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# Tropical Plant Collections: Legacies from the Past? Essential Tools for the Future?

## Proceedings of an international symposium held by The Royal Danish Academy of Sciences and Letters in Copenhagen, 19th–21st of May, 2015

*Edited by Ib Friis and Henrik Balslev*

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# Synopsis

The symposium *Tropical Plant Collections: Legacies from the past? Essential tools for the future?* was held on 19$^{th}$–21$^{st}$ May 2015 with botanists from eighteen countries. Balslev and Friis introduced the themes and voiced their concern about negligence of tropical plant collections in many European and American institutions and the dire conditions of funding and staffing in many tropical herbaria and botanical gardens. This happens at the same time as the collections become increasingly important for a series of modern approaches to evolutionary and biodiversity research and the needs of the biodiversity crisis.

Friis gave a broad overview of the history of herbaria and botanical gardens and the changing conceptual frameworks behind their existence. Baldini talked about early Italian botanical collectors and the fate of their collections. Baas accounted for the Golden Age of Dutch botany during pre-colonial and early colonial periods. With the presentation by Cribb on the botany of the British Empire we were fully into the colonial period, focussing on the Royal Botanic Gardens at Kew. The situation in North America  was treated by Funk, who illustrated the development of collections of tropical plants in the USA over the past two hundred years. Sebsebe Demissew taked about the situation in sub-Saharan Africa, particularly problems related to building and maintaining plant collections in new and poor nations. Onana outlined the history of botanical collections in Cameroon, covering a colonial period that involved Germany, Britain and France, until independence, which was brightened by exemplary collaboration. Muasya focussed on South Africa, which is the most developed country in sub-Saharan Africa with a well-functioning network of herbaria that covers widely different biota. Sanjappa outlined the history of botany in India with emphasis on the importance of The Botanical Survey of India, created during colonial times, but continued and developed after independence. Van Welzen and Schollaardt described the newer history of Dutch botany, with threats and decline until the recent amalgamations of the herbaria into one single large institution.

A section followed on North-South collaboration relative to botanical collections and floristic research. Newman and colleagues presented the *Flora of Thailand* project with a history different from most of the other examples because Thailand was never colonized. Nordal and colleagues described how Norway has had programs to train botanists from a number of African countries. Balslev and colleagues present a successful capacity building project in Ecuador, which has resulted in a world-class herbarium and a cadre of well-trained taxonomists. Prance described a successful MSc course which he helped initiating in Manaus Brazil in the 1970s, and which still train researchers in that country.

In a section on tropical plant collections and 'big data' Feeley demonstrated how dated herbarium records made it possible to trace elevational changes of species distributions, which is of importance to global change studies. Queenborough showed how herbarium collections can be used to study plant functional traits, and Antonelli documented the importance of herbarium voucher specimens for molecular phylogenetic studies and in comparative biogeography. Soberón gave a sobering account of 'big data', emphasising their potential in biodiversity research, but warned against developing the methodologies without a sound theoretical basis.

In two short sessions the focus was on applied phytochemistry and molecular systematics. Rønsted outlined the dependence on herbaria and botanical gardens' collections for modern drug discovery. Bakker gave an account of the tantalising possibilities for molecular systematics and other research in the use of herbarium collections, which have opened up for a plethora of additional data to be extracted from dried plant collections.

The final talk was Blackmore's account of the many roles that botanical gardens have had, continue to have and will have in the future, not least in preventing humans from becoming completely detached from the natural world on which we depend.

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## Dedication

We dedicate this volume to the memory of Kai Larsen (1926-2012) and Gunnar Seidenfaden (1908-2001), both members of the Royal Danish Academy of Sciences and Letters and deeply committed to the study of tropical plants. They were always convinced that Danish scientists should play a role in the study of botany in the tropics, and they inspired and encouraged us in our work in South America, Africa and South East Asia.

# Introduction

*Henrik Balslev and Ib Friis*

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On 19th–21st May 2015 seventy four botanists from eighteen countries, including seven countries in the tropics, were gathered in Copenhagen. The occasion was a symposium entitled *Tropical Plant Collections: Legacies from the past? Essential tools for the future?* organised by and held at the premises the Royal Danish Academy of Sciences and Letters.

Already at the beginning of the symposium, we were reminded about the links between the Academy and tropical plant collections. An early member of the Academy, Christen Friis Rottböll (1727–1797), was the first to write on tropical plants in the publications of the Academy. He described three new genera of flowering plants, one named after a former president of the Academy (Fig. 1), and some additional new species collected in southern India (Rottböll 1783). The material on which this publication was founded is still in the herbarium of the Natural History Museum of Denmark. Through the following centuries, other members of the Academy contributed significantly to the botanical collections of tropical plants and to the understanding of their taxonomy, structure, and biology.

But soon the themes of the symposium turned to the realities of today. The past decade has seen dramatic changes in the conditions of and care for collections of tropical plants kept in herbaria and botanical gardens. Botanical gardens have in many places been turned into amusement parks or simply recreational parks and many herbaria have been starved economically and staff-wise and some have even been relegated to warehouses, detached from scientific activities, and sometimes under conditions where they can only be consulted with difficulty. The scientific value on which their establishment were founded seems forgotten or neglected, or the collections are seen as irrelevant in a modern society. We are concerned to watch this development and we feel that many colleagues in other countries throughout the world have the same concerns. A particularly disturbing report came from the Netherlands, one of the first and in relation to its size most important countries in the world to establish collections of tropical plants and study them (Welzen & Schollaardt 2017), but fortunately and after long struggle, the efforts seem now to lead to a sustainable solution.

The symposium brought together scientists from old institutions in the North housing significant collections of tropical plants with scientists from countries in the South, with which the northern institutions have long-standing contacts. The aim was to take a closer look at the sustainable use of classical and new collections of tropical plants and its intersection with new scientific methods and technologies which are now being used world-wide. The symposium touched on several closely related topics:

What are the conditions for continued preservation, development, and use of already existing collections of tropical plants? In this context the symposium explored economic and political problems facing

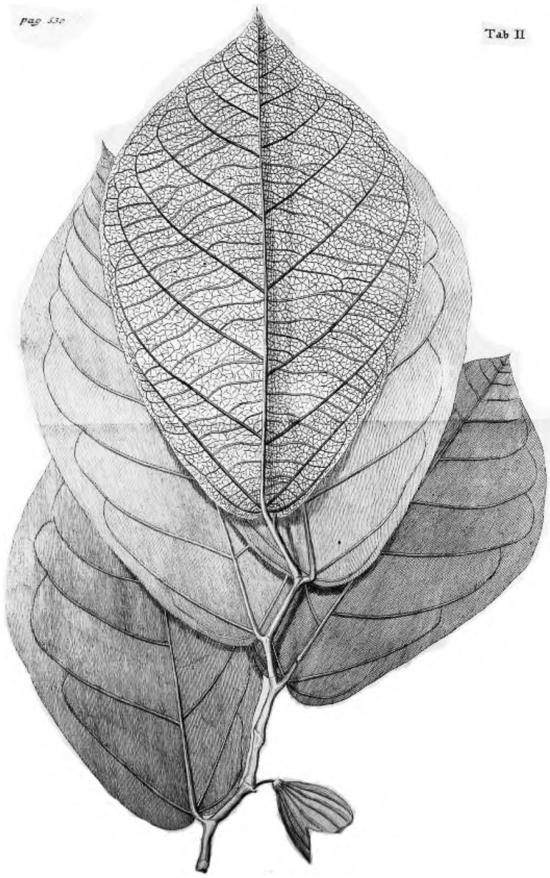


Fig. 1. The genus *Thottea* Rottb. (Aristolochiaceae) is a link between the early years of the Royal Danish Academy of Sciences and Letters and tropical plant collections. This engraving of *Thottea grandiflora* Rottb. accompanied the description of the genus published by Rottböll (1783), based on a specimen collected in 1779 in Malacca by J.G. Koenig and still kept in the Natural History Museum of Denmark (specimen no C10012834). The genus is named after Otto Thott (1703-1785), a representative of the Danish enlightenment. He published the first academic thesis on the economy of Denmark and Norway, held numerous posts in the Danish-Norwegian government until a revolution organized by J.F. Struensee in 1770, was a highly important collector of ancient Danish manuscripts and books, and – by Royal appointment – the second president of the Royal Danish Academy of Sciences and Letters (1763-1770). When the charters of the Academy were changed in a more democratic way, Thott was re-elected president by the members in 1776, but declined serving a second term. Today, *Thottea* is known as a genus of 26 species of shrubs and climbers, widespread in the forests of tropical Asia, some with known or potential medical properties.

the collections including the questions relating to access to biodiversity and the increasing threats to biodiversity caused by population growth, industrialization and climate change.

The symposium also addressed the scientific value of the collections as archives of scientific results, *i.e.* what might be called the *scientific heritage*, encompassing collections as documentation of past and present hypothesis about the taxonomy and evolution of plant species, and simultaneously acting as potential sources of new knowledge.

Plant species new to science are surprisingly often discovered in herbaria. A recent paper in *Proceedings of the National Academy of Sciences* (Bebber *et al.* 2010) has estimated the lag between date of collection and date of acknowledging and description of new species. Remarkably, only 16% of newly discovered species are described within the first five years after they were discovered in the field, the remaining 84% after much longer time. Nearly a quarter of the new species in the study were described from herbarium specimens that were collected more than 50 years before they were described in the scientific literature.

The collections housed in herbaria and botanical gardens are very important resources for research in both classical fields such as taxonomy and phytogeography, but also to a number of emerging and new fields such as genomics, molecular systematics, biodiversity research, macro-ecology, and eco-informatics. These collections are rich resources of information and often the only ones that can provide any kind of documentation on extinct or rare species or even, as shown in examples from India, make it possible to recover species thought to be extinct (Sanjappa & Venu 2017).

Collections of tropical plants in herbaria and botanical gardens had their beginning in the collections of medicinal plants in medieval Europe. Later they became an integral part of the enlightenment and the scientific discovery of world, not least with support of the still ubiquitous naming system of Linnaeus in which all living organisms have a generic name and species epithet as in the case of our own species, *Homo sapiens*.

In the 18th and 19th century, collections of tropical plants became a tool to create a complete catalogue of all plants and an instrument supporting the western colonization of the tropics. Many large European and North American botanical gardens started building their tropical collections in the 18th century, but only few botanical gardens and associated herbaria were established in tropical regions, some exceptions being the institutions in Calcutta and Rio de Janeiro. When the European countries began to colonise the world, botanical gardens and herbaria became the colonial powers' way of assessing the natural resources in their colonies. Since the middle of the 20th century the colonies gained independence and emerged as sovereign states that needed to know their own natural resources and to protect them against exploitation and unsustainable use. So over the past 50-70 years a high number of botanical institutions and related herbaria and botanical gardens have emerged in the former colonies. This history of and transition from European and North American dominance to emerging and independent botanical research and the building of collections in herbaria and botanical gardens in the tropics was exposed and discussed thoroughly at the symposium.

The threats to the world's biodiversity through global change involving global warming and unsustainable land use changes have emerged as an issue of extreme concern - not least brought to public attention world-wide through the UN convention on biodiversity in Rio in 1992 and the subsequent conventions of parties. In the symposium a series of attempts to collaborate and close the North-South gap in Cameroon (Onana *et al.* 2017), sub-Saharan Africa (Sebsebe Demissew *et al.* 2017; Nordal *et al.* 2017), India (Sanjappa & Venu 2017), Brazil (Prance 2017), Ecuador (Balslev *et al.* 2017), Thailand (Newman *et al.* 2017) and Central America (Baldini & Pignotti 2017) were demonstrated as dynamic and mutually productive.

Initially, collection-based research primarily resulted in classical taxonomic monographs and revisions and to large extent practical manuals and regional and national floras, as exemplified by the long line of manuals and regional floras produced during the colonial period of India and South Africa (Sanjappa & Venu 2017; Muasya 2017). This work, now rejuvenated to fit the needs of the present-days nations in the tropics, is still ongoing and involves many tropical countries. Unfortunately, these activities are facing unprecedented financial challenges and failing recognition in academic incentive structures in the North. At the same time botanists and institutions in the South increasingly recognize the needs to complete their national botanical inventories both for conservation purposes and to create a base-line for sustainable use of their plant resources. Botanical gardens strive to survive, while new structures, *e.g.* seed banks appear as repositories for plant genetic resources. In assessing the challenges facing research in tropical botany, the symposium particularly realised the threats confronting established institution in the North and the lacking growth of the new or more established institution in the South.

The universal spread of new types of collections, sparked by the rapid development of new methods, such as tropical seed banks, DNA- and cryopreservation of plant tissue has enabled a gamut of new techniques and methods in the study of tropical plant diversity. The symposium addressed the importance of the intersection between classical herbarium collections and botanical gardens and the development of molecular techniques such as genomics in the 21st century. Further, it argued how interaction between researchers who apply new methodologies and classical botanical research is necessary to reach broad ranging scientific syntheses and that this interaction needs to involve researchers and institution both in the North and in the South. A good example was provided by the highly biodiverse South Africa (Muasya 2017), where the development of the new techniques may be an example to other countries in the South.

As it turns out, much of the research based on highly technical methods involving molecular aspects does not make sense without reference to collections in herbaria and botanical gardens. First of all these collections provide material that is identified to the taxon it belongs to. Such materials often originate from freshly collected herbarium material from or in

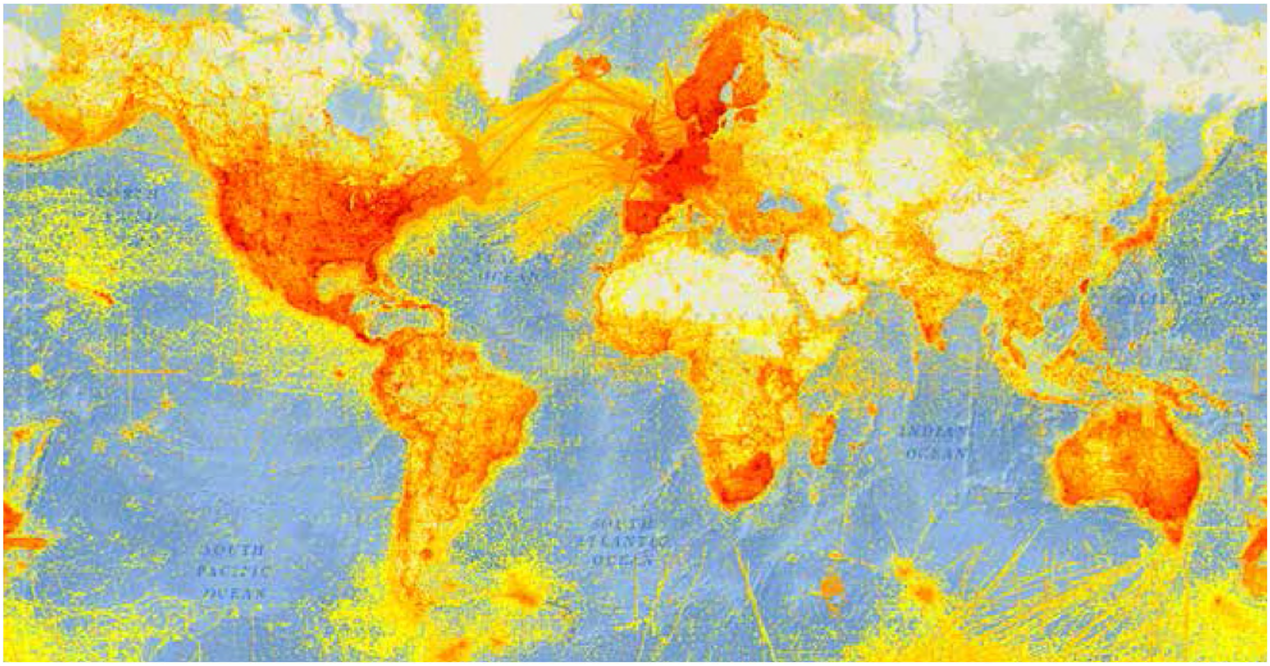

Fig. 2. Density and locations of 655,159,045 occurrence data with geo-referenced localities available in the Global Biodiversity Information Facility network (GBIF; http://www.gbif.org/occurrence). The data presented here include both occurrences based on specimens and observations without vouchers in collections (a significant majority of the records represents specimen data). The data set includes both records of animals (ca. 2/3) and plants (ca. 1/3) and organisms in both terrestrial and marine environments. This huge availability of primary biodiversity data is in sharp contrast to the few specimens of each species available and considered necessary at the time of discovery of *Thottea* (Fig. 1), but the contrast between the amount of data available from the less biodiversity-rich temperate regions and the biodiversity-rich tropics is also notable.

the South or from the living collections in botanical gardens. The efforts and costs to obtain representative samples is greatly reduced by sampling already existing collections when compared to the efforts needed to collect samples from natural populations (Bakker *et al.* 2017; Queenborough 2017). Over the past decades molecular researchers have developed methods that use herbarium specimens to extract the DNA needed for phylogenetic and other research. Considering the enormous coverage of herbarium collections from all over the world this opens up for a treasure trove of information which has been exploited in many recent studies.

Digitization of botanical data in databases such as the Global Biodiversity Information Facility (GBIF) and high resolution images of herbarium specimens held at the Global Plants Initiative (GPI), Global Plants on JSTOR, has drastically globalized plant diversity research (Fig. 2). GBIF now gives access to over 700 mio records of primary biodiversity data, many of which are from herbaria, and close to 27 billion records are downloaded from the facility every month (www.gbif.org). GBIF is a truly North-South collaboration in which the richer and industrialized countries in North America, Europe and Asia share information from their herbaria and other collections with developing countries in the South. This is often the former colonial powers in the North that make information about specimens in their collections available to the new nations in the South, and as such GBIF functions in the process of repatriation, but it is increasingly beginning to work in other directions as

South-North or South-South sharing of information (Sebsebe Demissew *et al.* 2017). At the same time data about soils, climate and other factors affecting the conditions for the occurrence of plants and shaping the patterns of diversity are becoming available in digitized and easily downloadable formats.

Combining plant data with digital data on many ecological features has made it possible to develop new ecoinformatic methodologies that help answering questions that could not even be asked before at geographic scales from very local to the Global ones. Because herbarium and botanical garden collections include the names of plants in combination with information about the locality where they were collected the combination of data from many herbaria can provide very accurate information about the distribution of species. If this information is combined with information about the ecological conditions (climate, soil, *etc.*) at the same localities, the data can be used to model the potential distribution of species using so-called Species Distribution Modelling. Such models – when combined with predictions for the expected changes in climatic conditions – can be used to model the future distribution of species. Herbarium collections also make it possible to study functional traits of a broad range of species over a diversity of habitats and ecosystems, for example leaf area and specific leaf area which are important for understanding fundamental characteristics of ecosystems (Quenborough 2017). Because herbarium records all have dates of collection the information can also be used to detect actual changes in distribution over time as demonstrated in a study of how climate change affects the position of various forest types along elevational gradients (Feeley 2017). Voucher specimens in herbaria can also be used to construct molecular phylogenies which, when combined with fossil evidence, can enhance our understanding of the biogeography and history of evolutionary lineages and how they have interacted with biotic and abiotic events in the past (Antonelli 2017). Although these herbarium and botanical datasets are far from the size of datasets derived from commercial activities and banking operations, they still qualify as 'big data' and can only be handled with previously unavailable algorithms and analytical methods, but also cause new complications unless followed up by new testable theories (Soberón 2017). These and other themes were explored in the symposium with emphasis on how primary data from herbaria and botanical gardens enhances new globalized digital plant research, truly 'big data' – as well as its practical uses for biodiversity.

