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ORIGINAL PAPER

The role of botanic gardens as resource and introduction centres in the face of global change

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Abstract One of the consequences of global change, especially demographic and climatic, will be a demand for novel plant germplasm of all kinds suited to the new ecoclimatic conditions predicted and plant introduction will assume a new importance. As a consequence, botanic gardens will face an unprecedented opportunity to regain their role as introduction centres and become major actors in the assessment of new germplasm, both of ornamentals as well as other economically important plants. Plant introduction has remained largely unchanged over the past 400 years and is as often *ad hoc*, poorly organized and insufficiently collaborative, but if it is to meet the needs of today's situation it needs to be overhauled. In particular: (1) the basis of plant introduction needs to be broadened; (2) closer cooperation with agricultural genebanks should be established; (3) agreement should be reached between botanic gardens and the agricultural sector on their respective responsibilities (4) the quality and sampling of the accessions should be more strictly controlled; (5) proper evaluation of the introductions before they are disseminated; (6) information on the accessions of introduced plants and their fate needs to be more effectively maintained and disseminated; and (7) full cognizance should be taken of policies to protect against invasive species and care should be taken to evaluate the risks that new introductions might represent. Finally, consideration should be given to preparing a set of guidelines or even a code of conduct for plant introductions by botanic gardens in association with other agencies.

Keywords Acclimatization · Germplasm · Global change · Underutilized species · Invasive species · Guidelines · Codes of conduct

Introduction: challenges and opportunities

Botanic gardens face both challenges and opportunities in responding to global and, in particular, climate change (Tables 1 and 2). Firstly, they will have to reassess their

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Table 1 Challenges faced by botanic gardens in response to climate change

Global warming and increasing aridity may make the growing conditions unsuitable and imperil the continued existence of some botanic gardens and the living collections that they maintain.
The accessions policy of gardens may have to change to take into account the new conditions—some species will no longer be able to be grown while the successful introduction of others that were previously unsuitable for cultivation will become possible.
Changes in flowering times may affect the availability of pollinators and increase or decrease hybridization between species, with serious implications for conservation collections.
Invasive species will become more common and cause problems for botanic gardens which will intensify calls for the adoption of Codes of Conduct to help control these

Table 2 Opportunities for botanic gardens in response to climate change

They can assess new germplasm for adaptation to new ecoclimatic conditions
They should form a key part of the country's national strategy for biodiversity conservation and sustainable use and work in close alliance with other institutions
Botanic gardens can play a major role in assessing the likely survival or migration possibilities of species
They can put their phenological observations to good effect in assessing the impacts of climate (Primack and Miller-Rushing 2009)
They can provide advice to the municipality and the public on what plants to grow in urban and periurban situations and provide demonstration gardens

accessions policies as the growing conditions in the predicted new climatic envelopes for some, if not many, of the plants currently cultivated will no longer be suitable for them. Secondly, the increased numbers of species put at risk as a result of the changing climatic conditions will force them to refocus and strengthen their conservation policies and increase their participation in recovery programmes for critically endangered species. Thirdly, botanic gardens will face an unprecedented opportunity to develop their role as introduction centres and play a major role in the assessment of new germplasm both of ornamentals as well as other economically important plants. These three challenges are interrelated to some extent but this paper focuses on the third one and outlines the issues involved in adopting or reinforcing the introduction and resource role of botanic gardens.

The plant introduction process

Plant introduction has a long history, dating back thousands of years (Del Tredici 2000) and has been practised by various civilizations and cultures, ranging from the ancient Chinese, Egyptians, Greeks and Romans through major episodes such as the post-Columbian period and the five main waves of mainly ornamental plant introduction since the sixteenth century (Stuart 2002) to the present day. Most civilizations have engaged in a two-way traffic of introduction and export of plant (and to a lesser extent animal) resources. Exploration and the introduction of plants into cultivation has been a major underpinning of agriculture, horticulture, trade and socio-economic development over the centuries. As noted in the St Louis Declaration (2002) 'Plant introduction and improvement are the foundation of modern agriculture, yielding diversity to our supply of plants used for food, forestry, landscapes and gardens, and other purposes'. As Thomas Jefferson famously said, 'The greatest service which can be rendered to any country is to add a useful plant to its culture'. He also wrote in a letter to M. Giraud (1797) 'I received the seeds of the bread tree… One service of this kind rendered to a nation, is worth more to them than all the victories of the most splendid pages of their history, and becomes a source of exalted pleasure to those who have been instrumental in it'. Plant introduction has been driven by commercial, scientific, medicinal and even personal goals (Ward 2004). The specific reasons for introducing plants are diverse and include scientific curiosity, biophilia, collections, medicinal potential, trade (such as in spices), agriculture, forestry, gardening, ornamental horticulture, and community benefit and social use (Heywood 2006).

The impacts of plant introduction have been far-reaching and have been a major driver in population growth and economic development in some cases. For example, the main impact of New World introductions in Europe and the Mediterranean was on the nutritional balance of the agricultural economy, with maize (*Zea mays*), potatoes (*Solanum tuberosum*) and beans (*Phaseolus*) producing many more calories per hectare than the traditional arable crops of pre-columbian agriculture such as wheat and barley. The introduction of crops with higher calorific value had a marked impact on demography, with the increased agricultural productivity allowing substantial population growth and consequent development (Malanima 2006).

The acquisition and introduction of new crops was almost a defining characteristic of the colonization process by the European powers as Calestous Juma notes in *The Gene Hunters* (1989): '…the acquisition of colonies was not enough unless linked with the availability of labour and plant genetic resources'. This involved the movement of stocks of economically useful plants from one part of the world to another on a massive scale in the furtherance of colonial agriculture. The combined networks of colonial botanic gardens served as a very effective mechanism for the transfer of germplasm around the world, long before the modern genetic resources movement was developed.

The initial focus of introductions was on plants that could add to the agricultural wealth of the country or those of medicinal value although ornamentals were also included and interest in these grew as gardening gradually became a leisure pursuit with the increase in wealth. The actual process of plant introduction is however poorly circumscribed and ranges from almost casual plant collecting to well organized and structured approaches (Ault 2000). The actors are likewise many and varied and have included travellers, explorers, field botanists, diplomats, surgeons, sea captains, civil servants, nursery owners, landowners, gardeners, and of course the celebrated professional plant collectors such as John Tradescant, John Bartram, Charles Curtis, David Fairchild, Francis Masson, Ernest Wilson, George Forest, David Douglas, Frank Meyer, Reginald Farrer, Robert Fortune, William and Thomas Lobb, Richard Spruce, John Gould Veitch who were responsible for bringing into cultivation many of our best known garden plants and trees (Gribben and Gribben 2008). An account of recent plant collectors is given by Ward (2004).

Responsibility for introductions gradually transferred to agricultural stations or Departments of Agriculture and some of the collectors were sponsored by official institutions, as in the United States where the renowned plant explorer David Fairchild had the splendid title of 'Agricultural Explorer, in Charge of Foreign Explorations'.[1] Another important figure was Frank Meyer, regarded as the doyen of agricultural explorers, who was employed by the US Department of Agriculture and from 1905 to 1918 was responsible for thousands of introductions from China to other parts of eastern Asia (Cunningham 1984; Kaplan 1998).

The basic procedures of plant introduction have remained largely unchanged over the past 400 years and it often is difficult to discern any general coherent policy lines. In fact,

[1] The US Department of Agriculture's plant introduction program celebrated its 100th anniversary in 1998.

despite its acknowledged importance, plant introduction, with a few exceptions, has been described as largely a random, poorly organized, insufficiently collaborative, badly publicized and inefficiently followed through process. Yet it could be argued that it has been remarkably successful in the sense that tens of thousands of species have been brought into cultivation. In Europe alone, about 17,000 taxa (12,000 species plus subspecies, varieties and hybrids) are grown in gardens (European Garden Flora Editorial Committee 1984–2000).

