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Research in botanical gardens

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Abstract

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C. 35,000 vascular plant species representing 15 % of the world's flora are presently cultivated in botanic gardens. They constitute an important potential for pure and applied research in many fields that depend on living plant material (especially if observations over prolonged periods of time are required), such as morphology, anatomy, cytology, physiology, biochemistry, autecology, reproductive biology and pathology. This potential appears, at present, to be greatly underutilized. Among the measures proposed in order to improve this situation are the substitution of items of undocumented source by plants of known wild origin; the systematic, permanent recording of the working garden staff's experience with plants under cultivation; the devising of improved systems to register and locate each garden's holdings, using computerized information retrieval systems that must be generally accessible and ultimately international; and, as a further step, a coordination of the individual gardens' holdings, collecting activities, exchange programmes etc. Thereby also another essential function of botanic gardens, *i.e.*, to serve (together with associated seed banks) as repositories for the world's plant diversity now so dramatically threatened in the wild, could be effectively improved. [Editors' abstract]

The botanical gardens that were established in Europe starting about 450 years ago were designed primarily to exhibit medicinal plants for the instruction of medical students (Stafleu 1969). It was not until about 300 years ago, however, toward the close of the 17th century, at the time of formation of the Berlin Botanical Garden, that people began to think in terms of preparing comprehensive accounts of all living organisms, and trying to assemble collections that were as complete as possible in their botanical gardens, zoos, and aquariums (Stearn 1961, 1971). By 1720, there were some 6000 kinds of plants in cultivation in the Botanical Garden at Leiden, largest that had been assembled up to that time (Stafleu 1969). As overwhelming numbers of new plants were encountered successively in the Cape, in Australia, and finally in Latin America, however, it became evident that there were far too many kinds of plants to be grown together in one place. In an effort to cope with this diversity, comprehensive botanical institutions, many of which were still called botanical gardens, grew up from the early 19th century onward.

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These usually included herbaria and libraries, and often extensive research facilities of other kinds.

Since the term „botanical garden" is, at least for some institutions — Berlin, Kew, Geneva, Lucknow, New York, and Sydney are a few of these — synonymous with „botanical research institute," it should not be surprising that all kinds of research concerning plants have been carried out at places called botanical gardens. At their broadest extension, botanical gardens may have on their grounds physiological laboratories, large herbaria with their own programs more or less related to the living collections, or even collections or museums of art objects, historical houses, or recreational facilities.

All of these combinations of elements have developed for historical reasons, and they go together to form the many, diverse, and vigorous institutions that share the name „botanical gardens" today. In them, research is not always featured; for example, in a recent survey only 10 % of botanical gardens in the United States and Canada (out of a total sample of 145) listed research as their primary purpose. Regardless of how the gardens perceive their own role, however, their collections of living plants do have great potential for studies of many kinds, as we shall discuss below. Furthermore, as WAGNER (1972: 6) has put it so well, a „botanical garden" with no research at all is little more than a kind of park; with research, such a garden develops a more profound significance to society.

In this paper, the focus will be on that research which deals with the living plant collections, the common element that gives botanical gardens their name. Herbaria and specific laboratories will be considered only to the extent to which they are related to the living collections, and as is well known, the relationship is often simply one of mutual proximity. For many groups of plants, however, among which cacti, bromeliads, and orchids are notorious, herbarium specimens are prepared with such difficulty that they are no substitute for living material even for routine taxonomic investigations.

The collections of living plants in botanical gardens constitute a resource for research in the same way as do the collections of animals in zoos, increasingly utilized for such purposes (Anonymous 1975 a, 1978, EBEL 1975—1976). Even though they normally represent only a very limited portion of the genetic variation of the populations from which they are derived, such collections are extremely valuable for most kinds of studies that require living plant material. For example, there grew up during the 19th century, chiefly at Berlin, Munich, and Kew, but also at other centers, a tradition of comparative morphological and anatomical studies. These studies were carried out primarily to determine more exactly or more easily than was possible with dried material the detailed morphology and other characteristics of the plants being cultivated. They formed the basis for the comprehensive classifications of plants that were introduced by ADOLF ENGLER and his co-workers towards the close of the 19th century and in the early years of the 20th century, and provided much of the basis for our current understanding of their phylogeny. This comparative approach, however, became much less important following World War I; only in the past 20 years or so has it been rejuvenated strongly, as at Munich, Leningrad, Copenhagen, and Perth. For any general approach of this sort, a very rich and diverse plant collection is indispensible and soon proves its worth. The same is of course also true for the role of the botanical garden in education and display; a diverse garden is often a more useful one (ORNDUFF 1978, VOS 1979).

In addition to their long-term maintenance of perennial and woody plants for multiple purposes, botanical gardens also play an important function as „habitats" (V. GRANT, pers. comm.) where specialized research collections, whether of annuals or perennials, can be built up and flourish. In this sense, a botanical garden is a place where trained staff and facilities are available so that plants can be grown, and grown well. Especially in universities, botanical gardens provide a continuity of professional care for experimental plants that it would be difficult or impossible to achieve by other means. In this connection, I wish to emphasize the special but underutilized and often unrecognized potential of the working garden staff of botanical gardens in contributing to our fund of knowledge about plants. Since the gardeners work with the plants on a daily basis, they may accumulate a great deal of information about them. Their education should be continued whenever possible, and they should be encouraged to publish their observations, or at least to record them in permanent form. Without taking this step, we are in danger of not being able to take advantage of much of the value of the living collections.