In recent time the relationship between North and South with respect to maintaining tropical plant collections has changed. Initially institutions from the North were dominating, but influence from the South has been continuously increasing – changing roles fostered by mutual interests, collaboration and new friendships between researchers in North and South, realisation of complementary possibilities with regard to access to scientific material, technology and resources. Although digitization, the building of herbarium- and botanical gardens collections in the South, and international North-South collaboration helps building our understanding of the biodiversity in the tropical parts of the world, much remains to be done (Sebsebe Demissew *et al.* 2017; Muasya 2017; Onana *et al.* 2017). Because of history, it has been amply demonstrated that the collections held in the North are indispensable for the understanding of biodiversity and the related resources and ecosystem services in the South (Baas 2017; Baldini & Pignotti 2017; Cribb 2017; Friis 2017). The countries in the North therefore must continue to engage in the exploration and documentation of plants and their importance to the new nations in the South. In a historical perspective, the symposium saw this as obvious obligations derived from the former exploitation of the South. Countries in the North cannot live up to these obligations if they continue the trend to relegate their own herbaria to inaccessible warehouses where the collection can only be consulted with difficulties. The same goes for the trend to change botanical gardens with important historical plant collections into amusement parks or recreational zones. Local politicians and administrators should not only look at short term benefits and impact as measured with new bibliometric methods. The impact of being serious about the obligation to those countries and areas where the collections came from should be given the serious credit it deserves and should supplement some of the new narrow ways of seeing impact in modern society and universities.

Possible solutions to the challenges raised in the previous sessions surely require enthusiasm, innovative thinking, futuristic views, and new ways of collaboration between North and South. The symposium discussed possible ways forward. One way, on which much hope has been founded since the signing of the Convention on Biological Diversity (CBD), may be to focus on the utility of tropical plants, as the focus was in the colonial period, but now with international agreements on fair benefit sharing. The importance of collections for the development of modern drugs is an example of this utility aspect which should be possible to explain to politicians and the general public (Rønsted *et al.* 2017). That said, there was an overwhelming agreement about the fact, that regardless of political, economic, and other impediments, tropical plant collections in herbaria and botanical gardens must continue to support a wide range of societal needs in research, conservation and sustainable management of natural resources. That can only happen through the continued strengthening of already existing North-South collaborations and also through establishing new ones in the many countries with emerging capacities for research.

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# Temperate and Tropical Plant Collections: The changing species concept and other ideas behind their development

*Ib Friis*

SCI.DAN.B. 6 · TROPICAL PLANT COLLECTIONS
*THE ROYAL DANISH ACADEMY OF SCIENCES AND LETTERS · 2017*

## Abstract

The first botanical gardens and collections of preserved plants in the 16th century served didactic purposes and should ensure correct identification of medicinal, ornamental and other useful plants. Collections of preserved plants were nearly all book-herbaria, emulating illustrated books and owned by individual botanists. Curiosity cabinets of nobles and prominent scholars were larger collections, in which all kinds of objects of natural history from remote regions could be incorporated. The Linnaean revolution favoured loose-leaf herbaria over the old book-herbaria: herbaria with loose sheets could be reorganised in agreement with new knowledge or theories and newly accessed specimens could be placed next to earlier ones of the same species. However, the Linnaean collections reflected the essentialist species concept, according to which all species consisted of individuals with similar essence and separated from other species by sharp discontinuities. Therefore only few specimens were accumulated per species. A.P. de Candolle saw the need for the study of variation within species and stressed the importance of many specimens per species. The Darwinian revolution in 1859 further increased that trend, requiring more specimens to allow the study of variation both within and between species. During the 19th and the 20th centuries larger botanical gardens and large public herbaria with tropical plants developed in European countries, particularly in countries with tropical colonies, eventually also in the United States and in some tropical countries, for example in Brazil (Rio) and India (Calcutta). Before and particularly after World War II new botanical gardens and herbaria were established in the tropics and the collections in Europe and North America continued to grow, facilitated by easier travelling and growing interest in exploring the World's biodiversity. New trends in the 21st century included a wider focus than the study of taxonomy and plant geography: for example conservation and climate change. Many factors may influence the future of tropical plant collections: the influence of growing world population and increasing urbanisation on conservation, increasing focus on technologically complex disciplines in the utilisation of collections and an increasingly complex international legislation, such as the Washington Convention, the Convention on Biological Diversity, and the Nagoya Protocol on Access and Benefit-sharing.

**Key Words:** Convention on Biological Diversity, Darwinian revolution, Linnaean revolution, methodology of plant collecting and herbaria, Nagoya Protocol, origin of herbaria, size of collections, Washington Convention.

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In this, the first presentation at the symposium – *Tropical Plant Collections: Legacies from the Past? Essential Tools for the Future?* – I will outline some of the concepts, ideas, trends and goals that have been behind the creation and maintenance of plant collections. When I started working on my presentation, I realised that it would not be possible to restrict myself to *tropical* plant collections. In many ways the tropical plant collections have developed along the same lines as the temperate collections, but under different conditions and sometimes with a delay of a hundred or more years. Very few tropical plants were accessed to collections in the 17th century, but gradually more and more were added in the 18$^{th}$, 19$^{th}$ and 20$^{th}$ centuries. I have also found it necessary to refer to the development of certain aspects of taxonomic botany, particularly the species concept. This is necessary because of the ways botanical collections have been created and maintained are very strongly influenced by the needs of the scientific studies, which these collections are to serve.

I will begin with the quote from a summary of the situation just after 1784 by the British botanist James Edward Smith, when the extremely important botanical collection of both temperate and tropical plants in the private herbarium of Linnaeus had been purchased and brought to England from Sweden. In the first pages of his "Introductory discourse on the rise and progress of natural history," which he delivered on the occasion of the foundation of the Linnean Society, J. E. Smith (1789: 1-8) outlined the development of natural history as a science, but also emphasised its deep roots of the study of plants and animals for practical purposes:

> 'In no country hitherto discovered, however barbarous and unenlightened, is the human race found so negligent and helpless as not to have investigated the natural bodies around them, so far at least as from thence to supply their necessary wants, and even to obtain conveniences and luxuries. … In a very early state of society the sum of human knowledge would become too much for every individual to acquire; of course some must necessarily pursue particular arts or enquiries in preference to the rest; … Botany was more especially attended to [than zoology] very early, as medicine, which, however it might have been degraded in the ages of barbarism, could never have been totally neglected, stood in immediate need of its assistance. The works of the ancients, and particularly those of Dioscorides, were then studied with the most pertinacious assiduity; remedies which this writer had recommended were deemed infallible, and virtues, which he had attributed to any plant, indisputable. The chief difficulty in almost every case was to find out the plant he meant; and this difficulty becoming at length as great as to be absolutely insurmountable, his commentators were lost in mazes of their own conjectures. It was happy for the credit of Dioscorides that this was the case, and that the world were so occupied by this kind of criticism, as seldom to have examined the truth of his assertions. Of these commentators some few had great original merit in giving figures of the plants of which they treated, and those figures are many of them executed with such perfection as to excite our astonishment; they have rarely been excelled at any following period. … and ever since the middle of the sixteenth century the press throughout Europe has teemed with similar publications; certainly to the great advancement of botany, although the merit of these works has been very various. For almost two centuries after the revival of letters in Europe the attention of naturalists was chiefly confined to the vegetable creation; and although since that time the animal and mineral kingdoms have received an eminent decree of cultivation, still botany has always kept its ground. … The institution of public botanic gardens is a memorable era in the history of botany. The first of these was, I believe, at Padua in 1533[1], where

1. Chiarugi (1953) has documented that 1533 was the year when the University of Padua appointed Francesco Bonafede to teach identification of medicinal plants. The world's first botanical garden associated with a university was established by Luca Ghini in Pisa in 1543-1544. However, in Tübingen (Germany) a private garden with medicinal plants was founded in 1535 by the herbalist Leonhart Fuchs (1501-1566) at the Nonnenhaus (House of the Nuns); it has not been maintained, and the following botanical garden in Tübingen was only founded in 1663. The world's oldest still existing botanical garden was established in 1545 in Padua by the above mentioned Francesco Bonafede; the garden in Firenze was established 1548. The following is a list of botanical gardens founded up to ca. 1700: Pavia (1558), Zürich (1560), Bologna and Valencia (both 1567), Leipzig (1580), Jena (1586), Basel (1589), Leiden (1590), Heidelberg and Montpellier

it still continues to make a tolerable figure, although now surpassed by several others, which have had more powerful protectors. The gardens of Florence, Pisa, Bologna and Leyden were soon after established, and all still exist.'

It is notable that Smith so clearly stressed the importance of the correct interpretation of Dioscorides' works, the teaching of medicinal plants and the illustration of herbals for the early study of botany. The herbals and other botanical books illustrated with woodcuts and the botanical gardens were essential for the correct identification of useful plants, particularly medicinal plants. The gardens were the foremost institutions for botanical education and research up to Smith's own days. He praised for example the excellence of the Kew Gardens, even among the other fine botanical gardens in Britain: "The royal garden at Kew is undoubtedly the first in the world, and we have a number of others, both public and private, each of which may vie with the most celebrated gardens of other countries" (Smith 1789: 52). He did not attribute a similar status to herbaria, collections of preserved plants. Herbaria were tools for individual botanists, as was the case with the herbarium of Linnaeus. Before the time of Linnaeus herbaria mostly consisted of pressed and dried plants glued into books, replacing the woodcuts of the herbals with real pressed and dried plants.[2] From the 16th and 17th century Smith mentions herbaria in the private possession of prominent botanists, the first one being that of Caspar Bauhin (1560–1624)[3]: "I have seen a great part of his herbarium at Basil [Basel] … This herbarium is inestimable on account of the difficulty of determining many of Bauhin's plants by his descriptions alone …" (Smith 1789: 14). When describing his own time, Smith still spoke of herbaria as individual collections that had been amalgamated to form part of great scholarly institutions, the natural history cabinets, and singled out the Natural History Museum in London as the most prominent in the world, and : "… the British Museum, which contains among other things the original herbariums of Sloane[4], Plukenet[5], Petiver, Kaempfer[6], Boerhaave[7], of many of the disciples of Ray, and several others, besides innumerable treasures of zoology, claims the first place."

(both 1593), Copenhagen (1600), Oxford (1621), Groningen (1626), Paris (1635), Amsterdam (1638), Uppsala (1655), Hanover (1666), Kiel (1669), Edinburgh (1670), Berlin (1672), Chelsea (London) (1673).

2. The Italian botanist Luca Ghini (1490–1556) is considered the creator of the first herbarium (*hortus siccus*), collected in 1544. His herbarium consisted of pressed and dried plants glued into books. No herbarium collected by Luca Ghini has been preserved (Stearn 1957: 103; Moggi 2012), and it is possible that other botanists had created herbaria before or at the same time as Ghini, but there is no doubt that the herbarium was invented somewhere in northern Italy in the first half of the 16th century, and several book herbaria from the middle of that century still exists in Italy (Moggi 2012; Friis 2017), and one early book herbarium, the En Tibi herbarium, of Italian origin, is kept in Naturalis in Leiden (Welzen & Schollaardt 2017). Only in the 18th century the book herbaria were replaced by loose-leaf herbaria. One of the earliest and still existing big loose-leaf herbaria is that of Adriaan van Royen (1704-1779) and David van Royen (1727-1799) in Leiden with ca. 10,000 loose sheets. The plants in this herbarium are mounted as appearing from vases, as was common in Dutch herbaria in the early 18th century (Thijsse 2003). Wijnands (1983) suggested that the van Royen herbarium may contain as many as 2000–3000 specimens relevant for the typification of Linnaean plant names.

3. Caspar Bauhin (1560–1624), Swiss, collected and pressed numerous plants kept loose in folded sheets of paper; ca. 2400 af these specimens are preserved at the herbarium in Basel (BAS) (Zoller 1966).

4. Hans Sloane (1660–1753), British, collected in 1687–1689 objects of natural history in Jamaica. The botanical specimens are still mounted in seven bound volumes. (Stearn 1957: 119–120; 122; Dandy 1958).

5. Leonard Plukenet (1642–1706) and James Petiver (1658–1718), both British, did not visit the tropics but collected numerous plants preserved in book herbaria; they were later bought by Hans Sloane and incorporated in his collections (Stearn 1957: 122; Dandy 1958).

6. Engelbert Kaempfer (1651–1716), German, travelled in Russia, Persia, India, South-East Asia, and Japan between 1683 and 1693 (Stearn 1957: 120–121; Dandy 1958).

7. Herman Boerhaave (1668–1739), Dutch, collected in 1685–1693 book herbaria in four volumes with dried plants from the Leiden botanical garden and other Dutsch gardens; they are now in the Hans Sloane collections (Dandy 1958).

(Smith 1789: 52). Two terms became common in connection with these kinds of books with collections of dried plants: A 'Hortus siccus' was always a collection of dried plants. A 'Herbarium vivum' was a book with a collection of pressed plants or images. Sometimes the documentation was mixed, so that the illustrations of some text were woodcuts, while other text was illustrated with preserved plants, or even the individual representation could be mixed, so that one part of the representation was an illustration, often the roots, rhizomes or tubers, while a real preserved plant represented the parts above ground. The 'Herbarium vivum' of Hieronymus Harder was prepared in 12 volumes, the earliest from 1562. One volume, from 1576 (Harder 1576), kept at the Bayerische Staatsbibliothek, is particularly rich in mixed 'illustrations' consisting of both preserved plants and drawings.

## From Aristotle to Linnaeus: Safe identification of useful plants

From the Antiquity, we have a few works on botany (Mayer 1982): Theophrastos' two large botanical treatises, *Περὶ φυτῶν ἱστορία* ('History of plants' or rather 'Enquiry into Plants'), and *Περὶ φυτῶν αἰτιῶν* ('On the Causes of Plants'). These works contained many theoretical considerations and were important contributions to plant morphology and biology; they also contained information about exotic plants brought by merchants or sailors. Theophrastos adopted a very general method for classification of the plants: trees, shrubs, undershrubs or herbs, presence or absence of spines, etc. Theophrastos used groupings from folklore, which resulted in some groups being quite natural (oaks, willows), while others were not. More important for the immediate development of botany was the work by the Greek physician Dioscorides Pedanius of Anazarbus, *Περὶ ὕλης ἰατρικῆς* ('On the material of medical doctors', better known by its Latin name, *Materia Medica*). The work contained information about and descriptions of ca. 700 species of plants and ca. 1000 drugs that were either of medicinal use or provided oils, spices, resin, fruits or other edible parts. Dioscorides arranged the plants according to their uses, which meant that the sequence in which the plants were listed did not have much to do with their appearance. If you knew the plant under a different name than the one listed by Dioscorides, or if you did not know a name at all, then you would have serious trouble finding the text dealing with it.

From the Antiquity, we have a few illustrated manuscripts that attempted to solve the difficulty of plant identification. *Codex Aninicae Julianae*, the most beautifully illustrated Dioscorides-manuscript from the late Antiquity, was commissioned in Constantinople and delivered in 512 to Princess Anicia Juliana (462–527 or 528), a scholarly and culturally interested daughter of the Western Roman Emperor Anicius Olybrius (?–472). *Codex Aninicae Julianae* and many other subsequent publications or revisions of Dioscorides' work were provided with drawings of the plants, making a reliable identification of the plants relatively easy, just like with the modern illustrated floras.

Better identification of medicinal and other useful plants only became possible when the idea of a hierarchy of taxonomic categories derived from Aristotelian logics was applied to biological classification. Aristotle (384–322 BC) dealt with the classification of all things in one of his six works on logic called *Τοπικά* (*Topics*; Latin: *Topica*) (Balme 1962; Mayr 1982). Aristotle distinguished between the essential and accidental properties of things, including organisms. Essential properties were constant and common denominators for each 'kind' of object. Individual organisms all belonged to one and only one 'kind'. Aristotle referred to a 'kind' as *ειδοσ* (*eidos*, 'form' or 'type'). In order to connect Aristotle's ideas about logic with later biological classification we mostly translate *ειδοσ* as 'species'. Each *ειδοσ* is assigned to a category of higher order with common features, which Aristotle called *γενοσ* (*genos*). Balme (1962) demonstrated that Aristotle did not use these terms consistently in his biological writing[8], and concluded: "The traditional assumption

8. Balme (1962) states that the word *γενοσ* (*genos*) appears 413 times in Aristotle's zoological writing, but in 354 cases it refers to a "kind" of animal, and only in the remaining cases to a

that Aristotle actually classified … [living organisms] into genera and species … is not supported by the evidence." Moreover, Aristotle, and indeed Theophrastos, did not recognize the biological integrity of each species, and accepted both frequent hybridisation between species, which we now consider too distantly related for hybridisation, and that mutation of one species into another (heterogony) was possible.

Also medieval herbalists accepted these ideas to be true; Albertus Magnus, for example, described five ways in which one plant could be transformed into another, and there was a widespread belief that species could arise by spontaneous generation. But after the Reformation the fixity of species became a firm dogma, and the species became the unit of creation (Mayr 1982).

The medieval manuscripts about plants nearly all dealt with medicinal and other practical uses, and they – together with the Bible – were among the first books printed after the invention of movable-type printing press by Gutenberg in the 1450s. One of the first was the rather fanciful *Hortus santitatis* (Anonymous 1491). Serious books on medicinal plants were often adaptations of Dioscorides' *Materia Medica*; for example Pierandrea Mattioli's edition of Dioscorides in Italian in 1544 (Mattioli 1544). This edition was provided with woodcuts of the plants and therefore fulfilled the purpose of identifying the plants without a scientific taxonomy. In the countries, north of the Alps there were problems using Dioscorides' work, but the problems were gradually solved during the Renaissance with better plant identification and the discovery of medicinal plants in the temperate floras.

The Aristotelian logic and the terms 'genus' and 'species' survived through the scholastic philosophy in the Middle Ages and became united with the ideas of the unchanging species characterised by constant and common features for each 'kind' or species. During the mediaeval age, the use of a common generic name became a tradition for groups of 'kinds' that could be recognised, and the essentialist species concept developed. The presence of the same essential characters defined the species, in which all individuals were of the same *eidos*, 'kind.' (Mayr 1982). Ray (1686) provided a biological explanation of this:

> 'In order that an inventory of plants may be begun and a classification of them correctly established, we must try to discover criteria of some sort for distinguishing what are called 'species.' … no surer criterion for determining species has occurred to me than the distinguishing features that perpetuate themselves in propagation from seed. Thus, no matter what variation occur in the individuals or in the species, if they spring from the seed of one and the same plant, they are accidental variation and not such as to distinguish species.'

## Pre-Linnaean Plant Collections: Book-herbaria and Curiosity Cabinets

The quotation from J. E. Smith's lecture described the state of botanical collections as they were just after the Linnaean revolution, and he discussed public and private botanical gardens, privately owned collections of preserved plants and natural history cabinets, for example as represented by the British Museum in London. The tropical plant collections mentioned previously had been collected by a single traveller or travelling scholar like Hans Sloane in Jamaica or Engelbert Kaempfer in temperate Asia, mostly Japan. We have mentioned that illustrated herbals were produced as manuscripts before the invention of the printing press, later as printed books with woodcuts and finally with engravings, and that book-herbaria in some ways imitated the herbals by gluing pressed plants into book. But almost until the time of Linnaeus such book-herbaria remained the private property of the people that had produced them. The Flemish medical doctor, herbalist and pioneering botanist Carolus Clusius (1526–1609) was called to Leiden in 1593 and became director of the new botanical garden. He initiated systematic collections of tropical plants by urging the staff of the

category we can accept as a genus. In the 96 cases where *eidos* is used, only 24 refer to a kind of animal, in all other cases to a category of higher rank.