Botanic gardens as introduction centres

Historically, many botanic gardens, especially those located in the tropics, have acted as plant introduction centres and played a major role in the spread of germplasm of agricultural, industrial, forestry and ornamental plants around the world. Their actions in helping establish the agricultural economies in several parts of the tropics and subtropics through the introduction of plantation crops such as coffee, tea, oil palm and rubber have been well documented (Brockway 1979; Heywood 1985; Holttum 1970; Purseglove 1959). Such actions were not confined to gardens such as Bogor (Indonesia), Howrah (India), Peradeniya (Sri Lanka), Pamplemousses (Mauritius) and Singapore but involved many other botanic gardens in tropical Asia, such as the Lalbagh Botanical Garden, Bangalore (India) and, the Caribbean such as the St Vincent Botanic Garden (Windward Islands) and the Bath Botanical Garden (Jamaica).

Lalbagh Botanical Garden, Bangalore, although dating from 1760, for over 150 years has been the hub of the horticultural trade and industry in the state of Karnataka since it became the State Botanical Garden in 1856. The first botanic garden in the New World tropics[2] was established in 1765 on St Vincent in the West Indies, promoted by the Royal Society of London. This garden which persists to the present day was instrumental in introducing breadfruit as cheap food for the slaves in much the same way as Pamplemousses did for cassava (*Manihot esculenta*). Other germplasm resources developed at St Vincent included nutmeg (*Myristica* sp.), arrowroot (*Maranta arundinacea*) and the celebrated sea island cotton (*Gossypium barbadense*) cultivars. The reputation of the St Vincent Botanic Garden as an acclimatization garden for the whole of the West Indies was influential in persuading the East India Company to go ahead and establish the garden at Calcutta. There the Indian (formerly Royal Botanic) Garden was originally envisaged by its founder Lt Col. Robert Kyd, the Military Secretary to the Government in India, as a trial garden to grow a range of useful crops such as Sago palm (*Cycas revoluta*) and Persian date palm (*Phoenix dactylifera*) as sources of nutritious food for the native population, and of teak (*Tectona* sp.), spices, tea (*Camellia sinensis*) and coffee (*Coffea* sp.) for trade.

The French involvement in tropical germplasm introduction followed a different pattern, the key central institution being the Muséum National d'Histoire Naturelle where the holder of the *Chaire des Cultures*, André Thouin, was responsible for introducing vanilla (*Vanilla planifolia*) from Mexico where it was grown by the pre-Hispanic cultures, to the Jardin de la Compagnie (the French East Indies Company) on the Island of Réunion from where it spread to other Indian Ocean islands. The Jardin des Plantes in Paris received

[2] It is worth noting that this was not the first botanic garden in the Western Hemisphere as sometimes stated— that honour goes to a medicinal garden attributed to Dr Lawrence Bohun, Physician General of Virginia in 1610, followed by that begin by John Bartram near Philadelphia in 1728 and still in existence today and the Linnean Botanic Garden also at Philadelphia in 1730.

seedlings of coffee from Amsterdam as part of the complex saga of the introduction of this crop to various parts of the world, in this case the neotropics.

These tropical botanic gardens were victims of their own success and led to the establishment of agricultural research stations and departments, thus leaving them without their main role which consequently led in many cases to their decline or closure. With the exception of ornamental plants, the involvement of botanic gardens in plant introduction largely disappeared following the creation of agricultural stations and centres in early twentieth century.

In the twentieth century, a number of gardens were opened in Italy for the introduction of plants from the colonies and in North Africa, the Jardin d'Essai, Rabat (Morocco) which opened officially in 1928 was an experimental garden that undertook trials on fruit trees and ornamental species. It fell into disrepair but plans for its major rehabilitation were announced in January 2009. An earlier foundation is the Jardin d'Essai du Hamma of Algiers, established under French rule in 1830, re-opened in May 2009 after 5 years of restoration work. Another North African garden that was of major importance for plant introductions is the experimental garden of El Saff about 50 km south of Cairo. A catalogue of the 2,000 species grown there was published by Bircher (1960). Also in Egypt were the experimental gardens of Zohriya (today the Zohira Trial Gardens) Gezireh west of Cairo, in which Delchevalerie (1870) established the first station for acclimatization of plants and where special attention was paid for propagation of tropical fruits such as the breadfruit tree (*Artocarpus altilis*), the sapodilla plum (*Manilkara achras*) and the mango (*Mangifera indica*) (Hamdy et al. 2007) An account of the flora of this garden was published by Delchevalerie (1871) with an update by Bircher (1998).

Mention must also be made of the remarkable plant introduction work carried out by Vavilov and the Institute of Plant Industry (Loskutov 1999) although the focus was mainly on new varieties of crops and did not involve many botanic gardens, an exception being the Nikita Botanical Garden which he said was in essence an agricultural establishment (Vavolov 1992, p. 446).

Botanic gardens and plant introduction today

In recent decades, with an increasing emphasis on conservation activities, plant introduction has not been a major concern of most botanic gardens and has tended to be overshadowed by the work of other institutions or commercial undertakings. Those gardens that are engaged in plant introduction today tend to direct most of their efforts at plants of horticultural merit as in the case of North American botanic gardens and arboreta such as the US National Arboretum, University of British Columbia Botanical Garden, and the consortium of six major botanic gardens and arboreta which form the Plant Collecting Collaborative, although expeditions organized by these gardens also provide plants of other interest, such as medicinal plants for study by ethnobotanists, rare and endangered plants studied for conservation purposes and food plants. The University of British Columbia Botanical Garden Plant Introduction Scheme (PISBG) has been introducing and recommending plants since 1985.[3] In Europe, the Barcelona Botanic Garden is experimenting with plants new to the Mediterranean climate with a view to their later introduction into gardening. In 2000 an agreement was made between the city council and municipalities in

[3] Introduction to the Plant Introduction Scheme of the Botanical Garden of the University of British Columbia (PISBG) http://www.ubcbotanicalgarden.org/research/industry/intro_to_pisbg.php.

the metropolitan area to maintain the Garden and enable the centre to experiment with new plants and methods to promote sustainable gardening.[4]

In some countries, a number of botanic gardens still include the introduction of agricultural, medicinal or other economically important plants as a significant part of their mission today. For example, many of Russia's 80 botanic gardens are plant introduction centres to a greater or lesser degree (Gorbunov 2001). The rich collections of economic plants in botanic gardens are a good basis for applied research which has always been an important part of the activity of Russian botanic gardens. For example, experimental nurseries of aromatic plants were established in some central regions of Russia and the Botanic Garden of the Komi Institute of Biology in Syktyvkar is involved in prospecting for new forage crops in the north of Russia, where it has successfully introduced high yielding cultivars of Sosnowski's hogweed (*Heracleum sosnovskii*), white knotweed (*Polygonum weirichii*), radish (*Rhaphanus sativus*) and comfrey (*Symphytum* spp.). The Central Siberian Botanic Garden, Novosibirsk, is engaged in developing local native plant resources, food and forage plants and cultivars of forage crops with high protein content (Krasnoborov 1998). Botanic gardens in Russia have played a significant role in the introduction of such species as magnolia vine (*Schizandra chinensis*), Chinese gooseberry (*Actinidia kolomikta*), sea buckthorn (*Hippophae rhamnoides*), Nanking cherry (*Cerasus tomentosa*), gumi (*Elaeagnus multiflora*) and species and hybrids of rowan (*Sorbus*), roses (*Rosa*), honeysuckles (*Lonicera*), and blueberry (*Vaccinium*). The Botanic Garden of Moscow State University has introduced more than 20 cultivars of *Hippophae rhamnoides*, which is a valuable crop with a high carotene content in its fruits.