In order for botanical gardens to be as useful as possible for research, they must contain collections of living plants that are as comprehensive as possible. These collections should ideally be assembled in the sense of a library, in which the plants are available for research whenever and for whatever purpose they may be needed. In practice, truly comprehensive collections are normally brought together in relation to the research of a particular individual or research group, and no one garden can hope to include more than a small fraction of the world flora. Among botanical gardens, Kew claims the highest representation of taxa — about 20,000 — but this still represents only about 8 % of the total. It seems clear that for most research purposes, specialized collections with particular goals are much more apt to be successful than those that are very broad; yet relatively few botanical gardens have an articulated plan which they follow in assembling their collections. Undisciplined collection policies are not likely to lead to the formation of useful collections (PEPPER 1978).

Some very notable and extensive special collections include the pine collection at the Institute of Forest Genetics, Placerville, California, which includes some 72 species out of a world total of about 110; the collection of aroids from Central America at the Missouri Botanical Garden, or the general collections of the same family at Munich; and the rich assemblage of succulent Aizoaceae at Hamburg (POPPENDIECK 1976). Extensive and specialized collections such as these are normally maintained away from the public areas of the garden, where the conditions that are most suitable for the plants can be provided.

Unfortunately, such collections are often dismantled or simply deteriorate after the specialists who built them up are no longer active at the respective institutions (POPPENDIECK 1979). Although they are often of very great value internationally, they may if they are not actively utilized come to be viewed as a drain upon the limited resources of the institution where they are housed. Even when financial considerations are not limiting, it is difficult to provide for such collections the meticulous and sustained care that is essential for their survival without the attention of a specialist who is deeply concerned with them. If sufficient seed-banking facilities were available, the plants might be stored in this form when they were no longer being studied actively, but in fact such facilities are rather expensive (but much less so than maintaining a collection of living plants) and severely limited in scope.

There are certain groups of plants, such as the gymnosperms, for which reasonably comprehensive collections are maintained as part of the permanent collections of botanical gardens at present. Concerning another such group, the palms, the late H. E. MOORE, Jr., estimated that there are about 157 genera and 492 species in cultivation, out of world totals estimated at 210 genera and 2780 species (MOORE, pers. comm.). Thus about three-quarters of the genera and a fifth of the species of this large and important family are already in cultivation, and more are being added every year. The most comprehensive collections are those at the Fairchild Tropical Garden, Bogor, Singapore, Peradeniya, Calcutta, and Rio de Janeiro. There are excellent prospects for continuing to enlarge the collections of palms at these and other institutions; this appears to be a particularly desirable goal in view of the ornamental nature and economic importance of the group, especially in view of the speed with which they are being destroyed in the wild. Orchids, gesneriads, bromeliads, and cacti are groups for which there have long been comprehensive collections maintained in botanical gardens. The same is true for genera of woody plants such as *Acer*, *Viburnum*, *Philadelphus*, and *Rhododendron*, largely because of their obvious horticultural value; each of these large genera is relatively well represented in botanical gardens.

Another approach to building comprehensive collections of plants in botanical gardens is a floristic one. Thus the Canberra Botanic Gardens, while balancing recreational, educational, and research facilities, have some 5000 species of native Australian plants, perhaps a quarter of the total, in cultivation. The Pretoria Botanical Garden, in South Africa, includes some 4500 wild and cultivated species, approximately a quarter of the total flora, and B. DE WINTER (pers. comm.) has estimated that they could probably cultivate about twice as many. Rancho Santa Ana Botanic Garden, in Claremont, California, features about 1500 species of native California plants, nearly a third of the total, all from documented wild sources, and yet this rich collection is relatively little utilized for research. The University of British Columbia Botanical Garden includes about half of the roughly 3000 native species found in the province. Other well known examples of extensive regional collections of living plants are those in the arctic greenhouse in Copenhagen (BØCHER 1976), and the rich collections of Aegean plants at the University of Lund. Kings Park in West Perth, Australia, has about 1200 species of the Western Australian flora in cultivation, together with about 250 additional native species (P. R. WYCHERLEY, pers. comm.). About 300 of the 1200 species just mentioned can be maintained in West Perth only in containers, these being a mixture of acid-loving plants such as *Cephalotus*, shrubs that occur in heavy soils such as *Eremophila* and *Leschenaultia*, and others that for one reason or another cannot establish themselves outside in the light; well-drained soil found at the site of the garden. There are about 3600 species of native vascular plants in the South West Botanical Province of Western Australia, and up to 7500 in Western Australia as a whole. Dr. WYCHERLEY has estimated that in order to increase the proportion of cultivated plants from these regions significantly beyond the 25 % of the flora of the South West and the 12 % of the flora of the State that are now in cultivation at Kings Park, it would be necessary to construct greenhouses for plants that cannot be grown out-of-doors for reasons of edaphic, climatic, or security factors (allowing the addition of perhaps 500 species from the South West, 2000 from the State as a whole); to acquire and plant an annex to the main botanical garden on a site with heavier soil somewhere in the vicinity of Perth (allowing the addition of perhaps 1000 plants from the South West); and to create local botanical gardens in other centers in Western Australia, probably under the auspices of the local authorities (which should theoretically allow the entire flora of the State to be brought into cultivation, if established on an adequate scale).

This latter strategy is essentially that which has been adopted in the Soviet Union (TSITSIN 1974, LAPIN 1976 a) and in the Republic of South Africa; it is also loosely envisioned for Australia as a whole, and for other countries, for example Canada (RICE 1972). Satellite gardens, the most famous of which is probably Tjibodas in relation to Bogor, have much to contribute in extending the scope of collections of the "parent" garden. For the tropics, where most of the forests will have been destroyed within 20 years, and virtually all within 50 years, the creation of a network of botanical gardens containing a large proportion of the estimated 150,000 species of tropical angiosperms seems out of the question. Nevertheless, tropical botanical gardens can be important centers of research and education, and they can play a leading role in exploration for useful plants. Some of them will also become more and more important repositories of species that are becoming extinct in the wild, as we shall mention again below. Judged from the figures just outlined, it may be estimated that botanical gardens collectively include about 35,000 species of vascular plants, or about 15 % of the world total. The prospects for increasing this proportion markedly do not, under present circumstances, appear good.