Fig. 1. Bound book herbarium, the Marcgrave herbarium, collected by Georg Marcgrave in the Dutch colony in Pernambuco, Brazil, in 1637–1644 and brought to the Netherlands, where it was used by Jan de Laet for editing *Historia Naturalis Brasiliensis* (Piso & Marcgrave 1648). After Jan de Laet's death 1649 the Marcgrave herbarium was purchased by Willum Worm, the son of the Danish scholar Ole Worm, who was in Leiden to arrange the publication of his father's *Museum Wormianum* (Worm 1655). The herbarium was brought to Copenhagen and incorporated in Worm's collections. After Worm's death it was acquired by King Frederic 3, who included it in his collections. The herbarium was studied by N. Wallich during his time as a student of botany in Copenhagen, and later by Eugen Warming in connection with his studies of Brazilian plants (Andrade-Lima *et al.* 1977). More recently the herbarium has been studied by a number of visiting botanists. Now in the Natural History Museum of Denmark (photograph by Jørgen Andersen).

Dutch East India Company[9] to collect seeds and living plants and dried plant specimens for the botanical collections in Leiden (Baas 2002, 2017); this seems to be one of the earliest attempts of producing public or university-owned collections of tropical plants.

Early colonisation of the tropics resulted in book herbaria (Fig. 1). An example will illustrate this. In the middle of the 17th century, the Netherlands invaded Brazil, which was otherwise being colonised by Portugal (Andrade-Lima *et al.* 1977; Wagner 2008). After an unsuccessful attack on Bahia (Salvador) the Dutch West India Company attacked Pernambuco, and in 1636 Count (later Prince) Johan Maurits van Nassau-Siegen was appointed governor-General of the Dutch colonies in Brazil. He called scientists and artists to his newly established colony, including the German scientist Georg Marcgrave (1610–1644), who arrived in 1638 and made a collection of Brazilian plants. After Marcgrave's death in Angola, Jan de Laet (1581–1649) received his herbarium in Leiden and used it for editing a posthumous edition of Marcgrave's work (in Piso & Marcgrave 1648).

Appearing during the Renaissance was also the idea of a 'Kunstkammer', collected by royalty or scholars. There were two kinds of 'Kunstkammer':

(1) The Royal or Princely 'Kunstkammer', which mainly contained works of art or crafts, but sometimes also objects of natural history. The earliest

9. The company mostly referred to by the British as the 'Dutch East India Company' had many slightly varying names: 'the United East India Company', 'the United East Indian Company', 'the United East Indies Company', or, in Dutch, 'Vereenigde Oost-Indische Compagnie' or 'Verenigde Oostindische Compagnie', and was often just known as 'VOC'.

Fig. 2. A piece of stem of *Clusia rosea* Jacq. (Clusiaceae) from the West Indies (48 cm long). Adventitious roots have grown around the trunk of a host so it resembles a giant hand. This specimen was in the 'Kunstkammer' of the King Christian V of Denmark in 1674 (Gundestrup 1991 (vol. 1): 71). Now in the Natural History Museum of Denmark. (photograph by Jørgen Andersen).

Princely 'Kunstkammer' was established in Vienna in 1553 and has formed the basis of two major museums in Vienna, the Kunsthistorisches Museum and the Naturhistorisches Museum (Haag & Kirchweger 2012). Founded only a few years later, in 1560, was a 'Kunstkammer' in Munich, belonging to Albrecht V, Duke of Bavaria (ruled 1550-1579). This soon became one of the largest in Central Europe and among the first princely collections explicitly conceived as a site for storage and production of universal knowledge, although plants were scarcely represented in the collection (Pilaski 2007).[10] Also the Danish King Frederic 3 established a 'Kunstkammer' at his palace in 1650, but that also contained an element of 'curious' objects of natural history, such as a natural 'hand' formed by the roots of a climbing *Clusia rosea* Jacq. (Fig. 2; Gundestrup 1991).

(2) The private scholarly collections were usually less spectacular than the Royal or Princely 'Kunstkammer', and might contain everything the professor wanted to study or use for teaching his students. It was in Italy that such collections were first assembled. One of the earliest and most spectacular was Ulisses Aldrovandi's vast collection in Bologna from ca. 1550 (Findlen 1994). His collections were supposed to contain 18,000 objects of natural history and 7000 pressed plants in fifteen volumes. Presently the University of Bologna exhibits much of what is left of this vast collection.[11]

The Danish *Museum Wormianum*, gathered from 1621 and onwards by professor Ole Worm in his residence

10. Pilaski's statment does not take note of the fact that this 'Kunstkammer' for some time contained the important book-herbarium of the Oriental traveller Leonhart Rauwolf (1535-1596). Upon his return to Europe, Rauwolf prepared a book herbarium in four folio volumes with 834 European and Near Eastern plants. The herbarium was sold to Duke William of Bavaria and placed in the 'Kunstkammer' in Munich, but was taken to Sweden during the Thirty Year' War. About 1650 Queen Christina presented the herbarium to her teacher Isaac Vossius. In 1680 the University of Leiden purchased the volumes, and it is now at L.

11. With regard to plants, only parts of the Aldrovandi collection is now on public view (Biblioteca Universitaria di Bologna 2017). Numerous woodblocks of plant illustrations are on show, not Aldrovandi's 7000 dried plants in 15 volumes, which are kept with the *Erbario di Università di Bologna* (BOLO), where the volumes represent one of the world's oldest still existing book-herbaria with tropical plants. Aldrovandi's plants are mostly wild plants collected in Italy, but a few are exotic species.

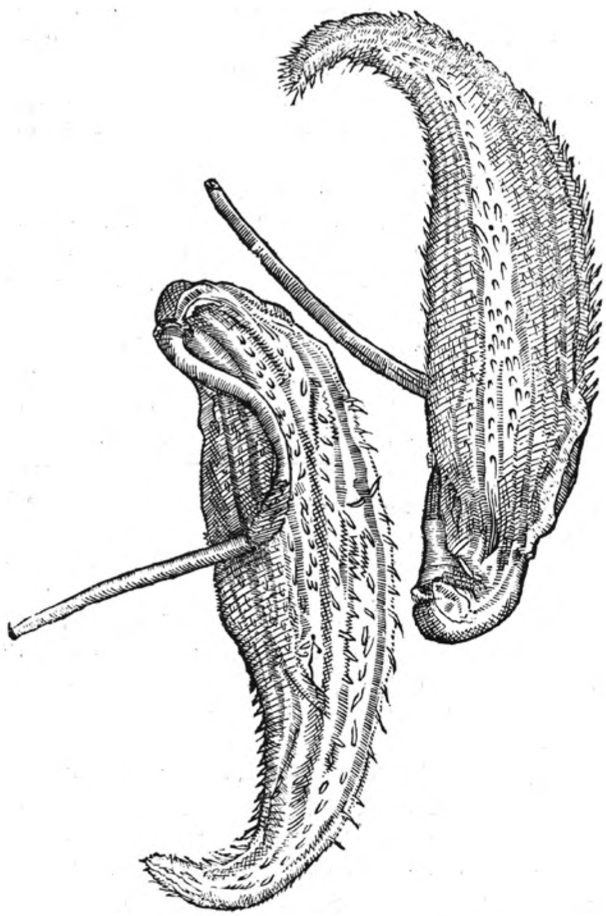

Fig. 3. Fruits of *Asclepias syriaca* L. from Ole Worm's 'Kunstkammer', illustrated in his *Museum Wormianum* (Worm 1655: 188). Worm's original material has not been traced; the fruits were received from the mayor of Copenhagen, Hans Nielsen, who had grown the plant from seeds in his garden. According to Worm this plant was identical with 'Beid el Ossar', a plant from Egypt, which was described and illustrated by Alpino (1592). Alpino's plant is *Calotropis procera* (Aiton) W.T. Aiton, widespread in drier parts of tropical Africa, Arabia and south Asia, and naturalised elsewhere, whereas *Asclepias syriaca* is indigenous in the warmer parts of North America and introduced early to the Mediterranean and the warm parts of Europe. This is an example of the many misidentifications in the pre-Linnaean literature, which were most frequent when the new material was not compared to authentic material.

at the University of Copenhagen (Worm 1655). The identification of the objects in these scholarly collections was sometimes far from correct, at other times the owner of the collection was tempted to identify the object simply by comparing it with descriptions and illustrations in published works, as can be seen in the example from Worm's museum in Fig. 3. It is not certain if Worm considered the previously mentioned Marcgrave-herbarium part of his *Museum*; in *Museum Wormianum* (Worm 1655) only the *Historia Naturalis Brasiliae* (Piso & Marcgrave 1648) is mentioned, not the herbarium.

Up to the beginning of the 19$^{th}$ century, the essentialist species concept was generally accepted, and all species in genera were given names beginning with the name of the genus and followed by phrase-names, consisting of one to many words, giving the essential or diagnostic characters of the species, This should enable the botanist to distinguish the species from all other known species by its name alone (Stearn 1957: 81–88). Mayer (1982: 260) has summarised the consequences of the essentialist species concept in four postulated characteristics:

1. Species consist of similar individuals sharing in the same essence.
2. Each species is separated from all others by a sharp discontinuity.
3. Each species is constant through time.
4. There are severe limitations to the possible variation of any one species.

These ideas culminated in the work of Linnaeus, who – as we will see in the next section – began to introduce changes, and his students an followers continued this trend until the next major shift in ideas, the Darwinian revolution.

## The Linnaean Revolution: A new nomenclature

The two main changes in botany caused by the Linnaean Revolution were (1) the establishment of a simple system for classification of genera (the sexual system), (2) the binary nomenclature that reduced the phrase name to two words, a generic name and a specific epithet, which Linnaeus called 'nomen triviale'. Not less important was the consistent use of these two innovations in works covering the entire plant kingdom, primarily the *Species Plantarum* (Linnaeus 1753). Of these two innovations, only the binary nomenclature has survived to the present.

Linnaeus and his pupils continued to use the essentialist ideas about genera and species; the number of species now in existence is identical with the number of forms that were created in the beginning. "We maintain that, in the beginning of things, a single sexual pair of every species of living [being] was created" (from S. Freer's translation of Aphorism 132 of *Philosophia botanica*; Linnaeus 1751: 86). "That new species can come into existence in vegetables [plants] is disproved by continued generation, propagation, daily observations and the cotyledons."[12] (from Aphorism 157; Linnaeus 1751: 99). Linnaeus did not deny the existence of variation, but in aphorism 158 of *Philosophia botanica* Linnaeus (1751: 100) he stated: "A variety is a plant that is changed by accidental cause: climate, soil, heat, wind, etc., and likewise it is restored by a change of soil." In Aphorism 162 (Linnaeus 1751: 101), he stated: "The species are very constant, since their generation is actual continuation. ... That varieties are the work of cultivation is clearly shown by horticulture, which frequently produces and modifies them." This had consequences for collections: one single complete specimen with root, stems, leaves, flowers, and fruits, could stand for the entire species with its essential characters. What mattered was to have as many species as possible represented in the collection, not many specimens of each species.

In Aphorism 11 in *Philosophia botanica* Linnaeus (1751: 6) made the famous remark: "A herbarium is better than any picture, and is necessary for every botanist." This indicated that a herbarium was an individualistic

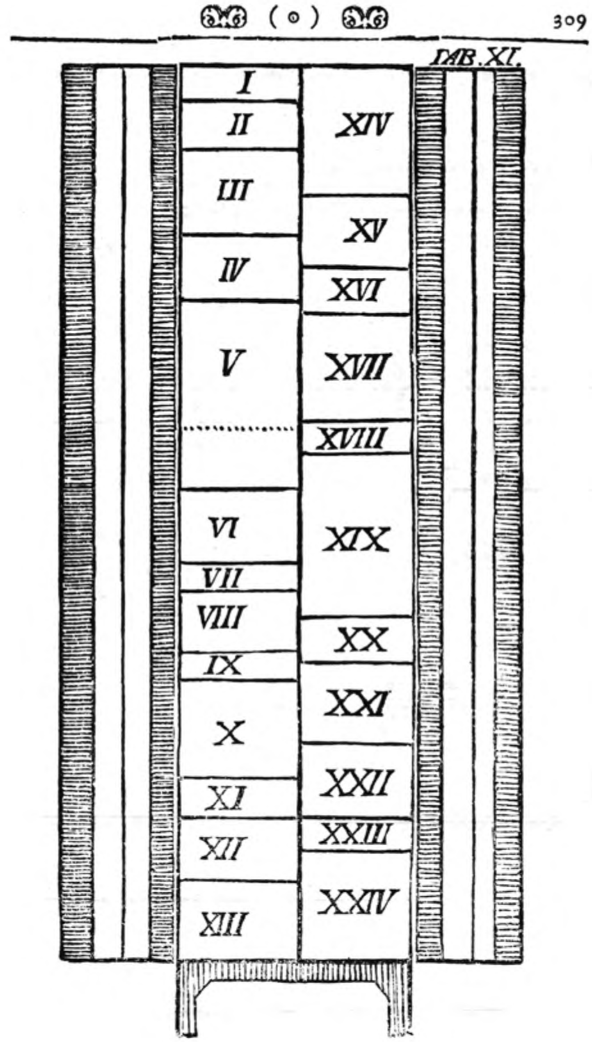


Fig. 4. A cupboard with two doors and two rows of shelves for a herbarium with specimens mounted on loose sheets of paper. The Roman numerals indicate the shelf-space to be allocated to each Linnaean class in the sexual system (Linnaeus 1751: Plate XI). In the legend to this plate Linnaeus stated that this was a herbarium arranged according to his sexual system with two long folding doors, nicely corresponding to a vertical partition. The cupboard would hold ca. 6000 specimens, which was almost the number of species known in 1751. The dimensions should be accurate: 7 ½ Paris feet from top to bottom, 16 inches wide, excluding the partition. Then the space to be allotted to each class is accurately indicated in inches.

12. This is the translation by S. Freer in his English edition of Linnaeus (1751). The reference to cotyledons in this context is not clear to the author. The original Latin text is: "Novas species dari in vegetabilibus negat generatio continuata, propagatio, observationes quotidianae, Cotyledones."

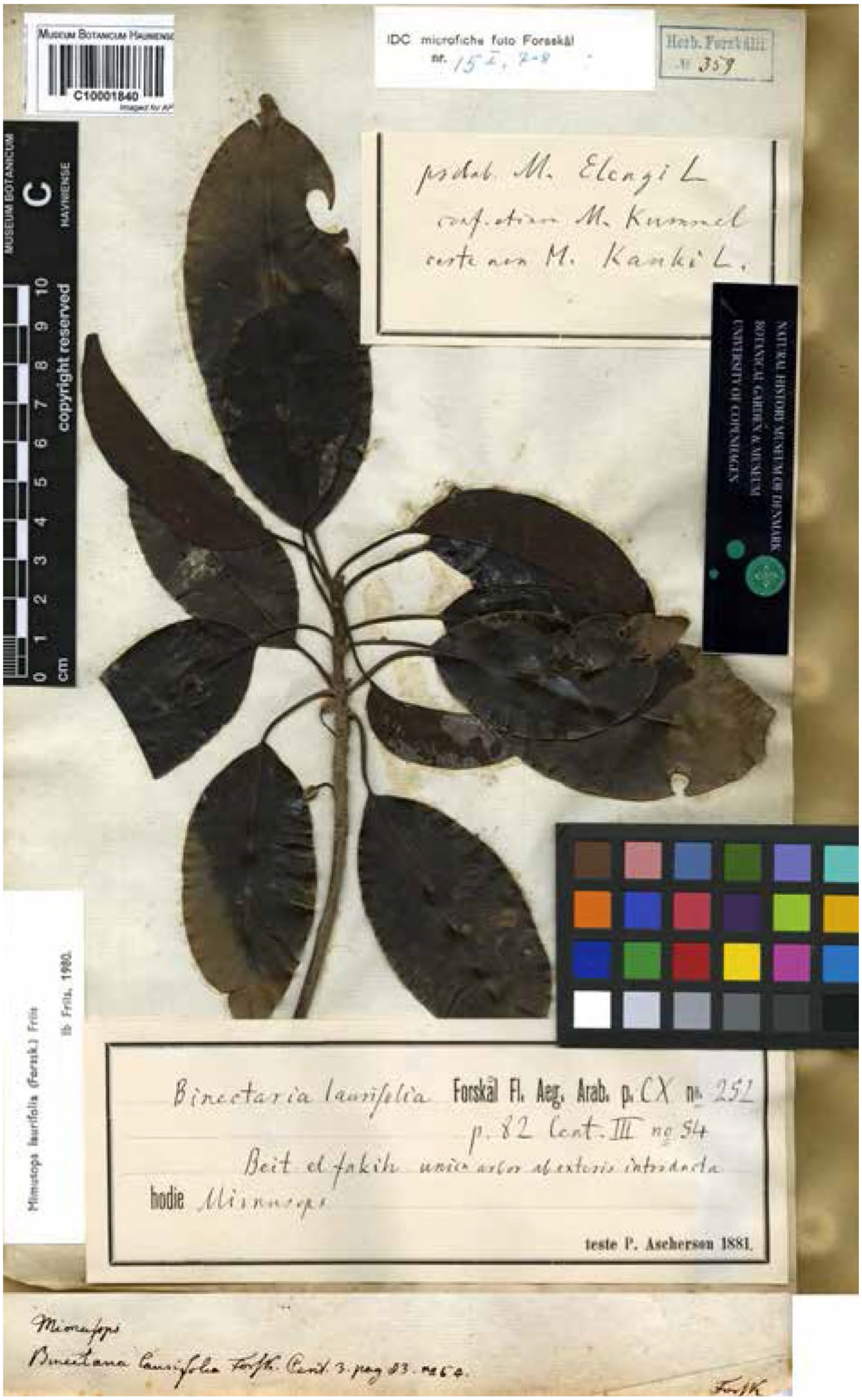


Fig. 5. Specimen of *Mimusops laurifolia* (Forssk.) Friis (Sapotaceae), collected by P. Forsskål at the town of Beit el Fakih in Yemen. This is one of two preserved specimens and type of the species name. Forsskål stated in his information about the plant that there was only one tree of this species at Beit el Fakih, and that it was introduced from elsewhere. In fact the tree occurs in a few localities with evergreen forest on the slopes of the Yemen escarpment, but is more widespread on the escarpments facing the Red Sea and the Gulf of Aden in Ethiopia and northern Somalia. There is no original Forsskål-label on this collection. The oldest annotations are the ones by Martin Vahl on the back of the sheet (inserted here at the bottom of the image). Vahl organised Forsskål's specimens to be mounted on paper and identified with his notes. The stamp in the upper right corner is an early attempt at numbering the Forsskål-collections, made in the second half of the 19th century. The large label at the bottom of the sheet was added by the German botanist P. Ascherson, who studied Forsskål's herbarium around 1880 (Hepper & Friis 1994: 50). The small labels are all from the last quarter of the 20th century. Now in the Natural History Museum of Denmark and digitised as C10001840.

and private collection; everyone should have one, as we have seen exemplified above. Linnaeus then goes on to give some simple advice on how to press plants and make a herbarium, and recommend that the pressed and dried plants should be glued to a loose sheet of paper, only one plant to a sheet, and not bound, as in book herbaria. In the same work, Linnaeus strongly recommended the herbarium of loose sheets that could easily be reorganized in agreement with new knowledge.[13] At the end of *Philosophia botanica,* Linnaeus (1751: 311, "Tabula XI") gave detailed direction for the size of cabinets needed to hold a complete herbarium, and how much shelf-space were needed for each of his classes in such a collection (Fig. 4). This clearly indicated that he did not see a herbarium as an ever-expanding collection. The number of specimens in Linnaeus' own herbarium changed, as he gave away specimens when he received new and more complete ones. It is estimated that about 16,000 specimens have at one time been in the Linnaean herbarium (Stearn 1957: 103). When J.E. Smith purchased the Linnaean herbarium it included ca. 13,800 specimens (Jackson 1922; "some 14,600 specimens", according to Jarvis 2007), only a slightly higher number than the number of species he accepted during his lifetime. The number of tropical plants in the Linnaean herbarium has not been counted, but it was probably less than 1/3 of the total. However, the number of specimens from the tropics was still limited in spite of the journeys to tropical countries undertaken by the students of Linnaeus.[14] P. Forsskål's visit to Yemen as part of his participation to the Royal Danish expedition to Arabia, 1761–1763, resulted in ca. 1850 specimens, representing ca. 1000 species, of which probably only half the number came from the tropics (Fig. 5; Hepper & Friis 1994).