In China, from 1954 onwards plant introduction was scientifically organized and a major function of the newly established botanic gardens was 'the exploitation of wild plant resources, introduction of indigenous and exotic, economic plants, breeding of new varieties so as to enrich the resources of cultivated plants'(Sheng 1980). The Wuhan Botanic Garden has been a centre for the introduction, cultivation, conservation and breeding of Kiwi Fruit (*Actinidia*) since 1980 and holds the world's largest germplasm collection (57 species and 60 cultivars).

The Turpan Eremophyte Botanic Garden, a 7 ha area of sand which was planted with desert arboreal plants, undertook a project on the introduction and cultivation of fine-sand binder plants in association with the Biology Department of the Academia Sinica. Other examples of botanic gardens with special crop-based programmes are given by Sharrock (2006).

Countries are increasingly looking to their native flora as a source of potential ornamental crops, notably Australia (Plummer et al. 2000), Israel (Halevy 2000), South Africa, and E. Asia (Okhawa 2000) and in Latin America, Boyle (1991) has described the genetic resources of the native herbaceous ornamental crops as vital to commercial horticulture. A special Ornamental Plant Germplasm Center was created in the USA in conjunction with the USDA National Plant Germplasm System and Ohio State University (Tay 2003).

Botanic Gardens Conservation International (BGCI) facilitates access to information on species in cultivation in botanic gardens through its Plant Search database.

Acclimatization and acclimatization gardens: back in vogue?

The process of introduction of exotic germplasm was often carried out through the use of acclimatization gardens or stations where the aim was to allow the new plants to adapt to

[4] http://www.jardibotanic.bcn.es/11_eng.htm.

the new environmental conditions. The concept of acclimatization in the sense of gradual adjustment of plants or animals to new climatic or other ecological conditions other than those to which they are accustomed is highly debatable.[5] It is in effect essentially a selection process rather than any physiological adaptation of individual plants or animals although some plants can be hardened off through gradual exposure to colder temperatures (this is sometimes distinguished as 'acclimatation' as opposed to acclimatization) while others succumbed to the cold as even Linnaeus was able to show in his acclimatization trials in the eighteenth century (Koerner 1999). But it was widely practised and the 1860s witnessed a tremendous burst of enthusiasm for acclimatisation experiments for both plants and animals. As Weigl (2003) comments, acclimatization as such was an important aspect of colonialism in that the survival of settlers depended on the successful survival of the plants and animals they brought with them and Hardy (1860) went so far as to say that 'The whole of colonization is a vast act of acclimatization' (transl. by Weigl 2003). Acclimatization societies were established in most of the British colonies. On the other hand, the comment of Francis (1862) 'So new to the world is the subject of acclimatization, as now understood, that it has little literature, and the advocates of it little experience' could almost have been written today as although the subject matter is no longer new, our comprehension of it remains poor.

Acclimatization was a somewhat haphazard affair in the period of the first introductions from America and only in the following centuries were various acclimatization gardens created in Spain for the plants brought from overseas (see detailed discussion by Puerto Sarmiento 2002). Although Cadiz was the main reception centre for seeds and plants during the eighteenth century, arguably the most important acclimatization garden was that of La Orotava on the island of Tenerife, Canary Islands founded in 1788 and still surviving today as a botanic garden. The plants were then transferred to the now defunct botanic garden at the Puerto de Santa Maria before being sent to Madrid. Of course, many of the species successfully cultivated in La Orotava did not survive their subsequent shipment to the mainland or withstand the harsh climate of the Castilian meseta and most of them succumbed. Others could only be grown under protection in orangeries or similar structures which were developed in response to the custom that started towards the end of the fifteenth century of growing oranges, lemons and other tender trees in Europe.

At the Royal Gardens of Aranjuez, Philip II attempted the acclimatization of species from all around the world. Species which fared well included southern magnolia (*Magnolia grandiflora*), tulip poplar (*Liriodendron tulipifera*), sugar maple (*Acer saccharum*), box-elder maple (*Acer negundo*) and black locust (*Robinia pseudoacacia*). In Madrid the Royal Botanic Garden also played a prominent role in both the dissemination of material of the introduced species to other parts of Spain as well as undertaking acclimatization experiments. One of the most celebrated is the Rio de Janeiro Botanic Garden which was founded in 1808 for the introduction and acclimatization of economically beneficial plants brought from other tropical regions of the world.

Much of what is termed acclimatization is no more than successful introduction of exotic organisms. Some biologists are highly critical of the whole concept of acclimatization. Low (2002), for example, calls it 'one of the most foolish and dangerous ideas ever

[5] Folk (1966) gives a detailed discussion of the various often conflicting uses of the term acclimatization. As noted by Mazess (1975) there has been a tendency to use it in the sense of adjustments made by a species over the course of several generations. This is effectively synonymous with 'genetic adaptation' as a result of natural selection and contrasts with the earlier idea of acclimatization being the adjustment of an individual organism to its environment. It is this latter usage that Mazess recommends although the nature and extent of such adjustment remains a subject that needs further consideration.

to infect the thinking of nineteenth-century men'. To some extent, the notion of acclimatization is tainted with its association with the now discredited theories of Lysenko who himself, according to Weiner (1985) attempted 'to identify I. V. Michurin, the horticulturist, as the source of his own inductionist ideas about heredity' although the real roots of these ideas are still shrouded in mystery. On the other hand, the concept of acclimatization is regaining some its earlier interest because of the growing concern with the possibilities of the adaptation of plants to climate change.

Plant introductions and the risk of invasions

While the majority of plant introductions have had a positive result in terms of human welfare (Mack 2005), and indeed few countries could have survived and developed by relying only on their native germplasm, inadvertently some of the introduced species have proved to have characteristics that make them invasive in some regions. Invasive species have mostly been introduced for horticulture through nurseries, botanic gardens or individuals (Reichard and White 2001). It is estimated that 80% of current invasive alien plants in Europe were introduced as ornamental or agricultural plants: seriously invasive plants introduced deliberately as ornamentals include Japanese knotweed (*Fallopia japonica*), summer lilac (*Buddleja davidii*), common rhododendron (*Rhododendron ponticum*) and giant hogweed (*Heracleum mantegazzianum*).

Ironically, the very characteristics that make some species attractive for introduction (ease of propagation, fast-growing, adaptable, high reproductive output, resistance to pests and diseases, tolerant of disturbance and a range of environmental conditions) are the same properties that increase the likelihood of the species becoming invasive (Heywood 1989; Dehnen-Schmutz et al. 2007a; World Bank 2009). Repeated local introductions through market outlets and development of traits that would increase the likelihood of escaped plants establishing themselves are considered equally important in the invasion process (Mack 2000; Kowarik 2003) and in an analysis of the British domestic market from 1885 to 1985, Dehnen-Schmutz et al. (2007a, b) showed that invading species were on average sold by more nurseries than non-invading species and that the probability that a species would escape from cultivation was significantly greater when more frequently available in the market and seeds sold at lower prices.