One of the ways in which this figure could be markedly increased would be to bring more annual plants into cultivation in botanical gardens. Annuals comprise about 20,000 species worldwide, and are much neglected in botanical gardens generally. Although they require special care, they certainly deserve more attention than they are accorded at present. Seed banks, which we shall discuss again below, might be especially suitable for dealing with annuals, many of which have highly resistant seeds. Other ways to increase greatly the world total of plants cultivated in botanical gardens would be to coordinate the programs of these gardens more effectively than is done at present, so that they might specialize more efficiently, and to encourage the formation of botanical gardens in the tropics and promote their welfare once they were founded.

Even if a comprehensive collection of living plants has been assembled at a particular botanical garden, experience has shown that it is often not utilized much by the scientific staff. Few gardens actually appoint scientists whose chief concern is with the living collections; those who are appointed usually focus their research on the associated herbaria or libraries, or on the laboratory, or are principally occupied with educational matters. In order to help to alleviate this problem, the Pretoria Botanical Garden, in South Africa, has appointed a "garden utilization officer", whose principal duty is to bring the living plants in the garden to the attention of the scientific staff while they are flourishing, and try to make them as useful as possible in research. Many other gardens, whose rich and diverse collections are not much used, might profit greatly from such an approach.

It is often difficult to arrange collections that include comprehensive representations of particular plants in a way that is esthetically pleasing. Like museums in general, botanical gardens have tended to try to develop simplified and consequently more beautiful and educational displays. This trend is in some measure at cross purposes with the research purposes for which the collections are also used (RAVEN 1978, CROWLEY 1979). The collections on display are increasingly used to demonstrate various styles of landscape horticulture (Vos 1979), and the ways in which cultivated plants have been modified by artificial selection. Moreover, any explicit demonstration of scientific research in relation to the collection is likely to result in a further simplification. These and allied trends in display technique tend to lead to a reduction in overall diversity of representation of plants in the gardens. In the light of these trends, and particularly in terms of the research purposes of botanical gardens, or their general contribution, it has been argued that their collections should be restricted largely to species, and that large collections of cultivated forms and hybrids should not be accommodated within them. In any event, the incorporation of large numbers of undocumented accessions into the collections of botanical gardens is clearly a luxury that the world can no longer afford — and neither can the individual gardens, if they take themselves seriously.

Collections which are important for research in that they contain a high proportion of diverse plants of documented origin can with suitable ingenuity be arranged in such a way as to please and educate the visitor also. In addition, such collections can be highly educational. One thinks of the Fairchild Tropical Garden in Miami, in which a very large collection of palms and cycads is arranged in such a way that it forms a very pleasing landscape; of the California native plants at the Rancho Santa Ana Botainc Garden in Claremont, which both explicitly and implicitly demonstrate the use of native plant materials in a summer-dry climate; and of the superb regional gardens at Berlin, or those at the Main Botanic Garden of the USSR in Moscow, which form such attractive and educational displays.

What kinds of research can be carried out more easily in botanical gardens than elsewhere? Permanently maintained collections of plants are particularly suitable for wide-scale comparative studies that require living material. Such collections can also be of great use for taxonomy itself. If the records are well kept, plants maintained in botanical gardens actually are preferable to plants of wild origin for studies in which the living plant is important, since the same individual can be tested in a variety of different ways, and repeated measurements or fixations can be made to test or to extend the original observations. By vegetative propagation, such selected and much-studied individuals can be preserved indefinitely for research purposes, or distributed to other investigators. Except for certain physiological attributes, most of these characteristics are, as far as we know, identical in the wild and in cultivation.

Comparative morphological studies have the longest tradition in botanical gardens, aside from studies of medicinal plants, and are still flourishing today at centers such as Kew; Kings Park, Perth; Leningrad; and the Fairchild Tropical Garden. All kinds of investigations that require the special fixation of living material, such as phloem studies of the kinds carried out by scientists such as KATHERINE ESAU, VERNON CHEADLE, and H.-D. BEHNKE, or the comparative studies of stigma morphology and pollen function which have received the special attention of the HESLOP-HARRISONS (e.g., HESLOP-HARRISON & SHIVANNA 1977), have been based to a large extent on botanical garden material. Developmental studies, including embryological ones, in which absolute homology between stages under investigation may be indispensable, can be carried out far better with botanical garden material than with sporadic samples from the wild, even if the latter are specially fixed. Botanical gardens, particularly those with extensive native plant collections, could be used by physiological ecologists to great benefit to determine, for example, the physiological potentials of different adaptive types when grown under common conditions. This information is, of course, essential in sorting out the role of environment vs. heredity in determining plant physiological response. The most successful studies which have combined common garden with field measurements have used herbaceous plants which can be easily and quickly cultivated. The utilization of plants in botanical research institutes would enable this approach to be expanded to long-lived species, which most research scientists find to be hard to cultivate. Such studies need not be restricted to within-population comparisons, since our knowledge of the physiological ecology of different strategy types — or species — is limited.

Phytochemical studies can be, and often are, carried out on herbarium specimens or material specially gathered in the field, but there is ultimately no substitute for living material. When such material is available, biochemical pathways can be traced and variation caused by different environmental factors can be studied. In addition, the dynamics of particular systems can be studied in a broad array of plant species using botanical garden material, as MARTIN ZIMMERMANN demonstrated in his survey of the sieve-tube exudates of some 500 tree species (ZIMMERMANN & ZIEGLER 1975). Labile compounds such as floral scents can be studied only if living material is available. HERBERT & IRENE BAKER have carried out many of their investigations of the composition of nectar using material cultivated in botanical gardens. It is certainly no accident that the seminal phytochemical studies of scientists such as JEFFREY HARBORNE, E. C. BATE-SMITH, and ANTHONY SWAIN were carried out in Britain, where the rich collections at Kew, Edinburgh, Cambridge, and other institutions were available to them and much utilized.