13. As we have seen, already Carpar Bauhin (1560–1624) kept pressed plants loose in folded sheets of paper in his herbarium, a method which, with modifications, was used 200 years later in the development of the herbarium of A.P. de Candolle in Geneva, and which is still used at the Conservatoire et Jardin botaniques de la Ville de Geneve (G). And, as mentioned elsewhere in this paper, the loose-leaf herbaria were well known in the Netherlands during Linnaeus' visits to that country in 1735–1738.

14. A map of the journeys by the students of Linnaeus was published at the end of Fries (1950). The tropical countries most visited were in South-East Asia and along the north coast of South America. The Cape of Good Hope (not tropical) was also frequently visited, and two students took part in Captain Cooks voyages: Daniel Solander in the first and Anders Sparrman in the second voyage.

## After the Linnaean Revolution: Variation becomes a subject of study

Augustin Pyramus de Candolle (1778–1841) changed the principles for developing herbaria. The first sentence in in book 3, chapter 2 in his *Théorie elementaire,* (in both editions of the book; A.P. de Candolle 1813: 157; 1819: 193), deals with the species concept and variation within the species. The ideas behind this are basic to the representativeness of specimens (my own translation and paraphrasing): "Nature only shows us individuals. This fact is true, but often the wrong consequences are drawn from it. Is it not necessary to realise that although all the oaks in a forest and all the pigeons in a dovecot are individuals, they are more similar to each other than they are to other creatures? Is it necessary to use science to realise that the acorns of the oaks and the eggs of the pigeons produce offspring that is more similar to the creatures that generated them than to the offspring of any other creature? From these two commonly accepted observations has the idea of species arisen." After a few more examples he concludes, somewhat like John Ray in an earlier quotation in this paper, that a species is a group of individuals that resemble each other more than they resemble any other individuals, and that they can produce through generations other individual specimens that look more like their ancestors than any other individuals. All this is in good agreement with the essentialist species concept.

However, A.P. de Candolle (1813: 160–182, 1819: 196–215) also discussed the concepts of varieties and hybrids, classifying them into categories and – mildly – criticizing Linnaeus for too rigid and superficial views on variation. Thus, he concluded, it is necessary to have enough specimens of each species to represent both the accidental variation of the species and the variation represented by hybridisation and real 'varieties', a concept not yet fully understood. According to other parts of *Theorie elémentaire*, particularly where the author promoted natural classification rather than the sexual system of Linnaeus, it is necessary to have representative observations of all the possible characters that can be used for such a natural classification.

The two editions of the *Theorie elémentaire* also dealt with practicalities of herbaria in a full chapter (in both editions of the book as part 2, chapter 6), stating that even the best description or illustration could not replace material of the plant itself. Because of A.P. de Candolle's emphasis on variation, he concluded that it was necessary to conserve significant material for comparison, the variation of the different parts of plants. This was best done in a herbarium, rather than in a botanical garden, because in a herbarium at any time one could study the organs one needed. This is discussed in detail in the second edition of *Theorie elémentaire* (A.P. de Candolle 1819: 323)[15].

At this place it is relevant to mention the Danish (Norwegian born) botanist Martin Vahl (1749-1804). Generally, Vahl was a strict follower of Linnaeus, but he also realised the need to see original material used by other botanists when they had established new species (Vahl 1790: Latin unpaginated Praefatio, translated into English in facsimile, p. viii-ix). Vahl realised the danger of identifying plants only with the aid of diagnoses, descriptions, and illustrations, a danger illustrated in this paper on Ole Worm's identification of *Asclepias syriaca* L. with *Calotropis procera* (Aiton) W.T. Aiton (legend to Fig. 3). Throughout his life Vahl wanted to revise the – in his opinion – far too uncritical new editions that appeared of Linnaeus's *Species plantarum*, and he criticized the compilers of these new editions for not seeing enough material when describing or accepting a new species. Vahl therefore made two long journeys through Europe, visiting most major plant collections, in order to see both new herbarium material and material studied by previous authors. Vahl does not seem to have questioned the sharp discontinuity between species or that species are constant through time. A.P. de Candolle shared Vahl's views on the importance of seeing enough, and particularly *original* material, and *Théorie élementaire* contains a section on the importance of this material, thus Vahl and A. P. de Candolle foreshadowed the modern type concept. A.P. de Candolle (1813: 280) pointed out that Vahl in his *Enumeratio plantarum* (Vahl 1804-1805) indicated if and where he had seen a dried specimen.

From the early decades of the 19th century the amount of plants that arrived in Europe from the tropics increased dramatically. One example will illustrate this: the *Prodromus*-herbarium, on which A.P. de Candolle founded his enumeration of all vascular plants except ferns and monocotyledons (A.P. de Candolle *et al.* 1825-1874), began at the beginning of the 19th century its existence with very few specimens, when A.P. de Candolle died in 1841 it contained 161,748 specimens, when A. de Candolle died in 1893 it had grown to 324,376 specimens, and when the accession to the herbarium ceased at the completion of the *Prodromus* and its supplements at the beginning of the 20th century the number of collections was 399,646 specimens (Conservatoire et Jardin botaniques de la Ville de Genève, undated).

A few important collectors, some of which also contributed to the *Prodromus* herbarium, can be mentioned: Indian and South Asian collections were provided by Nathaniel Wallich (1786-1854; ca. 20,500 collections, including those made by others, main set at K-W) (Vegter 1988: 1110); Wallich lived and travelled in India, Nepal (Fig. 6), Burma, and Singapore from 1807 to 1835 and moved to London, where he organised the vast herbarium of the British East India Company to be listed and numbered, and duplicates to be distributed to most of the important herbaria in Europe. Carl Ludwig von Blume (1796-1882) made numerous collections in the Dutch East Indies (present Indonesia), mainly on Java in 1822-1826; his main

15. As a further example of A.P. de Candolle's ideas about the variation to be studied in herbaria, one can cite these lines (A.P. de Candolle 1819: 323-324): "Il serait éminemment précieux pour la connaissance des lois réelles de la Taxonomie, de réunir d'une manière analogue des exemples variés de soudures plus ou moins complètes, d'avortements, de transformations ou d'aberration d'organes; il serait précieux pour l'étude des lois générales de la végétation, d'avoir des- herbiers où l'on trouverait des échantillons comparatifs des mêmes organes et des mêmes plantes crues dans un sol sec ou humide, découvert ou ombragé, au pied, sur le flanc ou an sommet des montagnes, dans les pays chauds ou froids, etc."

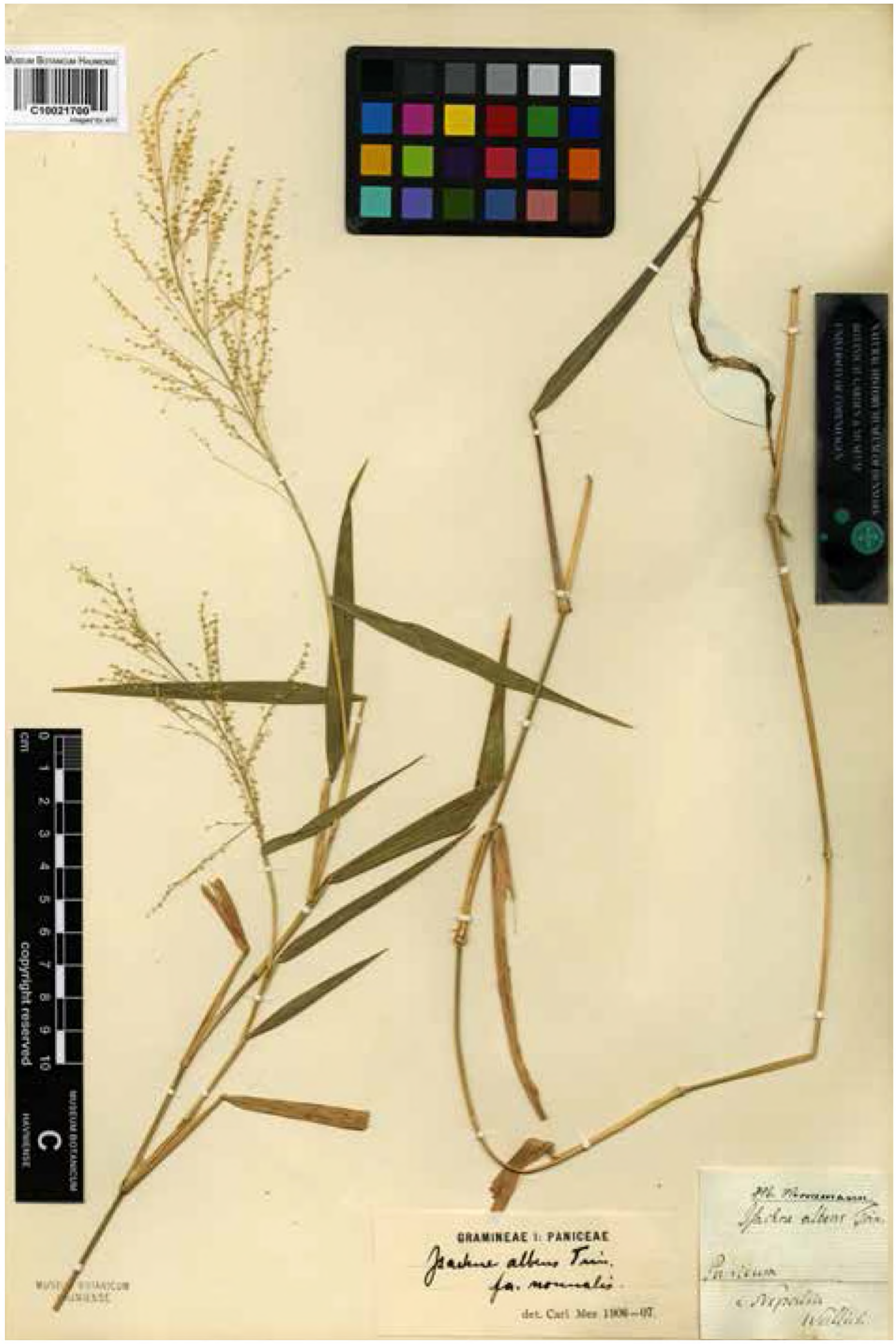


Fig. 6. Specimen of the grass *Isachne albens* Trin., collected in 1821 in Nepal by N. Wallich, sent to J.W. Hornemann in Copenhagen and now in the General Herbarium of the Danish Natural History Museum. Wallich was born in Copenhagen in 1785 and originally sent to India as surgeon at the Danish trading post Frederiksnagore (Serampore) north of Calcutta. In 1814 Wallich was appointed assistant surgeon in the East India Company's service, temporary superintendent of East India Company's botanical garden at Calcutta in 1815 and finally superintendent of that garden in 1817. In 1820–1821 Wallich made an 18-month expedition to Nepal. This and another specimen, stated to be collected at Sanko in Nepal, are almost certainly early distributed duplicates of the collections from Nepal, which were later incorporated in the Wallich Herbarium at Kew (K-W), and in the Wallich catalogue as No. 8658. Now in the Natural History Museum of Denmark and digitised as C10021700.

set is at L, but also at more than 20 other herbaria, including G-DC (Lanjouw & Stafleu 1954: 80), and Franz Wilhelm Junghuhn (1809–1864) followed this tradition with many collections from Java 1837–1839 and 1855–1864; elsewhere in the Dutch East Indies, particularly the Malay Archipelago (1837–1848, 1851–1855) and on Sumatra (1840–1842), the main set of these collections are at L (Chaudhri *et al.* 1972). Alexander von Humboldt (1769–1859; ca. 6000 collections, main set now at P, many duplicates) (Lanjouw


Fig. 7. *Dioon edule* Lindl. (1843), collected in 1842 by Frederik Michael Liebmann at Conchiquitla (Consoquitla) in the low mountains between Mt. Orizaba and the coastal town of Veracruz in southern Mexico. The originally collected plants are still in cultivation in the Botanical Garden, Natural History Museum of Denmark. On herbarium sheets and on watercolours Liebmann named the plants *Macrozamia littoralis* and *Macrozamia pectinata*, but the names were not taken up or validly published. Lindley described his new genus *Dioon* Lindl. [as 'Dion'] on a cone and a live plant brought to England at almost the same time as Liebmann made his collections (photographed by Ib Friis).

& Stafleu 1957: 292), Carl Friederich Phillip von Martius (1794-1868; ca. 7200 own collections, 63,000 including other collectors, main set BR, many duplicates) (Vegter 1976: 509) and Richard Spruce (1817-1893; ca. 10,000, main set K, many duplicates) (Vegter 1986: 938) are famous collectors in South America from that period. F. M. Liebmann (1813-1856) collected more than 95,000 specimens in southern Mexico, Cuba and the West Indies (Chaudri *et al.* 1972: 441), but his collections were only numbered after his return and the figure reflects sheets, not number of collections (Fig. 7, 8). From tropical Africa and warm temperate South Africa came the collections made by William John Burchell (1782-1863; ca. 5000 collections, main set at K) (Lanjouw & Stafleu 1954: 106), Friedrich Martin Josef Welwitsch (1808-1872; > 3000 collections, many duplicates, main sets at COI, LISU and BM) (Vegter 1988: 1136) and Georg Heinrich Wilhelm Schimper (1804-1878; probably ca. 4000 collections, widely distributed) (Vegter 1986: 840).

In the first part of the 18$^{th}$ century, European botanical gardens developed better heated greenhouses, allowing the cultivation of an increasing number of plants collected in the tropics (Fig. 7). At the same time, botanical gardens and herbaria started developing in the tropics, particularly in colonies of European countries, for example in Brazil (Rio) and India (Calcutta).

## The Darwinian Revolution and After: The delimitation of species in focus

When Charles Darwin (1809-1882) published his 'Origin of Species' (Darwin 1859) he was not the first to suggest the evolution of species as a fundamental theory in biology. That had been suggested already by Jean Baptiste Lamarck and others in the early 19$^{th}$ century, and it seems gradually to be realized that this would put an end to the essentialist species concept. Lamarck's new theories about the modifications of species were first seen in his manuscript lecture notes from May 1800 (Mayr 1982: 344-345) and elaborated in his book *Philosophie zoologique* (Lamarck 1809). The need for larger collections with more specimens had already been suggested by A.P. de Candolle because of the need to understand variation. After Lamarck and Darwin, it became essential to study as much material as possible in order to circumscribe species, define their natural variation and delimit species against similar species. The growth of one of the largest her-

Fig. 8. Specimen of *Urtica chamedryoides* Pursh. (1814), collected in September 1841 by F.M. Liebmann near the top of Mt. Orizaba (Pico de Orizaba) in southern Mexico at 10,000 ft. (ca. 3100 m). Liebmann (1851: 292) described it as a new species, *Urtica orizabae* Liebm. He sorted and annotated his own collections, but did not provide them with labels. His notes about localities and dates of collecting were written directly on the sheets on which the plants were mounted, just as Linnaeus, Forsskål, and Vahl had done. When later incorporated in *Museum botanicum Hauniense*, all Liebmann's specimens were numbered and provided with printed labels. Now in the Natural History Museum of Denmark and digitised as C10013025.

Fig. 9. The Herbarium of the Royal Botanic Gardens, Kew, interior of what is now Wing C. Built in 1876–1877 for storage and work with herbarium specimens over three floors, the upper two galleried on iron columns. The design maximised admission of natural light as gas-light presented a serious fire hazard. In 1903 the building was stripped of its elaborate ironwork and wooden panelling, fire-proof concrete floors laid, and the galleries widened. The original interior can be seen in an early photograph reproduced in R. Desmond's history of Kew (Desmond 1995: 248). The building was added to the oldest part of the present herbarium complex, the Hunter House, to hold the rapidly growing collections. At the appointment in 1841 of the first director of the Royal Botanic Gardens, William Hooker, there was no official herbarium at the gardens. Hooker made his own collections available to staff and visitors on the ground floor of the Hunter House; the collections grew so quickly that this pupose-built wing was added in 1876–1877. The next wing, currently Wing B, also with three floors, was added in 1902. Wing A, with four floors, was added in 1932. A fourth Wing D closed the quadrangular courtyard in 1969. A basement with compactors was added under the quadrangle in 1990, and a fifth Wing E was added in 2009. Photo and information kindly provided by David Goyder, Kew.

baria focussing on tropical plants, the Herbarium of the Royal Botanic Gardens, Kew (Fig. 9), but similar stories can be told about the growth of the other big herbaria with tropical plants in for example Berlin (B; growth interrupted by destruction of most of the herbarium in a fire during World War 2), Bruxelles (BR), Geneva (G), Leiden (L, now incorporating the herbaria from Wageningen (WAG) and Utrecht (U), see Welzen & Schollaardt 2017), Missouri (MO), New York (NY), and Paris (P).

This change in collection-based plant taxonomy was well reflected in the work of Alphonse de Candolle, son of A. P. de Candolle. In *La phytographie* (A. de Candolle 1880), he presented his general review of analytical and descriptive plant taxonomy. He stated that testing species descriptions against specimens in good herbaria with much material is the best way to achieve accuracy in taxonomy, or at least in descriptions. Unfortunately, tropical plants were often only known from few specimens, and if described as new species and given a name, it was necessary to test the taxonomy when more material became available, and possibly establish synonymy if the studies revealed that the variation of two or more previously accepted species overlapped. A. de Candolle listed three important uses of herbarium material:

(1) It helped to fix the names of plants with preserved material that could be studied for verification;
(2) It provided material allowing the botanist to study the variation of plant species and describe this variation;
(3) It made accessible material of previous botanists, and thus made it possible to test and understand previously published descriptions and taxonomic conclusions.

A great and well-equipped herbarium would make much more widely sampled material available than for example a botanical garden, would contain specimens from a wide range of habitats, altitudes, geographical range, of different age, and from collections made at different times of the year. Living collections, on the other hand, would allow better anatomical studies and better information about colour, fragrance, etc., if the living material was tested against good and ample herbarium material. A. de Candolle criticized earlier botanists who published only descriptions and illustrations without documenting these with herbarium material. Making good collections in remote countries was a challenge and that some eminent botanists had provided more service to science as field collectors than as herbarium taxonomists. Phillibert Commerson (1727-1773), Carl Friedrich Drège (1791-1867) and Richard Spruce (1817-1893) were singled out for praise as collectors, in spite of their having published nothing or very little.

In his advice to collectors A. de Candolle emphasized well-known virtues: to select good and representative material and to preserve it well by careful pressing and drying of the specimens, but he added that the new requirements of botany made it necessary also to collect as much material as possible for many duplicates from the same locality and to number this material carefully, so that the various duplicates of the same collections could be identified, even when in separate herbaria.