Botanic gardens, especially in the tropics, are often implicated as a source of plant invaders. One of the earliest examples recorded was that of false acacia (*Robinia pseudacacia*), native to the southern Appalachian and Ozark mountains of the United States, which was introduced to the Jardin Royale des Plantes Médicinales (later the Jardin des Plantes) Paris in 1635 as an ornamental tree by Vespasian Robin (1579–1662). It was subsequently widely cultivated for agricultural and commercial uses and has now become a serious invasive in several areas of the world, including Europe and parts of the USA. The black wattle (*Acacia mearnsii*), one of the world's worst invaders (Lowe et al. 2000, 2004), native to Southeast Australia and Tasmania, was introduced into the Cape Town Botanical Gardens, South Africa in the 1830s and its seeds (along with those of other Australian *Acacia* species and Australian tea tree (*Leptospermum laevigatum*), were then supplied to the Grahamstown Gardens, thus contributing to the infestation of the Eastern Cape. *A. mearnsii* subsequently invaded shrublands, grasslands and savannas and now occupies some 2.5 million ha.

Because botanic gardens are one of the major sources of potentially invasive species, they have an obligation to take active steps to screen new introductions for potential invaders. The risks of introducing invasive plant species and their likelihood of escaping

Table 3 Invasion risks of the collections in the Amani Botanic Garden, Tanzania (from Dawson et al. 2008)

Of the 214 alien plant species surviving from the original plantings in the early twentieth century, 35 had only regenerated, 38 had locally naturalised while 16 had spread widely in the botanical garden. A further 16 species with unclear introduction records in the garden were also found to be naturalised. A greater proportion of introduced species were potentially invasive than might be expected from previous analyses of global floras. Overall, just over half of all naturalised and spreading species were also observed in forest fragments and edges. The proportion of species that had been recorded elsewhere as naturalised/invasive was significantly related to their status in ABG, with 94% of spreading species and 79% of naturalising species being recorded as naturalised or invasive elsewhere, compared to 57% of species that were only regenerating and 49% of species only surviving'.

may be assessed using some form of risk analysis and assessment and various approaches exist (Heywood and Brunel 2009; Reichard 2000). Botanic gardens should consider adopting the International Standard on Phytosanitary Measures No. 11 on Pest Control (ISPM 2004) as adapted by the European and Mediterranean Plant Protection Organization (EPPO 1997) which is in the form of a decision scheme. Various national schemes have been published, for example in the UK (Baker et al. 2008), Australia (Biosecurity Australia 2001), Germany and Austria (Essl et al. 2009). The National Tropical Botanical Garden, Hawaii, USA, has adopted the Hawaii-Pacific Weed Risk Assessment (HWRA) to screen new plant imports as well as its existing collections for potential invasives). The HWRA is a research collaboration between the University of Hawai'i and the US Forest Service which developed and evaluated an adaptation of the Australian/New Zealand Weed Risk Assessment protocol for use in Hawaii and other high Pacific islands.[6] The Hawai'i Exotic Plant Evaluation Protocol provides an additional level of screening[7] (see also Jefferson et al. 2004).

Tropical botanical gardens are considered to have played an important role in the distribution, naturalisation and spread of non-native plants worldwide and Dawson et al. (2008) used the Amani Botanical Garden (ABG), Tanzania, as a case study to highlight appropriate methods to assess the risks posed by existing and future collections in such gardens. The results of the study are summarized in Table 3.

Plant introduction and global change

With the growing world population and an estimated required doubling in food production needed by 2050, we are now facing demands for a major acceleration in the development of improved crops with higher productivity. There will be parallel demands for improved industrial and energy crops (El Bassam 1996). A substantial increase in research is needed, ranging from genetic and ecophysiological studies and screening for suitable germplasm, to understanding and characterising the growth and function of plant phenotypes as a whole (plant phenomics).

Accelerated climate change will have serious consequences for horticulture, agriculture and forestry with displacements of the major cultivation zones in some parts of the world. This will lead to a demand for the introduction of new and adaptable exotic species for agriculture and to meet increasing demands for biofuels and restoration and reforestation

[6] For details see: http://www.botany.hawaii.edu/faculty/daehler/wra.

[7] http://www.hear.org/wra/hpwra/evalofexplihi.pdf.

(World Bank 2009). In addition, crop cultivars will in many cases need to be reengineered so as to be suitable for the new range of environmental conditions in the displaced climatic zones, such as day-length, soil conditions, water quality and availability. Crop wild relatives will assume an even greater importance as sources of desirable characteristics to develop cultivars adapted to these new conditions.

We are presently over-dependent on a few plant species: global food security relies increasingly on a handful of crops with more than half of the daily global requirement of proteins and calories being met by just three crops—maize, wheat and rice; only 103 species of food plant provide 80% of our per capita supplies (Prescott-Allen and Prescott-Allen 1990); and only 150–200 crops are grown commercially on a significant global scale. On the other hand, ethnobotanical surveys indicate that, worldwide, more than 7–8,000 plant species are cultivated or harvested from the wild (Rehm and Espig, 1991). While we will continue to rely on the major staples for our basic nutrition, the need to broaden the basis of agricultural production and diversification of crops, especially those that are termed 'underutilized', with a view to making a significant contribution to improved health and nutrition, livelihoods, household food security and ecological sustainability is now receiving increasing attention (e.g. Batello et al. 2004; Frison et al. 2006; Heywood 2008; WRI 2005).

Underutilized crops are difficult to define and various terms have been applied to them such as 'neglected', orphan', 'minor', 'promising', 'niche' and 'traditional' which are often used interchangeably. The Strategic Framework for Underutilized Plant Species Research and Development (Jaenicke and Höschle-Zeledon 2006) uses the following definition: 'those species with under-exploited potential for contributing to food security, health (nutritional/medicinal), income generation, and environmental services'. Most of these species form part of local dietary complexes and are grown on a small scale in traditional agricultural systems alongside or to complement the staples that are cultivated. Many if not most of them are at the lower end of the domestication spectrum while others are wild-harvested (Heywood 1999a, b). They not only add variety to local diets but often supply much if not most of the daily requirements for vitamins, minerals and trace elements (Guarino 1997; Ogle et al. 2001). Recently two of the major initiatives involved in developing these resources, the Global Facilitation Unit for Underutilized Species and The International Centre for Underutilised Crops (ICUC), combined forces as Crops for the Future,[8] which is hosted in Malaysia by Bioversity International in a joint venture with the University of Nottingham, Malaysia Campus. A global search has begun for food crops with traits that are able to withstand changes to the climate. The project, co-ordinated by the Global Crop Diversity Trust, is searching national seed banks for 'climate proof' varieties, including maize and rice. The team will screen seeds for natural resistance to extreme events, such as floods, droughts or temperature swings. They hope the strains will help protect food production from the impacts of climate change.

Another important initiative was the launch in 2006 of the Global Horticulture Initiative (GHI) following 2 years of consultations involving ISHS, AVRDC, CIRAD, the Consultative Group on International Agricultural Research (CGIAR), the Global Forum for Agricultural Research (GFAR), some key national agencies for international development (USAID, GTZ, CIDA, CTA and others), and many other agencies, institutes and universities. 'The motivating idea was that the value of horticulture enterprise for improving incomes and life quality in developing countries has been seriously under-recognized. It follows therefore that agencies conducting or supporting research for development should

[8] http://www.cropsforthefuture.org/.

put greater emphasis on horticulture and a “Global Initiative” is needed to initiate, coordinate, and advocate for more horticulture research for development’(Anon 2006).

Globally botanic gardens are custodians of as many as 100,000 species of cultivated plants and countless cultivars, some of which have considerable potential for development and exploitation. Many gardens do not, however, have a collections policy and much of what is cultivated is the result of ‘serendipitous collectionism’, owing more to the transient interests of individual staff members than to any institutional policy decision. The collections are often of limited value scientifically or as conservation material because of their inadequate sampling, documentation and long-term sustainability (Laliberté 1997; Heywood 1999a, b, 2009b) although some of these collections are spectacular and attract great public interest.