There are several areas of biosystematics in which the collections of living plants in botanical gardens could be of great use. One concerns the nature of differentiation within and between species of woody plants. Most of our knowledge in this area is derived from field observations, and only herbs have been used to any extent experimentally. A few such studies of woody plants, such as those of *Ceanothus, Picea, Pinus, Populus* and *Salix*, are being carried out in collections especially built up for the purpose. The kinds of diverse collections of many genera held by institutions such as Kings Park in Perth, the Fairchild Tropical Garden, or the Arnold Arboretum, however, offer virtually unlimited possibilities for investigating these questions. Such institutions have the capabilities of growing hybrids to maturity and studying them, even if the process requires many years. Even progeny testing for woody plants, extremely valuable for understanding the patterns of variation observed in nature, can best be carried out in botanical gardens.

In an analogous fashion, studies of genetic differentiation and the formation of ecotypes have generally been confined to herbaceous plants, and botanical gardens seem appropriate places for analogous studies of trees and shrubs on a long-term basis. Applying the results of such studies to taxonomy, one might find that differences observed in the field either persist, disappear, or become greater under uniform cultivation. I strongly advocate the multiplication of such programs in botanical gardens, which seem especially well suited for them.

For the tropics, the special significance of investigations of this sort is evident. There is no genus of tropical trees or shrubs that is well known biosystematically, a staggering fact when it is recalled that nearly half of all flowering plants are tropical trees and shrubs. A genus of tropical plants such as *Erythrina*, with well over half of the approximately 110 species represented in gardens such as the Pacific Tropical Botanical Garden in Hawaii, would seem to be an exceptionally suitable choice for biosystematic investigation, whether viewed in terms of its worldwide tropical distribution, diversity, or utility in ornamental horticulture (RAVEN 1974). Our knowledge of the evolution of plants rests on a very slender foundation, which could be broadened greatly by a few, chosen experiments that could be carried out in the botanical gardens of the tropics and subtropics, under conditions in which immediate results were not demanded. Many other aspects of the biology of plants which are virtually unknown from any point of view, but which are significant factors in major ecosystems in the tropics, could likewise be investigated easily in representative tropical botanical gardens.

There are many other features of biological interest that should be investigated much more extensively in botanical garden material, both in the tropics and elsewhere. For example, we know something about the chromosomes of only about a third of the genera of flowering plants, and about the embryology of less than a tenth; many genera about which virtually nothing is known are cultivated in botanical gardens. Flowering and sex expression in *Acer* were the subject of an outstanding monograph by JONG (1976), who utilized principally the collection of 35 species, about a third of the genus, in cultivation at Wageningen, supplemented by other material cultivated in European botanical gardens. For a broad appreciation of even such physiological topics as seed germination, it is extremely useful to have the kinds of diverse collections of plants that are represented in botanical gardens. The same would be true of certain kinds of studies in such fields as air pollution damage and plant pathology. Thus the extensive collections at the Fairchild Tropical Garden provided an excellent basis on which to assess the susceptibility of different kinds of palms to lethal yellowing of coconuts.

One more area of special interest concerns the distribution of genetic self-incompatibility among most families of plants. This is an important factor in the evolution of angiosperms, easily determined if two or more living plants of a species are available, but not possible to determine from herbarium specimens or short-term observations in the field. There are, for example, thousands of individuals of *Nothofagus*, the southern beech, in cultivation, and this is one of the key genera in tracing the past migration of plants in the southern hemisphere. Despite this, there appears to be no published report concerning the self-compatibility of *Nothofagus*, a factor of critical importance in evaluating the past migrations of this genus and the plants and animals associated with it. Self-incompatibility systems vary to a considerable extent, and are primitive in the angiosperms as a whole, as well as in most families. How much could be learned about them from observations in botanical gardens!

Still another aspect of the biology of plants that could well be investigated more extensively in botanical gardens is the field of plant propagation. In order to define basic principles in various aspects of this field, diverse collections of plants are necessary. Recently, botanical gardens such as Kew, with its new laboratory for work in sterile-culture propagation, have become active in the field. The National Botanic Gardens in Canberra conduct research focused primarily on the propagation and cultivation of Australian native plants. At gardens such as the Cambridge Botanical Garden, the Jardín Botánico „Viera y Clavijo" in the Canary Islands, and the North Carolina Botanical Garden in Chapel Hill, the focus of such studies is on threatened and endangered species. Such activities are of great interest educationally as well as scientifically, and gardens such as these tend to be recognized as important assets by those who support them.

All of the kinds of research just outlined can be applied to the investigation and development of plants of horticultural or other economic value, if such is seen as an important part of the role of an individual garden. The taxonomy of cultivated plants is a much-neglected subject which can be pursued very well in botanical gardens. By evaluating plants, sometimes following hybridization, institutions such as the US National Arboretum, with its extensive programs focused on genera such as *Pyracantha*, *Lagerstroemia*, and *Hibiscus*, make important contributions in this field. The reintroduction of species using new strains with desirable characteristics not present in what is often a limited genetic base, is potentially an area of horticulture in which botanical gardens could play an important role, and follows directly from regional studies of such subjects as frost hardiness, phenology, and the like. Programs of plant introduction, hybridization, and selection are carried out widely, for example, at a number of gardens in the People's Republic of China; thus, at the Kunming Botanical Garden there is an extensive program of breeding and selection in *Camellia*. Cultivars, especially of lilacs, are maintained at institutions such as the Royal Botanical Garden in Hamilton, Ontario, and there are of course extensive collections of this kind at Wisley. At the Los Angeles State and County Arboretum, the introduction to the horticultural trade is the most important objective; over 80 kinds of plants have been introduced by this arboretum during its 20 years. These have included strains in such diverse genera as *Agapanthus*, *Syringa*, *Hibiscus*, and *Camellia*. At the Royal Botanic Gardens, Sydney, plant introduction is also an important program, with current emphasis on Rutaceae, tribe Boronieae. Universities, in which botanical gardens are associated with skilled faculties, students, and other resources, contribute much to the development of scientific horticulture. In the tropical countries of the world, there is probably even more to be gained by pursuing these goals; for example, the Aburi Botanical Garden, in Ghana, played a major role in the establishment of cocoa as the major export cash crop of the country (AYENSU 1978). Many more tropical plants are doubtless suitable for establishment in this way, and they are much less well known than those of temperate regions.