De Candolle praised two botanical collectors for innovation and consistent practice in making their collections: (1) Phillibert Commerson, global collector, was praised for being the first to follow the first of these recommendations, and his duplicates from remote parts of the tropics were deposited in up to twenty herbaria in different towns. However, de Candolle mentioned that it might be difficult to identify which specimens in different herbaria were actually duplicates of the same collection, for Commerson did not number his collections. (2) William John Burchell, collecting in South Africa, was one of the first to number his collections, and the idea of numbering collections spread quickly to other collectors when authors started citing them in the *Prodromus*. It was most likely because of this that Wallich and his collaborators made such efforts to number the duplicates from the British East India Company which they distributed from 1830 and onwards with reference to the published catalogue of the collections. With the idea of carefully numbering the collections followed the absolute requirement that the collector, collecting locality and year of collecting should be clearly indicated. This information was more important than a precise name, for it would always remain with the specimen, while the scientific identification might change.

Because it required special knowledge to understand some old herbaria, and these were closely associated with classical botanical works, it could – according to A. de Candolle – be advantageous to keep them as separate, special herbaria that reflected particular traditions or practices of their original private owners, such as the Tournefort herbarium in Paris, the Bauhin herbarium at Basel, the Linnaean herbarium in London, the Willdenow herbarium in Berlin and the *Prodromus* herbarium at Geneva.

In Demark, I may add, this should also continue to apply to the previously mentioned herbarium of Peter Forsskål (1732-1763) from Egypt and Yemen. But mostly it would be advantageous to integrate the work of many collectors in one large *herbarium generale,* where the botanists could with ease compare many specimens from many parts of the world.

The post-Darwinian period saw a vast increase in the number of collections from the tropics, particularly in herbaria in European countries with colonies (Great Britain, France, the Netherlands and Belgium). This was due to improved transportation of both material and scientists and progress with the understanding of health-hazards in the tropics, improved medication, such as vaccination programmes and malaria prophylaxis.

## The International Trend after the First World War: Collaboration and standardisation

After the First World War there was a strong move towards internationalism in botany, reflected in the renewed discussions about a unified nomenclature on both sides of the Atlantic, including making an end to the special 'Kew Rule'[16] with a united set of rules for priority in botanical nomenclature and rules for types, but only after ca. 1950 the collaboration became successful. Nicolson (1991), taking a pessimistic view, called the period from the beginning of the First World war up to ca. 1950 the 'dark age', emphasising the many unsuccessful attempts at agreements and progress at Botanical Congresses. After the Second World War there was also a strong urge for more collaboration between herbaria, a movement which to a large extent originated in the Netherlands and resulted in the creation of the International Association for Plant Taxonomy (IAPT) (founded on the seventh international botanical congress in Stockholm, 1950), the journal *Taxon* and the monograph series *Regnum Vegetabile*, of which the first volume, appearing in 1953, was a report from the very same botanical congress in Stockholm in 1950. Dutch botanists had important roles in all this, not least the energetic and productive Franz Stafleu (1921-1997), who, while attending to many other tasks, brought order in more than two hundred years of botanical literature and wrote a monograph on the spread of the Linnaean ideas (Stafleu 1971). A biographic obituary of Franz Stafleu was published by Werner Greuter (1998).

It is not surprising that ideas and results of these efforts were exemplified in a major Dutch botanical publication, the general parts of the *Flora Malesiana*, especially in parts of vol. I, mainly due to Cornelis Gijsbert Gerrit Jan van Steenis and his wife, Mrs. M.J. van Steenis-Kruseman (Steenis 1949-1958; Steenis-Kruseman 1950). The general chapters in this part of the flora contain detailed lists and reviews of the available taxonomic literature for the area covered by the flora, information about collectors and their collecting localities, chapters about where and how to collect, how to incorporate material in herbaria, dates of publication of important works, general considerations about taxonomy, delimitation of species and infraspecific taxa, etc. These texts largely follow the ideas and examples of A. de Candolle, who was also a pioneer of rules for botanical nomenclature in *Lois de la nomenclature botanique* (A. de Candolle 1867). In a way the introductions to the *Flora Malesiana* can be seen as a 200 years younger parallel to Linnaeus's *Philosophia botanica*

16. The so-called 'Kew Rule' was followed by botanists at the Royal Botanic Gardens, Kew, and by some other British botanical authors, to determine the choice and application of names in botanical nomenclature. *Index Kewensis*, used the Kew Rule until its *Supplement IV* (published in 1913). The Kew Rule applied the rules of priority for specific epithets only within genera, so that when transferring a species to a new genus, there was no requirement to retain the epithet of the original species name, and the priority of species names was counted from the time the species was established in or transferred to the new genus. This was contrary to the international rules that required, and still require, priority for epithets when species are moved from one genus to another.


Fig. 10. Specimen collected in the late 20th century in Uganda by Axel D. Poulsen, D. Nkuutu, and H. Dumba as no. 975. The collection was numbered when the plant was collected and the number is the same for all duplicate specimens. Holotype of *Chlorophytum occultum* A.D. Poulsen & Nordal (Asparagaceae, formerly Anthericaceae). Modern labels for herbarium specimens include information about collectors, their institutional affiliation, detailed information about the locality where the specimen has been collected, including geographical coordinates and altitude, collecting date and year, phytosociological information about the habitat, and such information about the plant which is not available from direct inspection of the specimen. Original determination and later redeterminations also appear from labels, as well as type status. Now in the Natural History Museum of Denmark and digitised as C10000932.

and a 75 years younger parallel to parts of Alphose de Candolle's *La Phytographie,* in which clear identification of authors and collectors, clear identification of herbaria, etc., were also promoted. The methodologies proscribed in the introductory chapters in *Flora Malesiana* are therefore also to large extent analogous with the recommendations of A. de Candolle, and I will not repeat them here. The virtues with regard to taxonomy praised by A. de Candolle and *Flora Malesiana* were indeed the virtues I was taught to respect when I first came in contact with tropical botany in the 1960s and still respect as the basis for sound taxonomic work, not least in the tropics.

## Tropical Plant Collections Now and in the Future

But in the 1960s and 1970s a new revolution started; phylogenetics was introduced as the testable method for the study of evolutionary relationships among groups of organisms, proposed first through mathematical analyses of morphological data-matrices and later through matrices of data obtained from sequencing of macromolecules (DNA, RNA). The English translation in 1966 of Willi Hennig's *Grundzüge einer Theorie der phylogenetischen Systematik* (Hennig 1950, 1966) could be taken as a starting point for this new revolution, which continued with the development of molecular techniques during the following decades. In the same decades computer technology developed fast, allowing handling of large amounts of data and electronic storing and transmission of images. Up to now, this has had two important consequences for botanical collections: digitization of plant material and the gathering and analyses of large-scale data.

The preserved collections are basically still pressed and dried plants mounted on paper, but now provided with much more detailed labels (Fig. 10) and supplemented with DNA collections and all the traditional collections (plant parts in alcohol, carpological collections, wood collections, anatomical slide collections, pollen collections, etc.).

Nowadays herbaria have a problem with their reputation, as everyone in the present symposium was aware of. It is almost too easy to assume that a methodology developed through more than 250 years ago is outdated, a burdensome legacy from the past. Herbaria with good coverage of the world's flora, as recommended by A.P. and A. de Candolle, are big, take up a lot of space and need permanent curation. If they are not well curated, they will gradually be more and more difficult to use, not follow the latest nomenclature and taxonomy and cease to reflect our knowledge of the plant world.

The same applies to botanical gardens. It is not easy to justify what it takes in expenses and manpower to maintain comprehensive plant collections to politicians, university managers and others, who do not work with herbaria and botanical gardens themselves, and it becomes even more complicated if we deal with tropical herbaria and tropical botanical gardens maintained in temperate countries. Examples of this are presented in papers in this volume by Sanjappa and Venu (2017) and Blackmore (2017). For botanists is seems self-evident that the relatively biodiversity-poor temperate countries have the tradition, financial and academic capacity to look after at least the collections that have already been gathered from the tropical and more biodiversity-rich countries, and perhaps to supplement them somehow, so they are still useful in international scientific collaboration.

However, it is obvious that the old idea of collections being representative samples of nature will come under further pressure in the future. Since the end of the 18$^{th}$ century a culture has developed among botanists granting free access to scientific information and material in plant collections, private or public, provided that this was for *bona fide* academic studies. This was a necessity for the writing of monographic studies covering plants with wide distribution areas which therefore had to be looked for in many herbaria in different countries. Specimens and other material was freely sent on loan or exchanged over country borders, at least in long periods during the last two hundred years.

The first step towards restrictions on sending specimens across borders was taken at a meeting in 1963 between members of the International Union for Conservation of Nature (IUCN), a membership international membership union created in 1948 and composed of both governments and civil society organisations with an interest in nature conservation (IUCN 2017)[17]. A draft resolution to control the exchange of

17. In Denmark, the Danish Ministry for Food and Environment, Agency for Water and Nature Management, and eight non-governments organisations are members of the IUCN.

threatened species was adopted. The final *Convention on International Trade in Endangered Species of Wild Fauna and Flora* (CITES 2017) was opened in 1973 for signing by countries that agreed to be bound by the Convention, and it entered into full force in July 1975. The basic aim of the convention is to ensure that international trade in specimens of wild animals and plants does not threaten the survival of the species in the wild, but any transfer from country to country of scientific material, such as loan and free exchange herbarium specimens, seeds and other propagules between botanical gardens are covered by the convention, and the customs authorities of countries that have signed the convention are instructed to confiscate any material of endangered species, which occur on the appendices of the convention and are sent across borders without the necessary permissions and documentation. This applies to more than 35,000 species of animals and plants, mainly plants, for example, all species of the genus *Aloe* and all species of orchids. Today, almost all countries in the world have signed this convention, and bureaucratic control has become relatively firmly established for legal exchange under CITES of scientific material between established academic institutions such as national herbaria and botanical gardens.

More wide-ranging is the *Convention on Biological Diversity* (CBD 2017). The United Nations Conference on Environment and Development (UNCED), also known as the Rio Summit, was held in Rio de Janeiro in June 1992 (UNCED 1992) and endorsed the *Convention on Biological Diversity*, largely a product of the preparations for the Rio Summit. This convention recognized for the first time in international law that biological diversity should be "a common concern of humankind", that policy for the country's biodiversity was an integral part of the development process in all countries, also those in the tropics, even if the biodiversity of these countries was not sufficiently known, and that the convention changed the fundamental concept of ownership of biodiversity from the "common heritage of humankind" (as opposed to "common concern of humankind") to the "sovereign right" of each country. This is being interpreted in such a way that national law under the umbrella of the convention regulates the movement of living or preserved specimens across boundaries. Thus the convention has made each of the more than 170 nations responsible for regulating access to their own biodiversity. In spite of all its virtues the CBD has opened up new and partly as yet unresolved questions on a global scale about the opportunity to study biodiversity represented to any sample of plants and animals in other countries than that of its origin, and to move specimens of biodiversity beyond national jurisdictions.

It is not yet clear what the exact consequences of the international legislation under the CBD will be for herbaria and botanical gardens which hold material from other than their own country. In 2010 a protocol was signed in Nagoya, Japan, by a range of the signature countries of the CBD. The intention behind the Nagoya protocol (2017) is to further access to biological diversity, including genetic resources, and a fair and equitable sharing of benefits arising from utilisation of biodiversity between the home country and the countries where biodiversity is utilised. Unlike with the CITES convention, an internationally accepted practise has not yet developed with regard to the consequences of the Nagoya protocol for herbaria and botanical gardens. The critical procedures are referred to in the Article 17 of the protocol; according to which each signature country is obliged to monitor the use of genetic resources by establishing one or more checkpoints. All access to genetic resources, which is taken to cover living and preserved specimens of animals and plants, is to be governed by prior informed consent between the original owner of the biodiversity and the user, for which mutual terms have to be established. If enforced down to single specimens, this will require a formidable bureaucracy at herbaria and botanical gardens with thousands or millions of specimens. International agreements between consortia of institutions housing natural history collections may smoothe the bureaucracy of the Nagoya protocol, as it has to some extent been possible with the transactions between institutions under the CITES convention. In October 2016, the Consortium of European Taxonomic Facilities (CETAF), a

European network of large natural history museums, botanical gardens and biodiversity research centres, signed a Memorandum of Understanding with the Botanic Gardens Conservation International (BGCI), standardising procedures under, for example, the Nagoya protocol, and CETAF has drafted a set of standard documents for exchange of material between its member institutions, but still it seems that this may be a challenge for institutions with dwindeling staff.

Possibly, digitisation of specimens and increasing use of DNA-sequence data for characterization of taxonomic units or clades may reduce the need for actual movement of specimens or other forms of biological material across boundaries, but according to the Annex of the Nagoya protocol, it is intended to cover not only material of biodiversity, but also intellectual property rights. The good intentions of the CBD and the Nagoya protocol must be put into a workable practice that will further, rather than hinder, basic research utilising plant specimens in the future. Herbaria and botanic gardens have a proud tradition of serving science world wide; it is to be hoped that this can and will be carried on.

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Herbaria in North and South

SCI.DAN.B. 6 · TROPICAL PLANT COLLECTIONS
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# The Golden Age of Dutch Colonial Botany and its Impact on Garden and Herbarium Collections

*Pieter Baas*

## Abstract

Apothecaries and surgeons aboard the first fleet of the Dutch East India Company (VOC) in 1602 were instructed to collect herbarium specimens and make detailed observations and illustrations of useful and interesting plants during their voyage. Yet it would take three decades before a first botanical account of some plants from Java would materialise, and much longer before the three great Dutch pioneers of Asian tropical botany and servants of VOC, Paul Hermann (Ceylon), Hendrik Adriaan van Rheede tot Drakenstein (Malabar Coast, India), and Georg Everhard Rumphius (Ambon, Indonesia) made their momentous contributions. Hermann's herbarium collections are currently mainly in London, but with significant subsets in Leiden and Gotha they were the basis of Linnaeus's Flora Zeylanica. Hortus Malabaricus, authored by the nobleman-soldier-diplomat cum amateur botanist Rheede remains a relevant source of ethno-botanical and pharmacognostic information, judged by its recent annotated translations into English and Malayalam by K.S. Manilal. In his powerful role in the VOC, Rheede moreover instructed VOC officials in India, Ceylon and the Cape Colony to send seeds and living plants to Dutch botanical gardens. Herbarium Amboinense by Georg Everard Rumphius, another self-taught botanist, was recently translated into English and richly annotated by E.M. Beekman and is even of greater significance. It is an inspiration for modern biopharmaceutical studies of tropical plants, selected on the basis of historical ethno-botany. These three highlights of Dutch colonial botany would form a basis on which 20th century initiatives such as Flora Malesiana and Plant Resources of South East Asia (PROSEA) still could build.

**Key Words:** Hermann, Botanical Gardens, Herbarium Amboinense, Hortus Malabaricus, Rheede, Rumphius

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One can argue that the Golden Age of colonial botany in the Netherlands roughly lasted from about 1600 when significant natural curiosities were brought back from the East, until the mid 18th century, after which both the East and West India Companies declined in significance. Doubtlessly the flourishing of tropical botany was only possible thanks to a strong 16th century tradition in the Low Countries, fostered by great Flemish herbalists Dodonaeus (1517-1585) and Mathias de l'Obel (Lobelius; 1538-1616), and the more universal scientist Carolus Clusius (1526-1609). Clusius equally appreciated the medicinal and ornamental value of plants, and showed an active interest in tropical plants ever since he had translated and revised Garcia da Orta's book on Indian spices and 'simplicia' in 1567 (Egmond 2015). In his old age as honorary professor of the young Leiden University Clusius had persuaded the authorities of the Dutch East India Company (Vereenigde Oost-Indische Compagnie, VOC) to instruct apothecaries and surgeons aboard ships of their first fleet to the East Indies "that they bring along branchlets with their leaves, laid between paper … Especially of the searched after spices: pepper, nutmeg, mace, cloves and cinnamon, but also of any other interesting plant. To make illustrations. And to record local names and uses, and how they grow" (Baas 2002). The whole instruction to the medical staff of the VOC almost reads like a 'Systematic Agenda 1600', but it would take decades before significant collections were accumulated and research yielded any results. Jacobus Bontius, physician of Jan Pieterszoon Coen, the cruel first VOC Governor on Java, was the first to write an account of 70 Javanese plants, published much later by Willem Piso (see De Wit 1949, who also recorded the role of several other 'minor' pre-Linnaean botanists in the Malaysian region).

Truly monumental botanical contributions, justifying the label 'Golden Age' had to wait until the second half of the 17$^{th}$ century when Paul Hermann (1646-1695), Hendrik Adriaan van Rheede[1] tot Drakenstein (1636-1691) and Georg Everhard Rumpf (Rumphius, 1627-1702) combined their service for the VOC with botanical studies in Ceylon (Sri Lanka) , Malabar (modern Kerala) and the Moluccas (Indonesia). In this paper I will briefly summarise their contributions, drawing from an earlier review paper in Dutch (Baas 2002) of the role of the VOC in 'Flora's pleasure gardens', and a paper on Rumphius (Baas & Veldkamp 2013). These publications were in turn largely based on thorough bio-historical studies by Karsten (1967) on Hermann, by Heniger (1986) and Manilal (2003 ) on Rheede, and by Buyze (2006), and Beekman (1999, 2011) on Rumphius.

These three botanical heroes, though often physically very remote from any colleague or centre of learning did not work in a vacuum. They knew that many people in the home country were very eager to increase their collections of natural curiosities and knowledge of the exotic plant world in the East, for enabling them to read God's *Book of Nature* (Jorinck 2006) and/or to obtain empirical knowledge on useful exotic plants. They could also fall back on a growing body of academic expertise represented by professors of medicine (incorporating botany) and botanical garden curators at Dutch universities and wealthy and knowledgeable amateurs associated with the VOC. In this paper I limit myself to the three 'tips of the iceberg' in the exploration of the East Indies. The early botanical explorations of the Cape Province in South Africa (Hermann and many others) and Japan (Kaempfer), as well as the early exploration of Brazil by Markgraf and Piso during the campaign of the West India Company lead by Johann Maurits of Nassau-Siegen in Pernambuco, Brasil, that would result in the landmark publication *Historia Naturalis Brasiliae* in 1648, are also very important highlights of the early Dutch colonial history, but will not be discussed here.

I use the term 'Dutch Colonial Botany' with some hesitation. Colonial implies the conquest of and domination over territory. Initially the Dutch activities in the Far East were only aimed at trade. However, in its fights for trade monopolies the VOC often acted with equally cruel determination as the worst territorial colonial powers of the era (Beekman 1999), yet one could argue in favour of the adjective 'pre-colonial' for the Dutch Golden Age of tropical botany (Baas & Veldkamp 2013).

1. Heniger (1986), in his authoritative biography has argued in favour of the spelling van Reede - without the h. But since hardly anybody followed that recommendation, and van Rheede tot Drakenstein is one of the ten spelling variants that were used during Rheede's life-time, I here conform to the spelling of his name "in current use".


Fig. 1. Herbarium specimen of the clove plant, *Syzygium aromaticum ('Caryophyllus aromaticus')* from the Paul Hermann Herbarium in Leiden.

## Three Pioneer Botanists in the Service of the VOC

### *Paul Hermann – scientist par excellence*

Of the three main pioneers discussed here Paul Hermann was the only academically trained scientist. Born in 1646 in Halle, Saxony, he obtained a medical doctor's degree in Padua, and then entered the service of the VOC. The Company sent him to Colombo, Ceylon to explore whether the use of local medicinal plants were a good alternative for the classical European simples that were hitherto used by the surgeons and apothecaries of the VOC, and had proved ineffective and easily subject to decay in the tropical climate. On return to the Netherlands Hermann was appointed Professor of Medicine and Botany and Prefect of the *Hortus Botanicus* at Leiden University. Here he could use all his VOC contacts to accumulate living plants for the greenhouses built in the small garden under his governance. No one less than Linnaeus wrote a biography, or rather a hagiography of the great Hermann, in which no superlatives were left unused to sing his eternal fame earned by his floristic studies in the Cape and Ceylon (Karsten 1967; Baas 2002). The significance of Hermann's herbarium collections (Fig. 1) for nomenclature and typification has been well documented (Jarvis 2007), and its impact on tropical botany is testified by its use by Linnaeus (1747) for his *Flora Zeylanica*, his only excursion into tropical flora writing. Most of Hermann's erudite research on tropical plants was published posthumously by his student William Sherard, the first and famous Professor of Botany at Oxford University in the UK.