If one considers that most of the underutilized species are local and seldom attract the attention of commercial companies or agricultural development agencies, there is clearly a gap that botanic gardens might be able to help fill. This will often involve working with local communities and integrating community-based action on indigenous crops and wild-collected or semi-domesticated species and traditional knowledge into climate change adaptation strategies. BGCI has encouraged gardens to play a more active role through its recent report *Botanic gardens linking biodiversity with improvements to human well-being* (Waylen 2006) and a number of botanic gardens are engaged in promoting the cultivation and use of local, underutilized plants for improved nutrition and health among their local communities (Waylen 2006; Sharrock 2008). So far, not many are involved in such developments, reflecting the tendency of botanic gardens not to form close links with commercial horticulture or participate in the activities of such bodies as the International Society for Horticultural Science (ISHS).

Climate change and the potential spread of invasive alien plants

A recent World Bank report (2009) notes that ‘Climate change is likely to aid the spread of invasive alien species, further threatening agricultural productivity and food security through spread of weeds, pests, and diseases of crops and livestock. The introduction of new and adaptable exotic species for agriculture and to meet increasing demands for biofuels, mariculture, aquaculture, and reforestation presents a particular challenge.

It is likely that there will be an increasing demand from the gardening public for species that will be more suited to growing in the new ecoclimatic conditions. The indirect effects of climate change, such as shortage of water, will have a serious impact on gardening and the kinds of plantings. An increase in demand for drought-resistant plants such as cacti and succulents is to be expected. The higher temperatures will increase the number and diversity of species that can be cultivated in some countries while in other countries these temperatures will cause stress and restrict the growth of many species. Flowering and fruiting times of some species will be affected and there will be a demand for new cultivars adapted to the new ecoclimatic conditions. The selection of trees cultivated will have important impacts on our landscapes. In some regions, species that can only be cultivated with difficulty today will prosper and some of them will escape from cultivation, becoming invasive.

As I have noted elsewhere (Heywood 2009a), perhaps the greatest dormant risk is the large number of plant species grown in gardens that currently survive outside their optimal climatic conditions in the reduced competition environment of cultivation. The great range of southern Mediterranean and South African grasses that are now becoming popular garden plants may offer the greatest threat yet to the native flora of Europe as these grasses are being chosen specifically for their toughness and ability to survive greater climatic extremes.

Another development that carries with it considerable potential risks is the expansion of the installation of green roofs and living walls. According to a recent report, 'more than 14% of flat roofs in Germany have been greened and in Switzerland this number has reached 12%. In Asia, a city such as Tokyo requires today that all new buildings greater than 1,000 m^2 must have 20% of their roof surface greened; the objective is to reduce temperatures in the city by 1°C. In North America, green roof surface area has increased by 30% in 2007, attaining a total of 370,000 m^2 (Trépanier et al. 2009). Although these initiatives are very much to be welcomed as a contribution to the sustainable use of roof space and the reduction of the carbon footprint of buildings, care need to be exercised in the selection of species to be used for this purpose. So far, the green roofs and walls have incorporated only a small number of species, often drought tolerant stonecrop (*Sedum* spp.) with little invasive potential, but these new growing spaces are now attracting more creative horticultural use and this has led to a much wider range of species being introduced from other parts of the world. Moreover, these species are being selected for their ability to establish from seed on substrates such as crushed concrete and other industrial waste in the harsh environment of a green roof (Hitchmough 2008). Such pre-selection for tolerance and competitiveness could result in an alarming scenario whereby an elite set of introductions will spread from their roof and wall habitats along roads and pavements through cities and into suburban areas, generating a wave of weedy but decorative invasive.

Concern has been expressed at the possible risks of some of the species being introduced as biofuel crops becoming invasive. Buddenhagen et al. (2009) for example comment that 'Despite reservations about their adverse environmental impacts, no attempt has been made to quantify actual, relative or potential invasiveness of terrestrial biofuel crops at an appropriate regional or international scale, and their planting continues to be largely unregulated'.

Botanic gardens and domestic gardens can be unintentional agents of assisted migration. In a recent study, Van der Veken et al. (2008) compared the native ranges of 357 native European plant species with their commercial ranges, based on data from the holdings of 246 plant nurseries throughout Europe and found that in 73% of native species, the commercial northern range limits exceeded natural northern range limits, with a mean difference of ~1000 km. They comment that 'With migration rates of ~0.1–5 km per year required for geographic ranges to track climate change over the next century, we expect nurseries and gardens to provide a substantial head start on such migration for many native plants. While conservation biologists actively debate whether we should intentionally provide "assisted migration", it is clear that we have already done so for a large number of species'.

Need for adoption of stricter guidelines and protocols

Since the coming into effect of the Convention on Biological Diversity, plant introduction has to operate under a new and developing regime of access and benefit sharing. Botanic gardens must ensure that the recently adopted Bonn Guidelines on Access to Genetic Resources and Fair and Equitable Sharing of the Benefit are properly implemented (CBD 2002). Gone are the days of free and unlimited access to plant resources across the world, sometimes referred to as colonial, ecological or green imperialism (Brockway 1979; Crosby 1986; Grove 1995; Drayton 2000), now replaced by national sovereignty and often quite severe access restrictions. Some botanic gardens have developed protocols or agreements for plant collecting which ensure the sharing with the host country of any benefits that might be derived from the use and exploitation of plant material collected. In the United Kingdom, several of the major Botanic Gardens, such as Royal Botanic Garden Edinburgh, National Botanic Gardens, Glasnevin and Royal Botanic Gardens Kew have already implemented guidelines compliant with the CBD to their own collections whereby they will only accept, exchange or transfer plants with organizations or individuals that they are confident will treat the material with due regard and undertake the same responsibility in growing it and in its further distribution. A requirement is that no plant material can be accepted without proof that it was collected in a *bona fide* manner with the appropriate agreements and Prior Informed Consent of the countries of origin (PlantNetwork 2009). Many European botanic gardens belong to the International Plant Exchange Network (IPEN), an exchange system for botanic gardens for non-commercial exchange of plant material, based on the CBD. Gardens joining the network must sign and abide by a Code of Conduct that sets out gardens' responsibilities for acquisition, maintenance and supply of living plant material and associated benefit-sharing. To ensure proper compliance with the access and benefit sharing requirements under the CBD, such agreements should become the norm. There is also a voluntary International Code of Conduct for Plant Germplasm Collecting and Transfer developed by FAO in 1993[9] which aims to promote the rational collection and sustainable use of genetic resources, to prevent genetic erosion, and to protect the interests of both donors and collectors of germplasm.

Although botanic gardens have been exchanging plants within the confined circles of the global botanic garden estate, through the *Index Seminum* (Seed List) system or by despatch of living plants, they are not usually suited to the commercial dissemination of new introductions, a role that corresponds primarily to the horticultural trade, especially nurseries. The introduction of species, especially ornamentals, into cultivation is an important and largely untapped field for many botanic gardens today and deserves much further consideration (cf. Heywood 2003). There is however a need to work in much closer cooperation with the horticultural trade than has been customary in many instances. As Del Tredici (2000) points out, the relationship of botanic gardens to the plant introduction process differs from that of the horticultural trade, with the latter more focussed on the distribution of plants than on their ecology or taxonomy. 'Given this complementary division of both labor and interest it makes sense for botanical gardens and nurseries to cooperate with one another on the introduction of new plants.' Example of such cooperation can be found in Australia at the National Botanic Garden, Canberra where about 30 plants from the wild are cultivated each year and passed to the Australian Nurserymans Association for distribution to the general public. In addition, the Nursery Industry Association of Australia has very much concerned itself with environmental issues and with the commercial exploitation of native species: many rare or threatened Australian species are now established in nurseries and grown in gardens working in association with the Australian National and other botanic gardens.