In addition to specific research application of the sort just reviewed, botanical gardens also can serve as centers for botanical exploration, for the maintenance of genetic diversity, and for the development of the means by which the useful characteristics of the plants discovered and grown in the garden can be applied to the needs of society. AYENSU (1976) has suggested that botanical garden personnel could likewise contribute significantly to our understanding of the biological status of threatened and endangered species in the field; such information is badly needed for the protection of the species concerned, both in an operational and in a legal sense. Whatever the nature of their collections, the gardens automatically provide for the screening of large numbers of diverse living plants under the local conditions. In order to make an even stronger contribution in this area, however, botanical gardens would have to expand their screening programs greatly and to rationalize them, testing wide and systematically selected arrays of genotypes of promising plants. This is in essence the overall function of the botanical garden system of the USSR, consisting of 115 botanical gardens with a total area of some 9000 hectares (LAPIN 1976 a); it is also one of the principal functions envisioned for the proposed Canadian National Botanic Garden System (Organizing Committee for NBGSC unpublished report). Knowledge about the native uses of plants will often be a vital asset in such programs, and a number of gardens (e.g., University of British Columbia; University of California, Berkeley) have also made special exhibits in this area.

As just mentioned, in the tropics where there is a rich and virtually untapped reservoir of wild plants of potential utility, botanical gardens could play a very critical role — especially during the next few decades, when nearly all tropical forests will be destroyed or converted to other purposes. Some tropical botanical gardens, such as the Jardín Botánico del Instituto de Biología de la Universidad Nacional Autónoma de Mexico, that in Xalapa, Veracruz (VOVIDES 1979), the Rimba Ilmu in Malaya (STONE 1977), and the Pacific Tropical Botanical Garden in Hawaii, have explicitly adopted such exploratory work as an integral part of their purpose. The gardens may of course also serve as important centers for taxonomic research, which would fit in well with programs of plant exploration; thus the Pacific Tropical Botanical Garden is organizing a new flora of the Hawaiian Islands.

If botanical gardens do indeed accept the preservation of genetic material as an important part of their purpose, how should this best be accomplished? It would seem that preservation in nature reserves, under conditions in which the plants are able to maintain themselves without the expenditure of human energy or effort, is always to be preferred (cf. RAVEN 1976, JACOBS 1977). Such reserves, whether they be located within the gardens themselves or at some distance, provide the best chance for long-term survival of the plants. They are also highly compatible with the research and educational programs of the garden.

Direct preservation by cultivating plants in botanical gardens is less likely to succed in the long run, but may ultimately be the only option possible for many species (cf. VENT 1978, SYNGE 1979). For instance, the extensive collections of New Caledonian and other Pacific Basin plants cultivated at the Pacific Tropical Botanical Garden and at the University of California, Santa Cruz, will become more and more important as the native habitats of these plants are destroyed. The preservation of plants outside of their natural habitats must never be used as an excuse for destroying these habitats, however (BUDOWSKI 1976). Whatever strategy is adopted, it seems unlikely that anything but a very small percentage of the world's flora could ever be preserved in botanical gardens. Careful choices must be made first if the overall plan is to be successful (FRANKEL 1976). A garden such as the Marie Selby Botanic Garden in Sarasota, Florida, which maintains very extensive collections essentially outside the public area, and then provides excellent displays for the public selected from this material, provides an interesting model in this respect. This garden deals exclusively with epiphytes, which usually are relatively small and can be kept in pots. Kew's collection of "alpines" is of course kept in a similar way. If the climate at the site of a garden is such that the plants can be maintained year-round out of doors, the situation is then relatively favorable, but continued human intervention forever will be necessary if the plants are to be preserved in this way.

If, in addition to growing rare plants, the gardens are able to work out the means for propagating them successfully, the chances of their continued survival will of course be greatly enhanced. If they are able to disperse them to other gardens, both public and perhaps especially private, then the change of survival will be increased still further (AYENSU 1976, POPPENDIECK 1979). In the state of Texas, for example, a conscious effort is being made to utilize threatened and endangered native trees and shrubs in plantings around the state buildings. In 1979, the East Bay Regional Parks Botanical Garden in California sold limited numbers of threatened and endangered plants, mainly propagated by their volunteer group, to the public and, at the same time, distributed forms whereby those who purchased the plants were asked to register their purchases, so that if the plants were lost in the botanical garden from which they originated, they could be located again. In Europe, a comprehensive effort is underway to record and computerize the holdings of rare and endangered European plants in the botanical gardens of the continent, with strong leadership from England, and this will ultimately contribute substantially to the preservation of such plants. In the United States, the 3187 taxa listed in the Smithsonian Report on endangered and threatened plants (ANONYMOUS 1975 b) were cross-referenced by computer with the accession files of 39 botanical gardens maintained at the Plant Sciences Data Center. The resulting matches indicated that 132 taxa, or more than 4 % of nationally vulnerable plant species of the continental United States, were in cultivation (AYENSU & DE FILIPPS 1978).

Through these and other methods, botanical gardens can play an important role in increasing the interest of the public in endangered and threatened plants, and at the same time make an important contribution toward their survival. In selecting plants for direct care in botanical gardens, those of economic potential or high scientific interest should be given priority (cf. SOEPADMO 1977, WILLIAMS 1977).