### *Hendrik Adriaan van Rheede tot Drakenstein – amateur botanist and team leader*

Rheede belonged to the rich and influential nobility of the province of Utrecht in the Netherlands (Fig. 2). Having received only private tuition and no formal education he entered the military and administrative service of the VOC on his twentieth (Heniger 1986). Heroic action during the conquest of Cochin (Kerala, India) furthered his promotion to a high rank in the Malabar (~Kerala) operations of the VOC. Here he became overwhelmed with the botanical wealth of the region and impressed by the local knowledge of the Brahmins and Ajurvedic practitioners. During a two year intermezzo in Ceylon he was confronted with the call by Andries Cleyer – apothecary of the VOC headquarters in Batavia (Jakarta) – for further research into tropical medicinal plants and their local uses. This call would lead to Paul Hermann's mission in Ceylon (see above). Back in Malabar, this time as Commander, Rheede befriended the Italian physician, missionary, discalced priest, and botanist Mattheus of St. Joseph, a keen student of medicinal and other plants of the Middle East and later India. So, when Reede embarked on his ambitious *Hortus Malabaricus* project in 1674, he could recruit a team of collaborators – Mattheus of St. Joseph, Brahmins, Ajurvedic practitioners, interpreters, plant collectors (probably including soldiers under his command) and later in the Netherlands a changing series of professional (academic) botanists to create and edit a unique inventory of 689 plant species, mainly native, some introduced, beautifully illustrated and printed with pre-Linnaean names in Latin, Portuguese and Dutch and local names in Arabic, Malayalam and Konkani characters - a *novum* in botanical printing (Rheede 1678-1692; Manilal 2003). The accuracy of the plant descriptions was verified by Nicolson *et al.* (1988) and found to be in excellent order. This is remarkable when one considers the numerous linguistic pitfalls possible in a project that synthesised information from the local languages (mainly Malayalam) via the early colonial Portuguese language into Dutch and Latin. That linguistic achievement was recently extended by the critical translation into English and back into Malayalam by K.S. Manilal (2003, 2008). According to Manilal, Rheede and his team played a crucial role in preserving India's bio-cultural heritage: many of the original palm leaf manuscripts from which the medicinal uses were copied have meanwhile been lost.

Nicolson *et al.* (1988) only found one description and illustration impossible to interpret: a species

Fig. 2. Hendrik Adriaan van Rheede tot Drakenstein as portrayed in his *Hortus Malabaricus*.

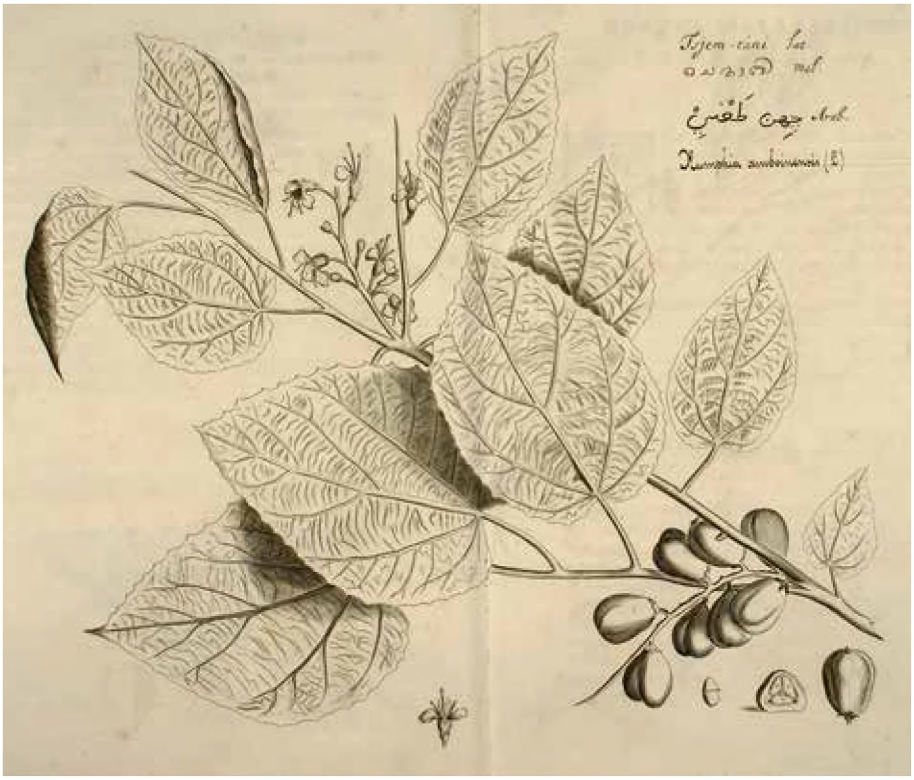

Fig. 3. Drawing from Hortus Malabaricus: 'Tsjem-tani', later named *Rumphia amboinensis* by Linnaeus (see text).

named 'Tsjem-tani', later renamed *Rumphia* by Linnaeus (1753: 1193), with the species name *Rumphia amboinensis* L., that does not seem to exist in nature (Fig. 3). Probably it is a species of *Croton L.* (Euphorbiaceae) with some grave mistakes in the Rheede's description and illustration. It is ironic that our third hero of the Golden Age of Dutch tropical botany Rumphius is thus remembered by a genus name of a plant that does not exist.[2]

## *Georg Everard Rumphius – the blind seer*

Rumphius's biography has been the subject of many publications, most recently by Beekman (1999, 2011), Buyze (2006), Veldkamp (2011), and Baas and Veldkamp (2013), and will not be repeated here. Readers of Latin or Dutch had no problems in consulting his magnum opus *Herbarium Amboinense* as published posthumously by Johannes Burman between 1741 and 1755. However, the critically annotated translation into English by M. E. Beekman published in 2011 three years after Beekman's death, has rekindled the interest in this rich resource for bio-historical and ethno-botanical research. Buenz (2007) and Buenz *et al.* (2005) have already given a foretaste of how the analysis of Rumphius's texts helps to focus modern bioprospecting studies with positive results about the medicinal value of *Atuna racemosa* Raf. (Chrysobalanaceae) and a convincing falsification of claims of great healing powers of the endocarp of giant coco-de-mer drift seeds (double coconut, *Lodoicea maldivica* (J.F. Gmelin) Persoon ), that had already been put in doubt by Rumphius (Buenz & Bauer 2013). A sometimes neglected aspect of Rumphius's texts is that they contain so many witty and even funny observations, like the mind enhancing properties of the roots

2. When this manuscript was in press, D.J. Mabberley discovered that Van Rheede's illustration and description most probably were based on a species of *Canarium* L. (Burseraceae), and that the illustrator apparently had mistaken its pinnate leaves for simple ones (Mabberley 2016).

of *Bidens biternata* (Lour.) Merr. & Sherff (Asteraceae) applied by the school teacher of Rumphius's daughters, and the very tongue-in-cheek genus name *ABCDaria* for *Acmella paniculata* (Wall. ex DC.) R.K. Jansen in recognition that this plant was used by a local imam to improve the ability of his pupils to read and write Arabic. The many references to lust-enhancement by the consumption of fruits, seeds or other plant parts of for instance durian and cloves are also highly amusing to read (Beekman 2011; Baas & Veldkamp 2013).

## Impact on Systematics and Collections

Widjaja and Kartawinata (2013) have reviewed the long history of botanical enquiry in Indonesia. From the early botanical iconography sculpted on the walls of the 8th century Burobudur temple on Java up to the more recent *Flora Malesiana*, the PROSEA (Plant Resource of SE Asia) projects and current studies focused on Indonesian flora conservation. It is evident that contributions during the Golden Age of Dutch colonial botany, such as Rumphius's *Herbarium Amboinense* established a foundation and inspiration of many of the later and current developments. Similar analyses can doubtlessly also be made for the impact of *Hortus Malabaricus* and the Ceylonese herbarium collections of Hermann on later floristic inventory and ethno-botany of India and Sri Lanka, respectively.

Ironically, no or hardly any herbarium collections survive from Rheede or Rumphius's endeavours. A few specimens have been traced in Florence (Baas & Veldkamp 2013) and very recently a specimen of *Biophytum sensitivum* (L.) DC., (*'Herba senticus* Rumph.*'*) in the Hermann herbarium has been diagnosed as a plant probably sent to him by Rumphius from Ambon (Veldkamp, personal communication 2015). This does not mean that Rheede's and Rumphius's activities did not have an impact on the living collections in the Netherlands. Rheede's instruction from 1691 to VOC servants in the 'Western Quarters' of VOC's sphere of influence: Ceylon, India, and the Cape province in South Africa, was only strictly obeyed by Ceylon, but yielded many tropical accessions for especially the *Hortus Medicus* of the municipal university of Amsterdam. In addition most scientists, university garden curators, and ornamental plant enthusiasts with an interest in tropical flora were part of informal networks involving the governors of the VOC, ship captains, surgeons, and sailors sustaining a constant stream of natural curiosities, including seeds and plants from the Far East to the Dutch Republic (Baas 2002; Jorinck 2006). Even the great microscopist Antoni van Leeuwenhoek (1632-1723) acquired material from VOC ships of ebony from Mauritius, rootwood and seeds of nutmeg and bark of cinnamon from Ceylon, coconut seeds and stems from Java, and *Aloë* leaves from South Africa, for microscopic study and communication to the Royal Society in London (Baas 1982, 2001).

## International Impact

Already in the days of Clusius there was much international contact within Europe between plant collectors, herbalists and private and academic garden enthusiasts (Egmond 2015). Towards the end of the Dutch golden age of colonial botany, the international appeal of the Low Countries culminated in the three-year visit of Carolus Linnaeus from 1735 to 1738 (Blunt 1971). In the Leiden and Amsterdam botanical gardens and in Bennebroek on George Clifford's estate 'De Hartekamp' he saw many dried and living plant collections from the East and West Indies that must have acquainted him first-hand with many taxa to be included later in his *Species Plantarum* of 1753. The first edition of that starting point for Linnaean plant nomenclature only included few references to Rumphius's herbal, which was strange when we consider that he often stayed in Burman's house when the latter was involved in editing and translating it into Latin. However, already in 1754 his student Stickman validated a full list of binomials for plants from *Herbarium Amboinense* (Stickman 1754; Jarvis 2007; Baas & Veldkamp 2013). Rheede's *Hortus Malabaricus* also received international recognition from Linnaeus who based more than a hundred of his species on it (Jarvis 2007) and others like the influential botanist John

Ray in England aquired their understanding of tropical plants on it (Baas 2002).

With the decline of the Dutch East and West India Companies in the second half of the 18th century, we also see that the Dutch Golden age of Tropical Botany came to an end. Clifford's and Hermann's herbaria were acquired by Joseph Banks to form important assets for the later Natural History Museum in London, and a Golden Age of colonial botany would dawn for the United Kingdom, assisted by Dutch (pre-)colonial collections. The Netherlands had to wait for a century or more before its tropical botany could play a significant role on the international stage again, this time with the Botanical Gardens of Buitenzorg (now the 'Kebun Raya' in Bogor, Java) and the Rijksherbarium in Leiden as dual engines, and the herbaria of Utrecht and Wageningen University catering for systematic and floristic studies in Suriname and the Dutch Caribbean islands, and tropical West Africa respectively (see Welzen & Schollaardt 2017).

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# The Botany of the British Empire

*Phillip Cribb*

## Abstract

Most of the world's major herbarium collections and botanical gardens, fundamental institutions for systematic botany, were built during periods of Empire and colonisation. This applies as much to the USA and USSR as it does to the former European powers. The great British botanical institutes and gardens at the Natural History Museum (BM), Royal Botanic Gardens, Kew (K) and Edinburgh (E) are no exception, their living and preserved plant collections having influenced plant science, agriculture and horticulture worldwide over many generations.

**Key Words:** Hans Sloane, Joseph Banks, Joseph D. Hooker, Royal Botanic Gardens, Kew, The Commonwealth, William Hooker

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> 'There scarcely exists a garden or a country however remote, which has not already felt the benefit of this establishment (The Royal Botanic Gardens, Kew). All our public gardens abroad – those in Ceylon, Mauritius, Sydney & Trinidad; & cultivators of the soil, Governors of our own colonies, & consuls are supplied with various products of such divers (sic) as may be deemed suitable to them'.
>
> William Hooker letter to the British Government (quoted in Desmond 2007)

The United Kingdom has three botanical institutions of international significance: The Natural History Museum, London, The Royal Botanic Gardens, Kew, and The Royal Botanic Garden, Edinburgh. Although these often collaborate or have mutually agreed specified areas of research I will concentrate during this presentation on the development of botanical collections and botany in the British Empire on the role of one of these, the Royal Botanic Gardens, Kew, one of the world's largest and most influential botanical gardens. I will discuss its relevance to the botany of the British Empire and Commonwealth and its continuing influence and relevance.

When I was employed on the staff of the Royal Botanic Gardens, Kew, I was asked in the early 1990s to undertake a review of Kew's collections. I was somewhat surprised to end up with details of 17 separate collections of varying size and importance based at Kew, including the 7,000,000 or more herbarium specimens, the comprehensive botanical library and archives, the Economic Botany collection of 50,000 items, the 70,000 bottle spirit collection, the 300,000 botanical illustrations and the rapidly growing Millennium Seed Bank. Our predecessors understood clearly the utility and significance of such comprehensive collections. Their relevance today is often dismissed or ignored and the activities of the botanists that work on them considered as old-fashioned science. In this presentation, I will discuss how the Empire influenced the development of major British collections, such as those at Royal Botanic Gardens, Kew, and how those collections influenced the Empire. I will then consider the significance of those collections for botanical science today.

Botany and its associated collections came to England somewhat later than their development in continental Europe. Broadly the rise and development of botany can be considered through four periods. Its origins lie in the Renaissance in the 16th century, it was driven forward during the Enlightenment of the 17th and 18th centuries, transformed into a full-blown science during the days of Empire and invigorated by the technical developments associated with computing and the discovery of how to use DNA for taxonomic and other studies since the 1960s, a period that coincided with the loss of Empire and rise of the less formal associations of Commonwealth and European Union.

## The Rise of Botany and Botanic Gardens in Britain

William Turner (1508-1568) was the author of *A new Herball* (Turner 1551-1568), the first herbal published in England. He studied in Italy and travelled widely on the Continent where he came under the influence of Guillaume Rondelet (1507-1566) in Montpellier. Rondelet had been a student of Luca Ghini (1490-1556), the first to prepare books of pressed plants (herbaria) to aid identification (see Friis 2017). Botanic gardens and their collections arose originally from man's need for useful plants. In the European tradition, apothecaries' gardens were places where simples, plants with medicinal or supposed medicinal properties, were cultivated for use. In Britain, the first botanic garden, where plants with medicinal properties could be studied, was founded in 1621 at Oxford University. It was followed in 1670 by the Royal Botanic Garden, Edinburgh and, in 1673, by the Chelsea Physic Garden, established by the Society of Apothecaries. This was a period of rapid change in the country. The Tudor dynasty had challenged the established European power of the French and Spanish with trading companies and piracy. By the early 17th century England had a foothold in the Caribbean, on the eastern seaboard of North America while the Honourable East India Company was establishing a presence in the Indian subcontinent. Exotic plants flowed into England from around the world. In many ways, some of these, such as coffee, tea, potatoes, maize and cocoa had a greater long-term impact on the world than the desired spices and gold for which many of the adventurers set sail. These were grown in botanic gardens prior to being cultivated on a wider scale.

## Cabinets of Curiosity and the Rise of Horticulture

The increasing wealth of England as a trading nation in the 16th and early 17th centuries provided the funds and leisure time for the development of gardens for royalty, the aristocracy and the landed gentry. John Tradescant (c. 1570-1638) was one of the first to appreciate the potential for servicing this growing market. He began his career as head gardener to Robert Cecil, 1st Earl of Salisbury at Hatfield House, who sent him to the Low Countries for fruit trees from 1610 to 1611. He was kept on by Robert's son William, to develop gardens at the family's London house, Salisbury House. He then designed gardens on the site of St Augustine's Abbey for Edward Lord Wotton in 1615-1623.

Later, Tradescant became gardener to the royal favourite George Villiers, 1st Duke of Buckingham, remodelling his gardens at New Hall, Essex and at Burley-on-the-Hill, Rutland. In 1618, Tradescant travelled to the Nikolo-Korelsky Monastery in Arctic Russia (his own account of the expedition survives in his collection). Then, in 1620, he travelled to the Levant and to Algiers during an expedition against the Barbary pirates, returned to the Low Countries on Buckingham's behalf in 1624, and finally went to Paris and (as an engineer for the ill-fated siege of La Rochelle) the Ile de Rhé with Buckingham. After Buckingham's assassination in 1628, he was then engaged in 1630 by the king to be Keeper of his Majesty's Gardens, Vines, and Silkworms at his queen's Oatlands Palace in Surrey.

On all his trips he collected seeds and bulbs everywhere and assembled a collection of curiosities of natural history and ethnography which he housed in a large house, 'The Ark,' in Lambeth, London. The Ark was a 'Cabinet of Curiosity', a collection of rare and strange objects, that became the first museum open to the public in England (the *Musaeum Tradescantianum* now forms part of the Ashmolean Museum at Oxford). He also gathered specimens through American colonists, including his friend John Smith (1581–1631). From their botanical garden in Lambeth, on the south bank of the Thames, he and his son, John (1608–1662), who later made two expeditions to North America, introduced many plants into English gardens that have become part of the modern gardener's repertory.

## Sir Hans Sloane and the Foundation of the British Museum

Sir Hans Sloane (1660–1753) was one of the most influential of those who followed in the Tradescant tradition of collecting curiosities (De Beer 1953; MacGregor 1994). In his youth, he collected objects of natural history and other curiosities which led him to study medicine in London. Following a period in France he returned with a considerable collection of plants and other curiosities, of which the former were sent to Ray and utilised by him for his *History of Plants*.

He was elected to the Royal Society in 1685 and a fellow of the College of Physicians in 1687. The same year he went to Jamaica aboard HMS *Assistance* as physician in the suite of the new Governor of Jamaica, the Duke of Albemarle. In fifteen months there; he collected about 800 new species of plants, which he catalogued and published as a work in two volumes *A Voyage to Madera, Barbados, Nieves, St Christopher and Jamaica* (Sloane 1707–1725). Sloane encountered cocoa while he was in Jamaica and devised a means of mixing it with milk to make it more pleasant. When he returned to England, he brought his chocolate recipe back with him where it was initially manufactured and sold by apothecaries as a medicine.

His practice as a physician among royalty and the upper classes was large, fashionable and lucrative and, in 1716, he was created a baronet, making him the first medical practitioner to receive a hereditary title. In 1719 he became president of the Royal College of Physicians, holding the office for sixteen years. In 1722, he was appointed physician-general to the army, and in 1727 first physician to George II. In 1727 he succeeded Sir Isaac Newton as president of the Royal Society; he retired from it at the age of eighty. He was a founding governor of London's Foundling Hospital, the nation's first institution to care for abandoned children.