Guidelines and codes of conduct for invasive species

As Dawson et al. (2008) point out, little appropriate guidance is normally available to botanic gardens regarding risk assessments of botanic garden collections. Because botanic

[9] http://www.fao.org/ag/aGp/agps/pgr/icc/icce.htm.

gardens are one of the major sources of potentially invasive species, they have an obligation to take active steps to screen new introductions for potential invaders and a growing number of gardens are adopting policies to this end.

Several of the IUCN Guidelines (2002) are highly relevant to botanic gardens, for example:

- ‘ex situ *c*onservation should only be initiated when an understanding of the target taxon’s biology and ex situ management and storage needs are at a level where there is a reasonable probability that successful enhancement of species conservation can be achieved; or where the development of such protocols could be achieved within the time frame of the taxon’s required conservation management, ideally before the taxa becomes threatened in the wild. Ex situ institutions are strongly urged to develop ex situ protocols prior to any forthcoming ex situ management. Consideration must be given to institutional viability before embarking on a long term ex situ project’.
- ‘all ex situ populations should be managed so as to reduce the risk of invasive escape from propagation, display and research facilities. Taxa should be assessed as to their invasive potential and appropriate controls taken to avoid escape and subsequent naturalisation’

The Council of Europe has prepared a Code of conduct on horticulture and invasive alien plants (Heywood and Brunel 2009) and at a national level, the United Kingdom has published a Code of Practice for Horticulture aimed at preventing the spread of alien invasive species (DEFRA 2005). Other Codes or guidelines aimed specifically at botanic gardens include the German-Austrian Code of Conduct for the cultivation and management of invasive alien plants in Botanic Gardens (Kiehn et al. 2007). In the USA, the St Louis Voluntary Codes of Conduct that arose out of a workshop “Linking Ecology and Horticulture to Prevent Plant Invasions” that was held at the Missouri Botanical Garden in St.Louis in December 2001, includes a Code for Botanical Gardens and Arboreta (Fay et al. 2001). A follow-up workshop was held in 2002 at Chicago Botanic Garden (Fay et al. 2002). Several US botanic gardens have endorsed the Voluntary Codes. However, as Dehnen-Schmutz and Touza (2008) point out, such codes or guidelines have no specific targets or time-frame and their effectiveness depends largely on how well they are promoted.

Summary: broadening the mission

Global change is causing a major reassessment of our priorities in many aspects of human activity including nutrition and food supply, health, development of energy crops, agriculture, horticulture, forestry, monitoring of, adaptation to and mitigation of climate change, and a wide range of conservation activities (including education). There will be a need for new plant introductions and breeding of appropriate germplasm. Botanic gardens have an unprecedented opportunity to play a part in many of these activities using their unrivalled skills and experience of growing, establishing and propagating plants. It is suggested that botanic gardens consider:

1. Broadening the plant introduction and exploration mission so that they can respond to some of the demands for new germplasm in response to climate change and not just for ornamental horticulture. Botanic gardens should consider working more closely with the agricultural and genetic resources communities in areas such as collection and conservation of:

- crop wild relatives for which there will be an increasing demand in the face of global change;
- economically and socially valuable wild species such as those which contribute significantly to nutrition and health; and
- minor and underutilized crops, including oil and energy crops

and working with local communities in the assessment, evaluation and improvement of local crops and semi-domesticates

2. Closer cooperation with agricultural genebanks. Botanic gardens and agricultural genebanks have different strengths and missions but they are complementary and there are obvious opportunities for synergies which will further both the mission of plant introduction and the global conservation effort.
3. Forging agreements between botanic gardens and the agricultural sector on precisely which species/species categories/genepools should be their conservation responsibilities so as to avoid duplication of effort
4. Improving the quality and sampling of accessions. Consideration should be given to defining rigorous standards in cooperation with the genetic resources sector for collecting, conserving and documenting activities, including:
   - sampling procedures,
   - seed and in vitro storage conditions,
   - viability testing procedures, accession sizes, and
   - adopting and adapting ecogeographical survey techniques and sampling protocols.
5. Undertaking proper evaluation and assessment of plant introductions before they are disseminated. Getting the plants into the country is not the most important part of the introduction programme but the first step.
6. Information on the accessions of introduced plants and their fate and its dissemination. The essence of any botanic garden is the plant collections that it grows and globally botanic garden accessions represent an extraordinary network of centres of plant diversity (albeit mainly cultivated) and constitute a major but much undervalued and certainly underutilized biodiversity resource. Despite the best efforts of BGCI and other bodies to assemble data on botanic garden holdings, it remains remarkably difficult to find out what is out there in the collections of the world's botanic gardens, let alone any details of the accessions, how to grow and propagate them, which gardens hold duplicates, and so on.
7. Taking full cognizance of policies to protect against invasive species and due care taken to evaluate the risks that new introductions might represent. Consideration should be given to preparing a set of guidelines or even a code of conduct for plant introductions by botanic gardens in association with other agencies.

References

Anon (2006) Launch of the global horticulture initiative chronica horticulturae 46 No. 2: 4

Ault JR (ed) (2000) Plant exploration: protocols for the present, concerns for the future. In: Symposium proceedings. Chicago Botanical Garden, Glencoe, IL, 18–19 March 1999

Baker RHA, Black R, Copp GH et al. (2008) The UK risk assessment scheme for all non-native species. In: Rabitsch W, Essl F, Klingenstein F (eds) Biological invasions—from ecology to conservation. Neobiota vol 7, pp 46–57