If botanical gardens regard the preservation of diversity as one of their most important goals, they should certainly give serious consideration to setting up seed banks (HONDELMANN 1976), as has been done for example at Kew, Lund, Copenhagen, and at Fort Collins, Colorado. In such banks, many species can be preserved in a small area, and hybridization is precluded except when the plants are propagated. Specialized collections that are assembled for particular purposes would not need to be abandoned once the research had been completed, if the seeds could be stored in a seed bank. In such a bank, it is also possible to preserve a wide sample of the gentic diversity of a particular species. Although there is inevitably selection when the plants are repropagated, it is less than if they are grown continuously. Thus after a given period of years the genetic diversity in the seed bank will resemble that in nature more closely than will the genetic diversity in a group of living plants in a botanical garden. Seed banks, like the collections of living plants in the gardens themselves, must be set up according to clearly defined principles if they are to be successful. A good model is the one provided by the seed bank of Brassicaceae developed by Prof. C. GÓMEZ-CAMPO and his collaborators in Madrid. It is also possible that deep-frozen tissue cultures might provide an even better method for the preservation of plants on a long-term basis, and this option too should be investigated (Anonymous 1978). Such banks cannot, however, even begin to play all of the functions expected of a botanical garden; as PAUL R. WYCHERLEY (pers. comm.) has pointed out to me, they are not especially attractive objects for gaining public support (cf. also ESSER 1976). There will always be a need, aside from the issue of preserving the species, to have diverse collections of living plants on display, for a combination of educational, cultural, scientific, and social reasons.

Regardless of how they may be preserved, the materials in botanical gardens may become important in the future as sources for restocking or recreating natural communities (LAPIN 1976 c). Indeed, reestablishment in nature, or at least under conditions in which their survival does not require human intervention, would appear to be the only guarantee of long-term survival for the plants concerned. Thus the Botanical Garden of the Hebrew University in Jerusalem is building up a stock of *Paeonia mascula* for reintroduction in the wild, where its populations have been severely damaged by wild boars that have become abundant within a nature reserve and now threaten the continued existence of the plant. At the botanical garden of the University of Malaya, the garden itself is attempting to recreate the original vegetation, which has been almost completely destroyed, on a portion of its grounds (STONE 1977). Similarly, the University of Wisconsin Arboretum is carrying out extensive experiments concerned with the reestablishment of natural prairie in an area where it once existed. In the Canary Islands, the Jardin Botánico "Viera y Clavijo" features a "synthesized" grove of natural laurel forest like that which once clothed large areas of the islands. Many gardens, such as those in Moscow, Berlin, and at Claremont, Santa Barbara and Berkeley in California, offer series of artificial plant communities representative of different areas. Such regional assemblages are often of great utility in taxonomic research. The problem is most serious for the tropics, where plant communities are so susceptible to damage and where they are being decimated so rapidly. Perhaps even there, if means can be found to preserve a sufficient sample of the diversity in time, some of the plant communities might eventually be reestablished using material from botanical gardens.

We come now to a general consideration that underlies any of the research purposes for which the collections of living plants in botanical gardens can be utilized. For all of them, the establishment of an improved system of indexing and locating the material is essential (AYENSU 1976, SYNGE 1979). In this modern era, computerization of the holdings of botanical gardens seems to be almost mandatory if the collections are to serve any serious research purpose. Furthermore, the implementation of computerized information-retrieval systems for the holdings of botanical gardens must ultimately be international, and must be made generally available, by international subsidy if necessary. Systems such as the program of the Plant Science Data Center, which has now been operating within the United States for over a decade, or the system in use at Kew, might serve as the basis for such an expansion.

The computerization of records on a local basis may be useful to the institution concerned but it does not really ultimately help to make the living collections of that institution available for investigators generally. As THOMAS MARBY has expressed it (pers. comm.): "...most phytochemists are simply not aware of what material (and in what form) is available from botanical gardens." This situation must be remedied if botanical gardens really take their research function seriously. Furthermore, for those collections in which the records have not yet been computerized, duplication of inventories is absolutely necessary to avoid situations such as the 1965 loss by fire of records concerning all woody plants at The New York Botanical Garden.

Since very few botanical gardens have specific research programs focused on their own collections, there are probably few of the collections in botanical gardens that can be justified individually on the basis of their research value. If all of the holdings of botanical gardens worldwide were known and accessible to the scientists who needed their material, however, collective justification would probably be a simple matter. Moreover, individual gardens could then plan their programs so that, in the area of research at least, they would be complementary (THOMPSON 1972). If they viewed the problem in this light, particular gardens might agree to maintain specialist collections for the common good, and funds should then be provided on a national or international basis for this purpose (CULLEN 1978). At any event, it is clear that the full potential of botanical gardens for maintaining plant genetic resources at a time when these resources are being lost at a spectacular rate will never be realized unless they can find the means to design and then agree to common goals. Human welfare demands nothing less.

For the overall role of botanical gardens, ROLF DAHLGREN (pers. comm.) has put it especially well: "I believe that it is the sum of the scientific possibilities combined with the teaching and educational aspects (possibly also pleasure, relaxation, joy, etc.) that can justify an expensive garden." Botanical gardens as collections of living plants must be justified from every possible point of view in order to be able to continue to assert their right to support. We have focused in this paper on the role of botanical research in gardens, but they are also very suitable as centers for the study of such fields as perception (cf. KAPLAN 1977), and for the development of valuable areas such as horticultural therapy. Botanical gardens are perhaps the most important centers for dispensing information of all kinds about plants, and in this role, they serve as the showcases of botany. By demonstrating especially local plants in a systematic, organized, and attractive way, they help to demonstrate the important principles of ecology and to underscore man's utter dependence upon the world of plants. As space becomes more and more limited in the world, botanical gardens will become increasingly important not only as centers of amenity but also as centers for science (VENT 1978); and regardless of the comprehensiveness of schemes whereby endangered and threatened plants may be brought together in botanical gardens, many plants — *Torreya taxifolia* seems now to provide a recent example — will exist only in botanical gardens in the future. In general scientific terms, and with specific reference to those characteristics that can be observed only in living plants or much more easily in living plants, there is no better place to gain an impression of overall diversity and to chart new lines of investigation.

