomic research with common garden-based living specimens, which are of crucial importance for both adequate and accurate descriptions and the delimitation of difficult taxa whereas traditional taxonomic revisions were based on herbarium specimens; ② It will support comparative biology and frontline plant science research. With increasing awareness of environmental and habitat changes in overall context of climate change on plant distributions *in situ*, the *Ex situ* Flora will provide intensive plant biological information from different gardens across a wide spectrum of different latitudes, regional climates and habitats in relation to the research on plant adaptive evolution, migration and distribution shifts and physiological or/and biochemical changes, etc.; ③ It will strengthen germplasm discovery and sustainability of plant resource, which should enhance the current programs in medicinal, industrial bio-energy, landscaping and ornamental plants, new functional fruits and vegetables and environmental meliorating plants, etc. The *Ex situ Flora of China* will include ca. 300 families, >3000 genera and approximately 16,000–20,000 species from *ex situ* living collections.

Since the *Ex situ Flora of China* is a long-term project, the three-phase outputs of project have been planned and implemented. The checklist of *ex situ* cultivated plants in China was the first phase output and was published in 2014 as a benchmark species list of the project. The second phase of the three planned outputs of the *Ex situ Flora of China* was the 13-volume *Encyclopedia of Chinese Garden Flora* which were completed and published by 2017. The encyclopedia aimed to concisely format each species with brief text description and color photographs from living collections so as to illustrate the main features of each species. The contents mainly include the Chinese name, Latin name, brief text of identification feature and an on-site photograph of the living plant. However, in view of long history and original records of *ex situ* living collections, some entries are not synchronized with updated taxonomic revisions, so that the editorial strategy of encyclopedia has been insisting on the principle of "respect historical facts and advance with the times". Some taxa have reasonably been adjusted and combined according to updated revisions of systematics. The *Encyclopedia of Chinese Garden Flora* includes one volume for pteridophytes and gymnosperms and 12 volumes for angiosperms, all arranged in alphabetical order by the Latin name of families. In each volume, each family is also arranged alphabetically by the Latin names of genera and species. For convenience, all books are indexed by Chinese plant names and Latin names. A total of 16,226 species belonging to 311 families and 3168 genera are included in the encyclopedia. The third phase is the core component of the project, *Ex situ Flora of China*. So far, sixteen family volumes have been published (Table 1). These sixteen out of approximately 80 volumes in the 15–20 years or even longer time frame have been considered pioneer volumes and trials of compilation formats. Many lessons have been learned that will lead to better understandings of status and facing problems of *ex situ* flora and garden living collections so that implementations of other volumes of the *Ex situ Flora of China* can be better organized in the future.

Table 1 Information in the published volumes of *Ex situ Flora of China*

Volume	Participating botanic gardens	Numbers of families	Numbers of genera	Numbers of species
Magnoliaceae	10	1	11	147
Myrsinaceae	6	1	6	90
Melastomataceae	9	1	16	40
Euphorbiaceae	6	1	58	176
Zingiberaceae	6	1	20	149
Acanthaceae	16	1	45	152
Aloe (Liliaceae)	8	1	1	180
Desert plant	2	30	79	133
Hamamelidaceae	9	1	17	53
Begoniaceae	4	1	1	173
Cactaceae	7	1	57	186
Urticaceae	4	1	14	101
Iridaceae	6	1	11	73
Lauraceae	10	1	18	112
Theaceae	8	1	11	112
Caprifoliaceae	16	2	16	165

The *Ex situ Flora of China* is the multi-decade project. Although project initiation and progress in early phases were promising and have attracted much interest from both the botanical field and botanical gardens communities as well as the public, the project is still facing many challenges. Nevertheless, the *Ex situ Flora of China* is the first integrative *ex situ* flora and will greatly benefit global *ex situ* conservation and provide basic and mega information services to agriculture, forestry, horticulture and medicinal industries in the future.

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