Batello C, Marzot M, Touré AH (2004) The future is an ancient lake. Traditional knowledge, biodiversity and genetic resources for food and agriculture in Lake Chad Basin ecosystems. FAO, Rome
Biosecurity Australia (2001) Draft guidelines for import risk analysis. Department Agriculture Fisheries and Forestry Australia, Canberra. http://www.daff.gov.au/corporate_docs/publications/word/market_access/biosecurity/iraguidelines.doc
Bircher WH (1960) Gardens of the Hesperides. Cairo, p 875
Bircher WH (1998) Delchevalerie "les plantes exotiques cultivées enEgypte", an updated english version. Taeckholmia 18(2):1–111
Boyle TH (1991) The genetic resources of Latin America's herbaceous ornamental crops–vital to commercial floriculture. Diversity 7:50–51
Brockway LH (1979) Science and colonial expansion the role of the British royal botanic gardens. Academic Press, New York, London
Buddenhagen CE, Chimera C, Clifford P (2009) Assessing biofuel crop invasiveness: a case study. PLoS ONE 4(4):e5261. doi:10.1371/journal.pone.0005261
CBD (2002) Secretariat of the convention on biological diversity Bonn guidelines on access to genetic resources and fair and equitable sharing of the benefits arising out of their utilization. Secretariat of the Convention on Biological Diversity, Montreal
Crosby AW (1986) Ecological imperialism. The biological expansion of Europe, 900–1900. Cambridge University Press, Cambridge
Cunningham IS (1984) Frank N. Meyer: Plant hunter in Asia. Iowa State University Press, Ames, Iowa
Dawson W, Mndolwa AS, Burslem D, Hulme PE (2008) Assessing the risks of plant invasions arising from collections in tropical botanical gardens. Biodivers Conserv 17:1979–1995
DEFRA (2005) Helping to prevent the spread of invasive non-native species. Horticultural Code of Practice, DEFRA, London. http://www.defra.gov.uk/wildlife-countryside/non-native/pdf/non-nativecop.pdf
Dehnen-Schmutz K, Touza J (2008) Plant invasions and ornamental horticulture: pathway, propagule pressure and the legal framework. In: Teixeira da Silva JA (ed) Floriculture, ornamental and plant biotechnology: advances and topical issues. Global Science Books, Isleworth, UK, pp 15–21
Dehnen-Schmutz K, Touza J, Perrings C, Williamson M (2007a) A century of the ornamental plant trade and its impact on invasion success. Divers Distrib 13:527–534
Dehnen-Schmutz K, Touza J, Perrings C, Williamson M (2007b) The horticultural trade and ornamental plant invasions in Britain. Conserv Biol 21:224–231
Delchevalerie G (1870) Cultures égyptiennes, Plantes tropicales utiles, officinales et industrielles qu'il conviendrait d'introduire sous le 30^{e} degré de lattitude d'Égypte et ses avoisinants. Namur, Typogr. de Paul Godenne, Librairie
Delchevalerie G (1871) Flore exotique du jardin d'acclimatation de Guézireh et des domaines de S. A. le Khédive. Le Caire, Typographie française Delbos-Demouret
Del Tredici P (2000) Plant exploration: a historic overview. In: Ault JR (ed) Plant exploration: protocols for the present, concerns for the future, symposium proceedings. Chicago Botanical Garden, Glencoe, IL, 18–19 March 1999
El Bassam N (1996) Renewable energy. Potential energy crops for Europe and the mediterranean region REU technical series 46. Federal Agricultural Research Centre, Braunschweig and FAO, Rome
EPPO Standard PM 5/3 (2) (1997) Decision-support scheme for quarantine pests. www.eppo.org
Essl F, Klingenstein F, Nehring S, Otto C, Rabitsch W, Stöhr O (2009) Schwarze Listen invasiver Arten—ein wichtiges instrument für den Naturschutz! Natur und Landschaft (in press)
European Garden Flora Editorial Committee (1984–2000) European garden flora. A manual for the identification of plants cultivated in Europe, both out-of-doors and under glass, vols 1–6. Cambridge University Press, Cambridge
Fay K, Fay KC et al (2001) Proceedings of the Workshop at the Missouri Botanical Garden, St. Louis, Missouri, 1–4 December 2001. http://www.centerforplantconservation.org/invasives/Download%20PDF/Proceedings_FINAL.pdf
Fay K, Fay KC et al (2002) Proceedings of the Workshop II at the Chicago Botanic Garden, Chicago, Illinois, 31 October 2002. http://www.centerforplantconservation.org/invasives/Download%20PDF/CBG_Proceedings.pdf
Folk GE Jr (1966) Introduction to environmental physiology. Lea & Febiger, Philadelphia
Francis GW (1862) The acclimatisation of harmless, useful, interesting, and ornamental, animals and plants, being a paper read before the philosophical society, Adelaide, South Australia on May 13th, 1862. Published by the Philosophical Society for gratuitous distribution, Adelaide
Frison EA, Smith IF, Johns T, Cherfas J, Eyzaguirre PB (2006) Agricultural biodiversity, nutrition, and health: making a difference to hunger and nutrition in the developing world. Food Nutr Bull 27(2): 167–179

Gorbunov YN (2001) The role of Russian botanic gardens in the study and development of economic plants. BGCNews 3, No. 7

Gribbin M, Gribbin J (2008) Flower hunters. Oxford University Press, Oxford

Grove RH (1995) Green imperialism. Colonial expansion, tropical island edens and the origins of environmentalism, 1600–1860. Cambridge University Press, Cambridge

Guarino L (ed) (1997) Traditional African vegetables. Promoting the conservation and use of underutilized and neglected crops. 16. Proceedings of the IPGRI international workshop on genetic resources of traditional vegetables in Africa: conservation and Use, 29–31 August 1995, ICRAF-HQ, Nairobi, Kenya. Institute of Plant Genetics and Crop Plant Research, Gatersleben/International Plant Genetic Resources Institute, Rome

Halevy AH (2000) Introduction of native Israeli plants as new cut flowers. In: IV International symposium on new floricultural crops. Acta Horticulturae 541

Hamdy RS, Abd El-Ghani MM, Youssef TL, El-Sayed M (2007) The floristic composition of some historical botanical gardens in the metropolitan of Cairo, Egypt. Afr J Agric Res 2(11):610–648

Hardy A (1860) L' Algérie agricole commerciale, industrielle. Paris

Heywood VH (1985) Botanic gardens and taxonomy–their economic role. Bull Bot Survey India 25: 134–147

Heywood VH (1989) Patterns, extents and modes of invasions by terrestrial plants, Chap 2. In: Drake JA, Mooney HA, di Castri F, Groves RH, Kruger FJ, Rejmánek M, Williamson M (eds) Biological invasions. A global perspective. Wiley, Chichester

Heywood VH (1993) Broadening the basis of plant resource conservation. In: Gustafson JP, Appels R, Raven P (eds) Gene conservation and exploitation l–13. Plenum Press, New York

Heywood VH (1999a) The role of botanic gardens in ex situ conservation of agrobiodiversity. In: Gass T, Frese L, Begemann F, Lipman E (eds) Implementation of the global plan of action in Europe–conservation and sustainable utilization of plant genetic resources for food and agriculture. Proceedings of the European Symposium, 30 June–3 July 1988, Braunschweig, Germany. International Plant Genetic Resources Institute, Rome, pp 102–107

Heywood VH (1999b) Use and potential of wild plants in farm households, farm systems management series 15. FAO, Rome

Heywood VH (2003) Conservation and sustainable use of wild species as sources of new ornamentals. In: Düzyaman E, Tüzel Y (eds), Proceedings of the international symposium on sustainable use of plant biodiversity to promote new opportunities for horticultural production development. Acta Horticulturae 598, 43–53

Heywood VH (2006) Changing attitudes to plant introduction and invasives. In: S Brunel (ed) Invasive plants in mediterranean type regions of the world 119–128. Environmental Encounter Series No. 59, Council of Europe, Strasbourg

Heywood VH (2008) The use and economic potential of wild species: an overview, chap 43. In: Maxted N, Ford-Lloyd BV, Kell SP, Iriondo JM, Dulloo ME, Turok J (eds) 2008: crop wild relative conservation and use. CABI, Wallingford

Heywood VH (2009a) The impacts of climate change on plant species in Europe. Convention on the conservation of European wildlife and natural habitats T-PVS/Inf (2009) 9, Council of Europe, Strasbourg

Heywood VH (2009b) Sibbaldia guest essay botanic gardens and genetic conservation. Sibbaldia No. 7 (in press)

Heywood V, Brunel S (2009) Code of conduct on horticulture and invasive alien species. Nature and Environment No. 155. Council of Europe Publishing, Strasbourg

Hitchmough JD (2008) Climate change: new ecology and planting opportunities. Talk to plant network conference climate change and planting for the future. http://www.plantnetwork.org/proceeds/westonbrt2008/14hitchmough/slide00.htm

Holttum RE (1970) The historical significance of botanic gardens in S.E. Asia. Taxon 19:707–714

IUCN (International Union for Conservation of Nature) (2002) IUCN technical guidelines on the management of ex-situ populations for conservation. As approved at the 14th meeting of the programme committee of IUCN council, Gland, Switzerland on 10th December 2002. http://intranet.iucn.org/webfiles/doc/SSC/SSCwebsite/Policy_statements/IUCN_Technical_Guidelines_on_the_Management_of_Ex_situ_populations_for_Conservation.pdf