For example, ROLF DAHLGREN (pers. comm.) has suggested that the material in botanical gardens could rapidly be surveyed for a variety of preselected chemical, anatomical, embryological, palynological and other features, according to an international scheme. By this method, perhaps as many as 35,000 species, which I would estimate as the maximum total holdings of plant species by the botanical gardens of the world, could be sampled for a given characteristic. This amounts to about one-eighth of all species of angiosperms. Herbarium vouchers would be prepared, but in most cases the plants would still be available for future study of the same and of additional features.

In order to foster comprehensive projects of this kind, countries such as the United States, Canada (RICE 1972, Organizing Committee for NBGSC, unpublished report), Australia, the USSR (TSITSIN 1974, LAPIN 1976 a, 1976 b), and South Africa, must consider in what ways to consolidate their networks of botanical gardens and then how to use them more efficiently for the purposes of science and society. Unfortunately, the International Association of Botanical Gardens (IABG) has not yet taken a role of leadership in the coordination of programs throughout the world, but perhaps it has the potential of doing so. At the 1978 Kew Conference on the practical role of botanical gardens in the conservation of rare and threatened plants, the delegates called on the IABG to clarify its role and enlarge its activities with respect to all aspects of botanical garden activities, including the coordination of collections, training programs, interchange of plants and of personnel, and other matters. It remains to be seen whether the IABG will accept this challenge, or some other group will assume the role of international coordination.

Especially in the tropics, where botanical gardens can well be justified as places for public instruction, and because of the important role they play in developing people who know about and care about plants, decisions must also be taken about the role that botanical gardens will play in the future. Since virtually all of the lowland moist tropical forests in the world, with the exception of the western Brazilian Amazon and Central Africa, will have been converted to other purposes by the end of this century, botanical gardens that are in a position to play a role in the tropics must decide what to do about preserving samples of the diversity of tropical plants for the future. All such schemes, however, and any improvement in the utilization of botanical gardens for research will clearly depend upon their explicit acceptance of some sort of philosophy whereby they can be linked into regional and international networks and the material they hold can be located when it is needed for any purpose.

To summarize, the living collections held by the world's botanical gardens could be especially useful for comparative studies of morphology, anatomy, cytology, physiology, biochemistry, autecology, breeding systems, and pathology. Most of these collections are greatly underutilized, however, because even though they collectively contain a considerable proportion of the world's flora, they are largely uncoordinated and the extent of their holdings is known only locally. If these difficulties can be overcome, botanical gardens will be able to play a major role in plant exploration, breeding and selection programs, and the conservation of genetic resources. We badly need their input in a world that is rapidly becoming less diverse, and one in which perhaps a billion people are undernourished even now. In other words, the collective potential offered by botanical gardens for human benefit is simply too great to allow the present lack of coordination and totally independent action characteristic of botanical gardens to continue if they are to make a serious contribution to research or to other human purposes.

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References

Anonymous, 1975 a: Research in zoos and aquariums. — Washington: US Natl. Acad. Sci., v + 215 p.

— 1975 b: Report on endangered and threatened plant species of the United States. — Washington: Government Printing Office, 200 p.

— 1978: Conservation of germplasm resources. An imperative. — Washington: US Natl. Acad. Sci., ix + 118 p.

Ayensu, E. S. 1976: International co-operation among conservation-orientated botanical gardens and institutions. — In Simmons, J. B., Beyer, R. I., Brandham, P. E., Lucas, G. Ll. & Parry, V. T. H. (ed.): Conservation of threatened plants: 259—269. — New York & London: Plenum Press.

— 1978: The role of science and technology in the economic development of Ghana. — In Beranek, W. & Ranis, G. (ed.): Science, technology, and economic development. A historical and comparative study: 288—340. — New York: Praeger.

Ayensu, E. S. & De Filipps, R. A. 1978: Endangered and threatened plants of the United States. — Washington: Smithsonian Inst. and World Wildlife Fund, 403 p.

Bøcher, T. 1976: The arctic greenhouse. — In Simmons, J. B., Beyer, R. I., Brandham, P. E., Lucas, G. Ll. & Perry, V. T. H. (ed.): Conservation of threatened plants: 61—66. — New York & London: Plenum Press.

Budowski, G. 1976: The global problems of conservation and the potential role of living collections. — In Simmons, J. B., Beyer, R. I., Brandham, P. E., Lucas, G. Ll. & Perry, V. T. H. (ed.): Conservation of threatened plants: 9—13. — New York & London: Plenum Press.

Crowley, W. R. 1979: Interpretation for users. — Bull. Amer. Assoc. Bot. Gard. **13**: 24—29.

Cullen, J. 1978: Programs and policies with respect to maintenance of record systems. — Bull. Amer. Assoc. Bot. Gard. **12**: 123—129.

Ebel, F. (ed.), 1975—1976: Zu problemen botanischer Gärten. — Halle (Saale): Martin-Luther-Universität, 156 p., 4 pl.

Esser, K. 1976: Genetic factors to be considered in maintaining living plant collections. — In Simmons, J. B., Beyer, R. I., Brandham, P. E., Lucas, G. Ll. & Perry, V. T. H. (ed.): Conservation of threatened plants: 185—198. — New York & London: Plenum Press.

Frankel, O. 1976: The time scale of concern. — In Simmons, J. B., Beyer, R. I., Brandham, P. E., Lucas, G. Ll. & Perry, V. T. H. (ed.): Conservation of threatened plants: 245—248. — New York & London: Plenum Press.