Sloane purchased the manor of Chelsea in 1712, provided the grounds for the Chelsea Physic Garden. When Sloane retired in 1741, his library and cabinet of curiosities had grown to be of unique value and included the extensive natural history collections of Engelbert Kaempfer's from Japan, William Dampier's from NW Australia (made 70 years before Banks reached the continent), and Mark Catesby's from Florida and the Carolinas and also those of William Courten, Cardinal Filippo Antonio Gualterio, James Petiver, Nehemiah Grew, Leonard Plukenet, Mary Summerset, the Duchess of Beaufort, the rev. Adam Buddle, Paul Hermann, Franz Kiggelaer and Herman Boerhaave.

He bequeathed his collections to the nation and, together with George II's royal library, it was opened to the public at Bloomsbury as the British Museum in 1759. His Natural History collections were later to become the foundation for the Natural History Museum (MacGregor 1994).

## Sir Joseph Banks and the Rise of the Royal Botanic Gardens, Kew

Sir Joseph Banks (1743–1820) was the critical link between Enlightenment figures, such as Sloane, and the recognition of the strategic importance of plants for the nation that eventually led to the establishment of a national botanic garden at Kew (Gasgoigne 1998). As a wealthy and enthusiastic young man seeking adventure and sponsored by the Admiralty but largely self-funded, he accompanied Captain James Cook on his round-the-world voyage in 1768–1771. On his return he was feted and became a confident of King George III whose estate at Kew had been established as a botanic garden by his mother Princess Augusta with the help of Lord Bute. By 1773, Banks had become the unofficial director of the garden, a position that was formalised in 1797. Banks dispatched explorers and botanists to many parts of the world, and through his efforts Kew Gardens became arguably the pre-eminent botanical gardens in the world, with many species being introduced to Europe through them and through the Chelsea Physic Garden and their head gardener John Fairbairn. Banks directly fostered several famous voyages, including that of George Vancouver to the Northwest Pacific, and William Bligh's voyages to transplant breadfruit from the South Pacific to the Caribbean islands. He also chose Allan Cunningham for voyages to Brazil and the north and northwest coasts of Australia to collect specimens. The Royal gardener and botanist at Kew, William Aiton published in 1789 a catalogue in three volumes of the plants grown in the gardens at Kew, *Hortus Kewensis* (Aiton 1789). The second and nearly twice as large edition of this work was edited and much augmented by William Aiton's son, William Townsend Aiton (Aiton & Aiton 1810–1813) and listed plants from Australia (c. 300 species), South America (c. 260 spp.), Siberia (c. 220 spp.), and China (c. 120 spp.).

Banks was also instrumental in the colonisation of the east coast of Australia, giving glowing reports of its potential to the government who were looking for places to site penal colonies after the loss of North America during the War of Independence. Increasingly, Banks influenced the development of the botany and agriculture of the Empire through his numerous contacts in government and science, particularly through his role as President of the Royal Society. He actively supported existing botanic gardens in the colonies and campaigned for new ones (Desmond 2007).

During the reign of King George III, the East India Company established botanic gardens in India at Samalkot and Calcutta specifically to learn about native plants and to experiment with species suitable for cultivation there (see Sanjappa & Venu 2017). Initially the interest was in the culture of spices, such as nutmeg, pepper, cinnamon and cardamom, but the rich flora of the region sparked considerable local collecting and botanical expeditions. William Roxburgh (1751–1815), Nathaniel Wallich (1786–1865) and William Griffith (1810–1845), the first three superintendents of the Calcutta Botanic Garden were all pioneering collectors. Roxburgh established the first Indian herbarium and an associated collection of watercolour paintings of native plants drawn by local artists, Wallich made the first collections in Nepal, while Griffith ventured into Afghanistan in the First Afghan War, Bhutan with the first diplomatic embassy and Burma. Their collections form a large part of the herbarium of the East India Company which came to England in 1837 before being split into a set for Calcutta and another that eventually came to Kew at the beginning of the 20$^{th}$ century. It forms the basis for the botany of the Indian Subcontinent (de Candolle & Radcliffe-Smith 1981; Desmond 1992).

At this time, horticulture began to realise the potential of tropical plants and the Empire provided easy access. The nursery of Messrs Conrad Loddiges of Hackney, which flourished from 1771 until 1852, pioneered growing tropical plants for commercial horticulture. For example, it received plants from the professional collector Hugh Cuming (1771–1865) from the Philippines (Dance 1980). Cuming also sent many of his plant collections to William Hooker at Kew. Loddiges' example was followed by Messrs Low & Co of Upper Clapton, another London nursery, and soon afterwards by many other nurseries, notably Messrs James Veitch & Sons of Chelsea and Exeter, and Messrs Fredk. Sander & Sons of St Albans. Orchids were a particular focus for many of the collectors. Many of the finest plants to be introduced ended up at Kew and the link between Kew and horticulture continues to the present day.

One of Banks's greatest protégés was Robert Brown (1773–1858) whom he sponsored to join HMS Investigator as botanist on Matthew Flinders' circumnavigation of Australia (Mabberley 1985). There he collaborated with Ferdinand Bauer, the great botanical illustrator, and Peter Good, a gardener from Kew. Brown collected 3400 species in Australia, of which some 2000 were new to science and were published in his *Prodromus Florae Novae Hollandiae* (1810), considered now as the basis for the botany of the continent. Brown became Banks' librarian in 1810 and was bequeathed his collection and library on Banks' death. Brown, in turn, gave them to the British Museum (Natural History) where he worked for the rest of his life.

## The Hookers at Kew

The death of Banks coincided with a loss of interest by the Royal family in Kew. By 1838, concern about the state of Kew and its future led to the government commissioning John Lindley (1799-1865) and Joseph Paxton to prepare a report on the state of the garden and its future. The report strongly recommended that Kew should assume a role as 'an efficient institution for the promotion of botanical science throughout the Empire'. After some delay, William Hooker (1785-1865) was appointed as the first director of the Royal Botanic Gardens, Kew, under its new government patronage. It proved an inspiring choice. Hooker had already established a network of correspondents during his time as Professor of Botany at Glasgow. Notable amongst these was George Bentham (1800-1884) who started working at Kew in 1854 when he presented his herbarium and library to the Gardens. Hooker followed in Banks's footsteps, training gardeners and botanists and recommended the best for service in colonial gardens in Ceylon, India, Singapore, Australia, the West Indies, and Canada. Amongst others, Walter Hill was recommended for Brisbane, William Purdie for Trinidad and George Gardner for Ceylon. This network was then used to transfer exotic plants, both showy and useful ones, around the world, most notably to develop crops to enhance trade. A notably successful collaboration involved British diplomats who received instructions from Hooker to collect plants and plant products for Kew's economic botany collections. Two remarkable examples are the collections of rare hand-made paper collected in Japan by Harry Parkes from 1869-1871 (Uyama 2006) and Japanese lacquer and lacquer-ware assembled by John Quin in 1882 (Prendergast *et al.* 2001).

Kew received preserved collections from many officially sponsored expeditions. The Zambezi Expedition (1858-1864), led by David Livingstone and funded by the British Foreign Office, set out to ascertain whether the Zambezi was navigable in its whole length and to catalogue its natural resources in order to identify raw materials for British industry and to promote commercial markets and civilization to supplant the slave trade. Livingstone was accompanied by John Kirk, Charles Meller, Thomas Baines, Richard Thornton and Charles Livingstone. Kirk and Meller's collections came to Kew. At the same time John Hanning Speke (1827-1864) and James Augustus Grant (1827-1892) set out on a Royal Geographical Society sponsored expedition to determine the source of the Nile. Grant's collection also came to Kew.

On the elder Hooker's death in 1865, the directorship passed to his son Joseph (1817-1911), an eminent botanist in his own right. He had already travelled as surgeon botanist on HMS Erebus on James Ross's Antarctic expedition from 1839-1843. The expedition circumnavigated the southern ocean, visiting Tierra del Fuego, Tasmania, New Zealand and a number of other sub-Antarctic islands. From 1847-1851 he explored the Himalayas of Sikkim and north-east India, introducing amongst others, several species of rhododendron to British gardens, starting a horticultural craze for them. Hooker continued his father's development of Kew as a major botanical institute and also sponsored botanic gardens, botanists and collectors around the Empire. By now, a number of colonists were making systematic collections of plants for Kew and their own newly established botanic gardens. Hooker provided the British Government with advice and recommended staff for the overseas gardens (Desmond 2007). Kew provided an efficient identification service, sending back identifications that could be applied to the specimen retained in country and allowing local botanists to identify native plants accurately. Thus, botanic gardens and collections of accurately identified living and preserved specimens grew throughout the Empire with Kew directors and staff exercising a continuing influence over many decades.

At this time, two of the best-known examples of the encouragement of colonial agriculture are the collection of rubber and quinine from the Americas to the Old World. Richard Spruce (1817–1893) left England in 1849 and spent 15 years collecting over 30,000 specimens in the Amazon and Andes. His main set came to Kew along with seeds of quinine (*Cinchona* spp.) from the Ecuadorian Andes. Successfully grown at Kew, plants were rapidly despatched to Ceylon, India and elsewhere in the Far East where plantations were established. Quinine protected millions from malaria in the succeeding decades. Henry Wickham (1846–1928) is a more controversial character, often unjustly accused of bio-piracy. He sent seeds of rubber (*Hevea brasiliensis* Muell.Arg. ) to Kew in 1876 from Santarem region of Brazil. Kew sent the germinated seedlings to gardens in the Far East. The establishment of successful rubber plantations was largely down to the enthusiasm of Henry Ridley (1855–1956), then director of the Singapore Botanic Garden and his good relations with Chinese plantation owners in Malaya.

In parallel with Kew sending out its own collectors and expeditions and encouraging locally based botanical collection in the British Empire, the Hookers used their extensive network of contacts in Europe and North America to build up collections from regions outside the Empire. The significance of sharing collections was emphasised when the Berlin and Philippines herbaria were destroyed during the Second World War. Fortunately, duplicates sent by them can be found in other herbaria, including Kew.

## In-country Collectors

Kew and its associated herbaria and gardens continued to benefit from collections from the Empire. One of the most fruitful networks was that set up by Edgar Milne-Redhead, the Kew Herbarium's deputy keeper, at the end of the Second World War. He encouraged the colonial civil servants, medics, farmers and missionaries (or more specifically their wives) in tropical Africa to collect systematically for Kew. Large collections resulted from west, east and south-central Africa. Ladies, such as Marjorie Tweedie on Mt Elgon and Helen Faulkner in Tanga, Tanzania (then Tanganyika) made extensive herbarium collections and produced scrapbooks full of beautiful watercolour drawings of them. The latter are now in Kew's archives. *Upland Kenya Wildflowers* (Agnew 1974) was illustrated by Marjorie Tweedie's drawings. The most remarkable of Milne-Redhead's team was Mary Richards (1885–1977) who first visited Africa at the age of 65 and proceeded to collect 35,000 numbers in Tanganyika (Tanzania) and Northern Rhodesia (Zambia), including large numbers of novelties.

## The Commonwealth

The Second World War proved a watershed for the British Empire with many countries acquiring independence in its wake, beginning with India and Pakistan in 1947 and most of the remainder the Empire during the 1960s. However, the existing links were fostered by the creation of the British Commonwealth, which most of the newly independent nations joined. Three countries, Australia, India and South Africa sent liaison botanists to Kew to deal with requests from their fellow countrymen. The Australian liaison botanists stayed a year, whereas the Indian and South Africans stayed three years at Kew. Most of them were young scientists who, upon returning home, rose to senior and influential positions in their own institutes. Research on the floras of Commonwealth countries continued at Kew with an increasing input from in-country botanists. The tropical African floras, such as the *Flora of Tropical East Africa* and *Flora Zambesiaca*, were written as regional monographs, greatly enhancing their scientific value and longevity. Increasingly, Kew has contributed to extra-Commonwealth floristics, notably in tropical Africa, South America, and China, both as authors and as editors of floristic accounts and relevant monographs.

Monographic work and revisions were also encouraged, many leading to doctoral thesis for Kew and Commonwealth botanists. I would like to highlight the series of monographs of monocotyledon families that have been produced in recent years, including *Genera Graminum* (Clayton & Renvoize 1999), *Genera Palmarum* (Dransfield *et al.* 2008), *Genera Aracearum* (Mayo *et al.* 1997) and *Genera Orchidacearum* (Pridgeon *et al.* 1995-2014). Each involved Kew staff, often as coordinators, editors and authors, but nearly all of them also involved a network of contributors from around the world. In the case of the last, 180 scientists contributed to its success. These monographs now provide the basis for future research and will hopefully inspire young scientists to enter the profession. When I started to work on orchids at Kew in the early 1970s I would have given my eye-teeth to have had a synopsis like *Genera Orchidacearum* as a starting point for my life's work.

Alongside the floristic and monographic work, Kew continued to produce important databases and tools for the botanical community, notably *Index Kewensis* (originally funded by a bequest from Charles Darwin) that has now transmogrified into IPNI (The International Plant Names Index), the *Authors of Plant Names* (Brummitt & Powell 1992) and others. Staff members also contribute to many international projects for the botanical community, an increasing number now that the world-wide web is so accessible.

Kew started as an institute to deal with the economic plants of the Empire and its economic botany collections continue to be relevant and a source of significant research and development programmes. The Plantas do Norde-Este (PNE) project that sought to bring high-quality plant information and techniques to local communities in the nine states in the arid and impoverished north-east of Brazil is a fine example of how botany can catalyse development. Seed money from Shell and the UK's Overseas Development Ministry brought together institutes in the region and local Non-Governmental Organisations (NGOs) to provide information (from Kew's SEPASAL database of useful plants of arid lands), techniques and seed sources (from the Millennium Seed Bank) to solve local problems, such as fuel wood deficiency, control of goat grazing, increasing honey yields and living pharmacies to local communities. Kew's participation acted as a catalyst for the institutes to collaborate and credibility to the project in the eyes of government in Brazil. The project is now funded in-country and continues its successful path.

Kew, Edinburgh and the Natural History Museum each have long-established relationship with British and foreign universities, running specialist courses and co-supervising students at various levels up to post-doctoral level. Training and technology transfer to sister institutions around the world has been a major element of the work of these institutes and remains a high priority.

Perhaps the most important developments of the late 20$^{th}$ century for systematic botany were the discovery of the structure of the DNA molecule by Watson and Crick in the 1950s, the increasing use of DNA sequences as taxonomic markers in the 1950s and onwards and the development of powerful computers that started in the Second World War but gained incredible momentum from the 1970s onwards. These have energised botanists and have brought the botanical community together and made possible collaborative approaches that could not have been contemplated before. However, I think that the influx of young enthusiastic and well-qualified scientists is equally important to a science that was rapidly being seen as old-fashioned by others.

## Conclusion

The British Empire provided easy access for British botanists to countries around the world. Collaboration with locally based expatriates, and more recently with local botanists and collectors, allowed for efficient use of time and resources for field-work. The government's establishment of botanic gardens in the colonies to encourage plantation agriculture and the study of potentially useful native species in every part of the Empire meant that botanists and collectors could use them as bases for intensive studies of the native floras. Specimens flowed back to the major British institutions at an impressive rate (60,000 a year to Kew when I started there in the early 1970s), duplicates remained in-country to enrich the national herbaria while those collections were enhanced by the accurate identification and naming provided by botanists at Kew and by the flow of potential new crops to the colonial gardens.

Although it is currently fashionable to decry this (e.g., Figueiredo & Smith 2010; Smith & Figueiredo 2011), many benefits for botanical science, agriculture, horticulture and conservation have accrued as a result. The major botanical collections, such as at Kew, have the advantage of relatively comprehensive geographical and systematic scope, good curatorial standards, accessibility, a large, dedicated and well-qualified staff and efficient and effective networks. Furthermore, many are situated in regions of relative political, climatic and geological stability that has enabled them to survive for two centuries or more. Comprehensive collections provide the basis for wide-ranging systematic and related projects, including training and technology transfer. Botanic gardens and botanical institutes around the world continue to consult and collaborate with Kew for the same reasons.

The Hookers' legacy provided Kew with a base for major botanical projects, the first being Bentham and Joseph Hooker's *Genera Plantarum*, competed in 1883. The collections at Kew have continued to grow and develop during the 20th and early 21st centuries. One result has been that Kew has taken a leading role in several large-scale and long-term projects that smaller institutes cannot contemplate on their own. Major floras, notably a series of southern and tropical African floras have been completed. Major monographs of economically important plant families have been successfully published. Kew botanists have played a significant role in the new APG III (http://www.mobot.org/MOBOT/research/APweb/). The institution has also continued to play a major role in training, conservation and development projects around the world. It established or helped establish the Herbarium Techniques and Botanical Garden Management Courses, the World Conservation Monitoring Centre for plants, the Survey of Economic Plants for Arid and Semi-Arid lands (SEPASAL) and Plant Resources of Tropical Africa (PROTA) programmes, the Millennium Seed Bank network and much else.

Institutes, such as Kew, the Natural History Museum and Edinburgh, face many challenges over the next few years such as the loss of political will and funding, taxonomy not being taught at universities, taxonomic expertise not being replaced and the demand for short-term, high impact science and marketable products. In a period of rapid change and the loss of taxonomic expertise, I provide here my assessment of the strengths, weaknesses, threats and opportunities for a collection such as Kew (Table 1). In a challenging time, the botanical community needs more than ever to speak with one voice and make clear the contribution it makes and can continue to make to solve the world's many problems, not least of which are overpopulation and the associated changes of climate that seem now to be inevitable. Taxonomic botany has a major role to play in meeting the challenges of feeding a rapidly increasing world population when biodiversity and ecosystems are increasingly threatened. It is a challenge that we can meet but only by working together and by challenging the political and scientific elites to recognise that collection-based systematic botany is still relevant and can provide solutions.

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**Table 1.** An assessment of the strengths, weaknesses, threats and opportunities for large herbarium collections such as that at the Royal Botanic Gardens, Kew.

| Strengths | Weaknesses | Threats | Opportunities |
|---|---|---|---|
| Systematic depth | Systematic and geographic holes | Loss of political will and financial support | Political imperative for sound and easily accessible plant taxonomy |
| Geographic depth | Unbalanced curation | Historical projects that have not been completed | Kew's track-record as a leading institute |
| Excellent curation | Non replacement of experienced staff | Lack of relevant training in universities | Modern techniques attractive to young scientists |
| Skilled staff | Poor systematic knowledge of newly recruited staff | Strategic muddle | New collaborations |
| International collaborators | Management by accountants | Retirement of experienced staff | Novel uses for herbarium collections |
| Long-term goals for research | Funding easier for short-term, high impact research | Short-term high impact emphasis for funding | Pressing needs of climate change and rapid loss of biodiversity |
| Long-term impact of research | | Lack of appreciation on long-term impact of systematic work | Increasing power of computing and access to information via the internet |

# North American Herbaria and their Tropical Plant Collections: What exists, what is available, and what the future may bring

*Vicki Ann Funk*



## Abstract

Herbaria, and biological collections in general, provide an invaluable record of the diversity of plants and animals through time and space and are used in studies addressing climate change, tracking invasive species, niche modeling, and assembling the tree of life. They are our only direct documentation of biological diversity and therefore serve as essential tools for research and education in biological sciences. According to Index Herbariorum there are ~2885 registered herbaria containing approximately 375,480,850 specimens. In North America there are 723 herbaria and over 85 million specimens accounting for 25% of the herbaria and 23% of the collections in the world. Herbaria in North America began by exploring local plant diversity, and over time some became research centers with broader interests. In fact, the 33 largest herbaria in North America (those with at least 600,000 collections) hold 63% of the specimens and have substantial holdings from outside the area. Nearly all of these large institutions were founded in the mid 1800's (oldest is the collection of the Academy of Natural Sciences, Philadelphia in 1812) and have large collections from the Neotropics. An informal investigation indicated that non-North American collections account for about half of those housed in the larger North American institutions. The 20$^{th}$ Century was a period of expansion and a large number flora and inventory projects were started, so it was characterized by intensive collecting, and staff growth fuelled by these projects. However, by the late 20$^{th}$ Century the creation of these projects had slowed as funding for such baseline efforts had mostly disappeared in North America to be replaced by question driven research that sponsors more targeted collecting efforts. Today many herbaria are under-valued, and their existence is threatened. More small and medium sized herbaria, especially at universities, are being downsized or closed and some are relocated to larger herbaria, removing them from their niche and creating additional pressure on the budgets of their new home. In the early days, collecting expeditions took most material to their home institutions. However, in the last 30 years, most large herbaria have increased their collaboration with tropical institutions by providing access to valuable historical collections and literature as well as graduate education and training allowing them to further develop their research and collecting programs. As a result, multinational projects are now underway leading to the discovery and documentation of tropical plant diversity and a shared responsibility for both the collection and preservation of specimens. Today staff and students from tropical herbaria are leading the majority of the collecting trips and sponsoring most new floras and inventory projects in the tropics. North American herbaria and their counter parts in the tropics are colleagues as well as friends, and are working together to document biodiversity and provide stability for collections everywhere.