ISPM (2004) International standards for phytosanitary measures No. 11. Pest risk analysis for quarantine pests, 2001. FAO, Rome

Jaenicke H, Höschle-Zeledon (eds) (2006) Strategic framework for underutilized plant species research and development, with special reference to Asia and the Pacific, and to Sub-Saharan Africa. International

centre for underutilised crops, Colombo, Sri Lanka and Global Facilitation Unit for Underutilized Species, Rome, Italy
Jefferson L, Havens K, Ault J (2004) Implementing invasive screening procedures. Chicago Bot Gar Model Weed Technol 18(sp1):1434–1440
Kaplan JK (1998) Conserving the world's plants. Agric Res Mag 46(9):4–9
Kiehn M, Lauerer M, Lobin W, Schepker H, Klingenstein F (2007) Grundsätzen im Umgang mit invasiven und potentiell invasiven Pflanzenarten in Botanischen Gärten des Verbandes Botanischer Gärten und der AG Österreichischer Botanischer Gärten. Gärtnerisch-Botanischer Brief 169(4):39–41
Koerner L (1999) Linnaeus: nature and nation chapter 6. Harvard University Press, Cambridge
Kowarik I (2003) Human agency in biological invasions: secondary releases foster naturalisation and population expansion of alien plant species. Biol Invasions 5:293–312
Krasnoborov IM (1998) The role of Siberian botanical gardens in food security principles development. Proceedings of the 5th international botanic gardens conservation congress, Kirstenbosch, South Africa, 14–18 September 1998. www.bgci.org/congress/congress_1998_cape/html/krasnoborov.htm
Laliberté B (1997) Botanic garden seed banks/genebanks worldwide, their facilities, collections and network. Bot Gar Conserv News 2:18–23
Loskutov IG (1999) Vavilov and his Institute. A history of the world collection of plant genetic resources in Russia. Int Plant Genet Resour Inst, Rome
Low T (2002) Feral future. The untold story of Australia's exotic invaders. University of Chicago Press
Lowe S, Browne M, Boudjelas S, De Poorter M. (2000, 2004) 100 of the world's worst invasive alienspecies a selection from the global invasive species database. The invasive species specialist group (SSC/ISSG), IUCN), first published as special lift-out in *Aliens 12*, December 2000. Updated and reprinted version Nov 2004
Mack RN (2000) Conservation fosters plant naturalization by reducing environmental stochasticity. Biol Invasions 2:111–122
Mack RN (2005) Predicting the identity of plant invaders: future contributions from horticulture. HortScience 40:1168–1174
Malanima P (2006) Energy crisis and growth 1650–1850: the European deviation in a comparative perspective. J Glob Hist 1:101–121
Mazess RB (1975) Biological adaptation: aptitudes and acclimatization. In: Watts ES, Johnston FE, Lasker GW (eds) Biosocial interrelations in population adaptation. Mouton Publishers, The Hague
Ogle BM, Grivetti ME (1985) Legacy of the chameleon. Edible wild plants in the kingdom of Swaziland, Southern Africa. A cultural, ecological, nutritional study. Part 2. Demographics, species availability and dietary use, analysis by ecological zone. Ecol Food Nutr 17:1–30
Ogle BM, Ha-Thi AD, Mulokozi G, Hambraeus L (2001) Micronutrient composition and nutritional importance of gathered vegetables in Vietnam. Int J Food Sci Nutr 52:485–499
Okhawa K (2000) Flower industry in northeast Asia: development and introduction of new crops. In: IV international symposium on new floricultural crops. Acta Horticulturae 541
PlantNetwork (2009) Strategic plan 2006–2010. CBD and plant collections. http://www.plantnetwork.org/strategy.htm. Accessed 30 July 2009
Plummer JA, Considine JA, Yan G, Hall D, Alford T, Seaton K, Growns D, Newell C, Webb M (2000) New developments from the Centre for Australian plants. In: IV International symposium on new floricultural crops. Acta Horticulturae 54
Prescott-Allen R, Prescott-Allen C (1990) How many plants feed the world? Conserv Biol 4:365–374
Primack RB, Miller-Rushing AJ (2009) *Tansley review*. The role of botanical gardens in climate change research. New Phytol 182:303–313
Puerto Sarmiento FJ (2002) Jardines de aclimatación en la España de la Ilustración. Ciencias 68 Octubre-Diciembre. http://www.ejournal.unam.mx/ciencias/no68/CNS06804.pdf
Purseglove JW (1959) History and functions of botanic gardens with special reference to Singapore. Gard Bull Singap 17:125–154
Rehm S, Espig G (1991) The cultivated plants of the tropics. Verlag Josesf Margraf and CTA, Weikersheim, Germany
Reichard SH (2000) Screening and monitoring for invasive ability. In: Ault JR (ed) Plant exploration: protocols for the present, concerns for the future. Chicago Botanic Garden, Glencoe, IL
Reichard SH, White P (2001) Horticulture as a pathway of invasive plant introductions in the United States. Bioscience 51:1103–1113
Sharrock S (2006) The role of botanic gardens in the conservation of crop wild relatives. BGjournal 3(1):16–19
Sharrock S (2008) Botanic gardens—promoting the use of underutilized plants for improved nutrition and health. Acta Hortic (ISHS) 806: 615–620. http://www.actahort.org/books/806/806_76.htm

Sheng CK (1980) Plant introduction and botanic gardens in China. Plant Sci Bull 26:25–28
Stuart D (2002) The plants that shaped our gardens. Harvard University Press, Cambridge, Mass
Tay D (2003) The herbaceous ornamental plant genebank: its role in the floriculture industry. Acta Hort (ISHS) 624:29–36. http://www.actahort.org/books/624/624_3.htm
The St Louis Declaration on Invasive Plant Species (2002) In: Linking ecology and horticulture to prevent plant invasions. Proceedings of the workshop at the Missouri botanical garden, St. Louis, Missouri, 1–4 December 2001. Appendix A. Missouri Botanical Garden, St Louis, Missouri
Trépanier M, Boivin M-A, Lamy M-P, Dansereau B (2009) Green roofs and living walls chronica. Horticulturae 49(2):5–7
Van der Veken S, Hermy M, Vellend M, Knapen A, Verheyen K (2008) Garden plants get a head start on climate change. Frontiers in Ecology and the Environment 6:212–216
Vavolov NI (1992) Origin and geography of cultivated plants. Translated by Doris Löve. Cambridge University Press, Cambridge
Ward BJ (2004) The plant hunter's garden. The new explorers and their discoveries. Timber Press, Portland, Oregon & Cambridge, UK
Waylen K (2006) Botanic Gardens: using biodiversity to improve human well-being. Botanic Gardens Conservation International, Richmond, UK
Weigl E (2003) Acclimatization: the Schomburgk brothers in South Australia. Humboldt im Netz. Int Rev Humboldt Stud 4(7):1–13. http://www.uni-potsdam.de/u/romanistik/humboldt/hin/hin7/inh_weigl_1.htm
Weiner DR (1985) The roots of 'Michurinism': transformist biology and acclimatization as currents in the Russian life sciences. Ann Sci 42:243–260
World Bank (2009) Convenient solutions to an inconvenient truth: ecosystem-based approaches to climate change. Environment Department, The World Bank, Washington, DC
WRI (2005) World resources 2005 – the wealth of the poor: managing ecosystems to fight poverty. World Resources Institute, Washington DC