Heslop-Harrison, Y. & Shivanna, K. R. 1977: The receptive surface of the angiosperm stigma. — Ann. Bot. (London) **41**: 1233—1258.

Hondelmann, W. 1976: Seed banks. — In Simmons, J. B., Beyer, R. I., Brandham, P. E., Lucas, G. Ll. & Perry, V. T. H. (ed.): Conservation of threatened plants: 213—224. — New York & London: Plenum Press.

JACOBS, M. 1977: Gardens, species, universities. — In STONE, B. C. (ed.): The role and goals of tropical botanic gardens: 211—217. — Kuala Lumpur: Rimba Ilmu University of Malaya.

JONG, P. C. DE, 1976: Flowering and sex expression in *Acer* L. A biosystematic study. — Meded. Landbouwhogschool Wageningen 76 (2): 1—201.

KAPLAN, R. 1977: Preference and everyday nature: method and application. — In STOKOL, R. (ed.): Perspectives on environment and behavior: theory, research, and applications: 235—250. — New York: Plenum Press.

LAPIN, P. I. 1976 a: The botanical garden system of the USSR and its importance in enriching plant resources in the country. — Bull. Amer. Assoc. Bot. Gard. 10: 77—86.

— 1976 b: Research in the field of introduction of winter-hardy arboreal plants made at the Main Botanical Garden, USSR Academy of Sciences. — Bull. Amer. Assoc. Bot. Gard 10: 87—96.

— 1976 c: Report of the International Association of Botanic Gardens plenary Session. — Bull. Amer. Assoc. Bot. Gard. 10: 249—257.

ORNDUFF, R. 1978: Using living collections — the problems. — Bull. Amer. Assoc. Bot. Gard. 12: 113—117.

PEPPER, J. 1978: Planning the development of living plant collections. — Longwood Program Seminars 10: 24—27.

POPPENDIECK, H.-H. 1976: Mesembryanthemums and the problems of their cultivation. — In SIMMONS, J. B., BEYER, R. I., BRANDHAM, P. E., LUCAS, G. LL. & PARRY, V. T. H. (ed.): Conservation of threatened plants: 55—60. — New York & London: Plenum Press.

— 1979: Research collection to reserve collection. — IOS Bull. 3: 219—222.

RAVEN, P. H. 1974: *Erythrina* (FABACEAE): achievements and opportunities. — Lloydia 37: 321—331.

— 1976: Ethics and attitudes. — In SIMMONS, J. B., BEYER, R. I., BRANDHAM, P. E., LUCAS, G. LL. & PARRY, V. T. H. (ed.): Conservation of threatened plants: 155—179. — New York & London: Plenum Press.

— 1978: Systematics *vs.* aesthetics *vs.* use. — Bull. Amer. Assoc. Bot. Gard. 12: 110—112.

— 1979: Research botanical gardens. — Longwood Program Seminars 11: 13—19.

RICE, P. F. (ed.), 1972: Proceedings of the Symposium on a National Botanical Garden System for Canada. — Techn. Bull. Roy. Bot. Gard. Hamilton 6, 72 p.

SOEPADMO, E. 1977: Conservation of wild fruit tree species. — In STONE, B. C. (ed.): The role and goals of tropical botanic gardens: 207—210. Kuala Lumpur: Rimba Ilmu University of Malaya.

STAFLEU, F. A. 1969: Botanical gardens before 1818. — Boissiera 14: 31—46.

STEARN, W. T. 1961: Botanical gardens and botanical literature in the eighteenth century. — In: Catalogue of botanical books in the collection of RACHEL McMASTERS MILLER HUNT 2: xli-cxl. — Pittsburgh: Hunt Botanical Library.

— 1971: Sources of information about botanic gardens and herbaria. — Biol. J. Linn. Soc. 3: 225—233.

STONE, B. C. 1977: Research themes for the University of Malaya Botanic Garden. — In STONE, B. C. (ed.): The role and goals of tropical botanic gardens: 63—67. — Kuala Lumpur: Rimba Ilmu University of Malaya.

SYNGE, A. H. M. 1979: Botanic gardens and island plant conservation. — In BRAMWELL, D. (ed.): Plants and islands: 379—390. — London & New York: Academic Press.

THOMPSON, P. A. 1972: The role of the botanic garden. — Taxon 21: 115—119.
TSITSIN, N. 1974: Plant conservancy and botanical gardens [in Russian]. — Priroda 1974 (11): 7—13.
VENT, W. 1978: Zur Bedeutung und Entwicklung botanischer Gärten. — Gleditschia 6: 9—18.
VOS, F. DE, 1979: The nature of present day collections. — Bull. Amer. Assoc. Bot. Gard. 13: 12—15.
VOVIDES, A. P. 1979: Mexico: practical conservation problems of a new botanic garden. — In SYNGE, H. & TOWNSEND, H. (ed.): Survival or extinction: 117—123. — Kew: Bentham-Moxon Trust.
WAGNER, W. H. 1972: Botanical research at botanical gardens. [In RICE, P. F. (ed.): Proceedings of the Symposium on a National Botanical Garden System for Canada]. — Techn. Bull. Roy. Bot. Gard. Hamilton 6: 1—6.
WILLIAMS, J. T. 1977: Conservation of genetic resources in the tropics. — In STONE, B. C. (ed.): The role and goals of tropical botanical gardens: 187—200. — Kuala Lumpur: Rimba Ilmu University of Malaya.
ZIMMERMANN, M. H. & ZIEGLER, H. 1975: Appendix III: list of sugars and sugar alcohols in sieve-tube exudates. [In ZIMMERMANN, M. H. & MILBURN, J. A. (ed.): Transport in plants I. Phloem transport]. — Encyclopedia of plant physiology 1: 479—503. — Berlin, Heidelberg & New York: Springer.

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