**Key Words:** biological collections, foundation of new herbaria, growth of herbaria, relationships between temperate and tropical herbaria

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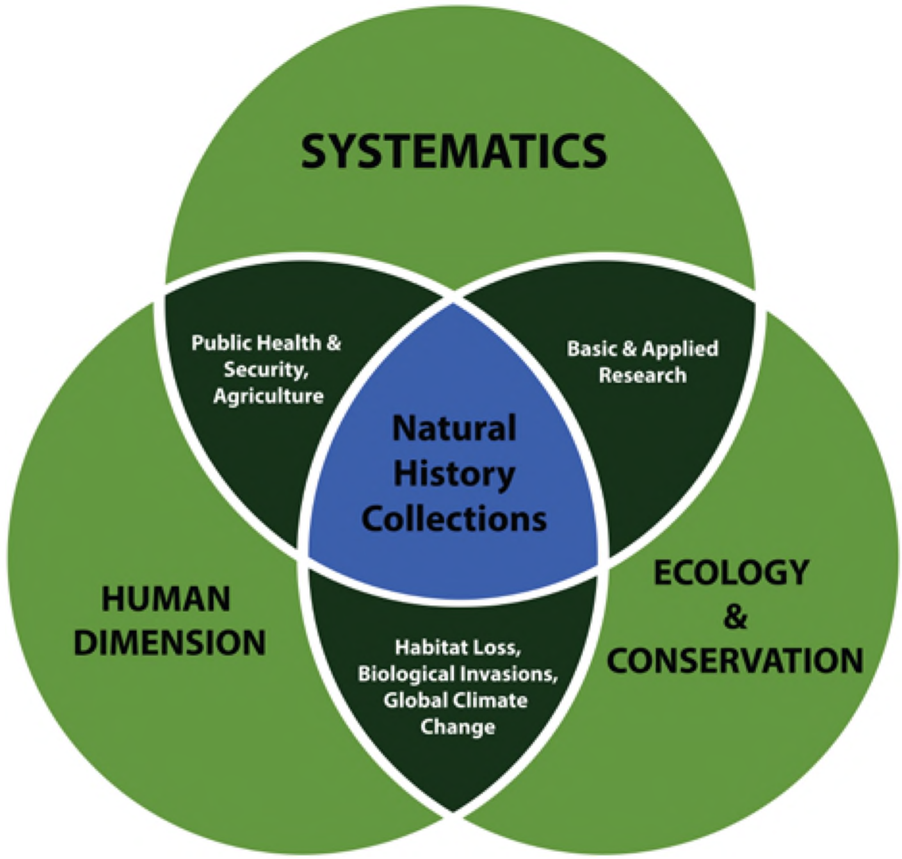
Biological collections provide an invaluable record of the distribution of biodiversity throughout the world and through recent and geological times, and they are the only direct documentation of the biological, physical, and cultural diversity of the planet (Wen *et al.* 2015).

There is an essential link between the economy and the environment, and we must recognize that the health of our lands, waters, plants, and animals is essential to our survival. To protect these resources we need a continuously expanding knowledge base to formulate environmental and economic strategies. Biodiversity collections are the foundation of this knowledge base.

Natural history museums, botanical gardens, universities, and other repositories of biological collections house an enormous number of specimens of organisms from around the world and through time. The total number is estimated to be 3 billion (Kemp 2015), but data from this study indicate that it may be closer to 5 billion (see discussion below). These traditional samples are accompanied by countless ancillary collections found in associated libraries and archives housing illustrations, microscope slides, seed and wood samples, databases, photographs, films, and more. All collections contain data about a specific point in time and space, and the collective information of all of these data is enormous. Such data syntheses are used to study change through time by organisms, earth, our solar system and the Universe. From basic questions such as: "How many species are there?", "How do we tell them apart?", "Where do they grow/live?", "How are they related to one another?" and "How should we classify them?" to using these data as the foundation for our investigations into the evolutionary and biogeographic history of the organisms we study as well as to estimate and document global patters of biodiversity, predict the effects of climate change on diversity, determine what areas should be conserved, and a host of other evolution and conservation related questions (Fig. 1).

There have been many articles that address the importance of collections (e.g. Funk 2003a, 2003b, 2006; Holmes *et al.* 2016; Kemp 2015; SA2000 1994; Wen 2015), and there are also many recent examples of the use of plant collections for a variety of topics including work on the 'origin of temperate forests' (Manos & Meireles 2015) and studies, based on specimen information, that document and predict climate change (Ellis *et al.* 2012; Johnson *et al.* 2011; Primack *et al.* 2004). Likewise collections have been used for studies on species loss and the increase and decrease in total species based on the timing of the introduction of invasive species (Ellis *et al.* 2012; Feeley 2012; Martin *et al.* 2014), and collections data have been combined with microsatellite data and habitat modelling to test competing hypotheses concerning historical distributions (Fant *et al.* 2014). One of the most frequent uses is as a repository for vouchers from surveys, chromosome and pollen studies, molecular sequencing, etc. These are extremely important, given that the identifications on herbarium material may need to be verified. For instance, Goodwin *et al.* (2015) have shown that of the 4500 specimens of African gingers that

Fig. 1. The importance of natural history collections in science and society (with permission from Wen *et al.* 2015)




they studied, 58% were misidentified, and 29% of the Dipterocarps had different names on the same collection housed in different herbaria. Without vouchers, we cannot know with certainty, the name that goes with the sequence, the pollen grain image, or the chromosome number. Of course, an additional importance of collections is that they are mined for leaf material for DNA-based studies, and this is likely to increase as next generation sequencing increases the usability of fragmented DNA, for instance, Beck and Semple (2015) used Next-generation sampling pairing genomics with herbarium specimens to give a species-level signal in *Solidago* (Compositae) and 93 of the 95 herbarium specimens (5-45 years old) were sequenced successfully using an Illumina platform. These examples are few, but they show that biodiversity collections, and herbaria in particular, are not static repositories, instead they are windows into the past, present, and future and essential tools for research in biological sciences (Fig. 2; Funk 2003a, 2003b; Johnson 2015; Schilthuizen *et al.* 2015).

Here the focus is on herbaria, where scientists and natural historians have documented earth's plant and fungal diversity for over 300 years through specimen preservation and study. From the time of Linnaeus, explorers traveled the globe bringing back preserved and living plant material to be studied and grown, first in Europe and then North America. Some countries did a good job of setting up local herbaria and gardens that ultimately provided a sound foundation for biodiversity studies in those countries, others did not.

The first documented herbaria were in Europe, and it was not until the mid-1800's that North American herbaria came into prominence. Keeping in mind the importance of collections and how central they

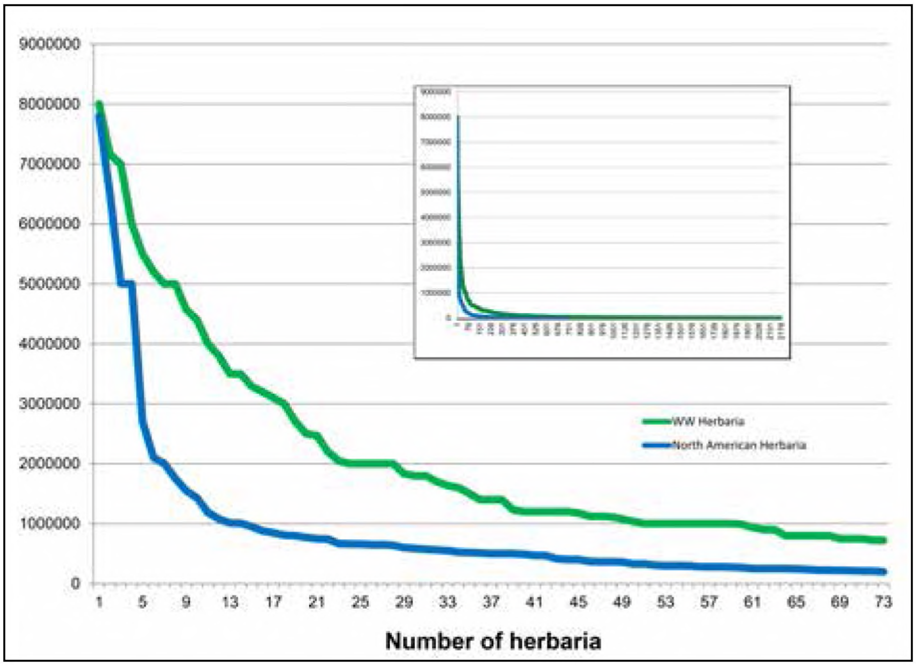



Fig. 2. Number of specimens (Y axis) in the 73 largest herbaria (larger graph) and number of specimens in all herbaria (smaller graph). Both North American herbaria and herbaria world wide ('WW Herbaria') are shown.

are to scientific and conservation studies and to questions concerning endangered species, climate change, and invasives, etc., we can examine where the tropical collections are located in North American (north of Mexico) and discuss their accessibility.

## Materials and Methods

The primary source of information for this study was a version of *Index Herbariorum* that was downloaded in March 2016 as a csv file and converted into Excel (IH; Thiers continuously updated). Several entries that appeared to be in need of new information were updated by contacting the person in charge of the herbarium or by accessing the herbarium's website. All numbers used in this study should be considered approximate, as there is always some confusion as to what collections are reported for each herbarium Code (abbreviation).

*Index Herbariorum* (IH) is a guide to the herbaria of the world. Participation is free and voluntary but the benefits are so great that most herbaria of any size join. The IH entry for each herbarium includes its mailing address, URL, a description of its contents (e.g. number and type of specimens), founding date, as well as names, contact information and areas of expertise of associated researchers. Each institution is assigned a permanent unique identifier in the form of a one to eight letter code (sometimes called an abbreviation or incorrectly an acronym), a practice that dates from the founding of IH in 1935. These codes were used throughout this study and a list of all herbaria cited in this paper can be found in the Appendix. The 'International Association for Plant Taxonomy' (IAPT; then housed at U) published the first six editions of IH (1952–1974). Patricia Holmgren, then director of the New York Botanical Garden Herbarium (NY), was senior editor of the subsequent two editions, ed. 7–8. The last hard copy of IH was ed. 8, published in 1990 (Holmgren *et al.* 1990), and since then the index has been available only online. In September 2008, Barbara M. Thiers, Director of the NY Herbarium (now Vice President for Science) became the editor (Thiers, continuously updated). Soon the website will allow users to update their own records, which should allow faster updates and less work by NY staff. For the purpose of this study, a few changes were made in the data from IH the most important one was that herbaria that are located at the same physical address but with different codes were combined (e.g., CAN* = CAN + CANA + CANL + CANM). The goal was to obtain a clear idea of the amount of resources available at a single facility and to determine the origin of the material. This kind of change was only done a few times and they are clearly indicated in the Appendix.

It is important to remember that all information in IH is 'self-reported' and therefore relies on the accuracy of the numbers provided by the individual herbaria. Some herbaria such as CANB and P have a good idea of how many specimens they have, while others are forced to use a metric (i.e. number of cases times the estimated average number of sheets per case) to obtain an estimated number. More and more herbaria are attempting to obtain accurate numbers, and so results of future studies should be more precise.

## Results and Discussion

There are 2885 herbaria listed in IH (that have useful information) housing 375,480,850 specimens (Table 1). However, a large percentage of the specimens (36%; 137,350,297; Tables 1 & 2) are found in the 34 largest herbaria (those with 2,000,000 or more specimens; Tables 1 & 2). In North America there are 723 herbaria with 85,530,469 specimens (23% of WW total). North American herbaria with 550,000 or more specimens (top 33; Table 3) provide 63% of the specimens found in North America. In fact the four largest herbaria in North America have more than 24,400,000 specimens which is more than 28% of the total holdings in North American herbaria.

We can use these data to estimate the total number of collections in museums and academic institutions worldwide. We know, based on figures in IH, that there are 76,187,380 herbarium specimens in the USA and we know the global total (375,480,850) so approximately 20% of the World's herbarium specimens are located in the USA. Taking that one step farther, it has been estimated that we have 1 billion collections (of all organisms) in the USA (Kemp 2015), if that also represents 20% of the global collections then we must have closer to 5 billion specimens globally rather than the 3 billion mentioned by Kemp (2015).

Table 2 presents a worldwide listing of herbaria based on the number of collections they hold and provides information on the geographic location(s) where most of the collections were gathered. The list is broken into seven groups each of which is separated by a natural gap in the number of specimens. Four of the top 12 herbaria (by number of specimens; Table 2) are located in North America, with NY ranking as the

**Table 1.** Number of herbaria world-wide (WW) and in North America (NoAm; north of Mexico). **Blue Bold** indicate North American herbaria.

| | | |
|---|---|---|
| Number of herbaria world wide | **2,885** | |
| Number of specimens (total) | | **375,480,850** |
| Number of specimens in the **34** largest herbaria | **137,350,297** [36%]; all herbaria | ≥2,000,000 |

| | | |
|---|---|---|
| Number of herbaria in North America | **723 [25% of WW]** | **(Canada 84 + USA 639)** |
| Number of specimens (total) | **85,530,469 [23% of WW]** | |
| Number of specimens in **33** largest herbaria | **53,553,400 [63% of NoAm]** | ≥550,000 |

**Table 2.** The largest herbaria in the World and the origin of their specimens. See appendix for city and country of each herbarium code. Groups were determined by natural breaks in collections size. If two herbaria have the same number of specimens, they are ordered by herbarium code. When two or more herbaria with a different herbarium code have the same physical address they are combined and are indicated in the tables with an * and listed in the Appendix. WW stands for collections with world wide coverage. **Bold blue** indicates North American Herbaria, **Bold red** indicates tropical herbaria, **Bold green** indicates Asian and Pacific non-tropical herbaria, Black indicates herbaria in the rest of world, mainly in Europe, Eurasia, and the UK.

| Rank | Code (in *Index Herbariorum*) | Number of specimens | Strength |
|---|---|---|---|
| Group 1 | | | |
| 1 | P* | 8,000,000 | WW, especially Africa, Madagascar, SE Asia, New Caledonia, former French Territories. |
| **2** | **NY** | **7,800,000** | **WW, especially USA, tropical Americas.** |
| 3 | LE | 7,160,000 | WW, especially temperate. |
| 4 | K | 7,000,000 | WW, especially Africa, Asia, Brazil, Australasia. |
| Group 2 | | | |
| **5** | **MO** | **6,500,000** | **WW, especially tropical Americas, Africa, Madagascar.** |
| 6 | G | 6,000,000 | WW, especially Mediterranean, Middle East, South America, Africa, Madagascar. |
| 7 | L | 6,000,000 | WW, especially tropical Asia, tropical Africa, Pacific, Europe, Central & South America. |
| Group 3 | | | |
| 8 | W | 5,500,000 | WW. |
| 9 | BM | 5,200,000 | WW, especially Africa, North America, West Indies, Himalaya. |
| **10** | **US** | **5,100,000** | **WW, especially the Americas, Pacific Islands, Philippines, India.** |
| **11** | **GH** | **5,005,000** | **WW, temperate Areas, West Indies, Mexico, Asia, Malaysia.** |
| 12 | FI | 5,000,000 | WW, especially Mediterranean. |

Group 4

| | | | |
|---|---|---|---|
| 13 | S | 4,570,000 | WW. |
| 14 | LY | 4,400,000 | WW. |
| 15 | BR | 4,000,000 | WW, especially Belgium, Central Africa. |

Group 5

| | | | |
|---|---|---|---|
| 16 | B | 3,800,000 | WW, especially Europe, Mediterranean, SW Asia, Africa, South America. |
| 17 | JE | 3,500,000 | WW, especially Europe, SW Asia, Cuba. |
| 18 | MPU | 3,500,000 | WW, especially Mediterranean, Africa, Americas. |
| 19 | H | 3,290,500 | WW, especially areas of boreal and temperate Northern Hemisphere. |
| 20 | M | 3,200,000 | WW. |
| 21 | UPS | 3,100,000 | WW. |
| 22 | E | 3,000,000 | Especially Asia, Arabia, Turkey, Bhutan, Brazil, Mediterranean, Chile, Argentina, S Africa. |

Group 6

| | | | |
|---|---|---|---|
| 23 | C | 2,707,000 | WW, especially Nordic countries, Greece, Ethiopia, Thailand, South America. |
| 24 | F | 2,700,000 | WW, especially tropical and North America. |
| 25 | LD | 2,500,000 | WW especially Scandinavia, Mediterranean, South Africa. |
| 26 | PE | 2,469,596 | WW, especially China. |

Group 7

| | | | |
|---|---|---|---|
| 27 | PRC | 2,200,000 | WW, especially central Europe, Carpathian Mts., Balkan Peninsula. |
| 28 | UC | 2,100,000 | WW, especially California, w. North Am., Mexico, Andes, Pacific, E Asia. |
| 29 | KW | 2,048,200 | WW, especially Ukraine. |
| 30 | BO | 2,000,000 | Flora Malesiana region. |
| 31 | CAL | 2,000,000 | Especially India, S & SE Asia. |
| 32 | CAS | 2,000,000 | WW, especially W North America, N Latin America, Europe, China, Galapagos. |
| 33 | PR | 2,000,000 | WW, especially Czech Rep., Slovakia, Europe, Balkan Peninsula, Australia, Iraq, Iran. |
| 34 | ZT | 2,000,000 | WW. |

End of consecutive numbers - Miscellaneous Group

| | | | |
|---|---|---|---|
| 39 | TI | 1,700,000 | Vascular Plants of E & SE Asia. |
| 40 | TNS | 1,636,000 | WW, vascular plants, mainly of Japan. |
| 42 | DAO* | 1,550,000 | Especially Canada, north temperate plants. |
| 47 | MEXU | 1,400,000 | New World, especially Mexico, Central America. |
| 50 | MEL | 1,200,000 | WW, Australia, especially Victoria. |
| 51 | NSW | 1,200,000 | WW, Australia, especially New South Wales. |
| 52 | PRE | 1,200,000 | Southern Africa, some from other parts of Africa. |
| 57 | KUN | 1,114,000 | China, especially Yunnan, Sichuan, Guizhou, Tibet; SE Asia. |
| 59 | ENCB | 1,080,000 | Mexico and neighboring areas. |
| 61 | AD | 1,040,000 | WW, especially Australia. |
| 62 | CAN* | 1,010,500 | North Temperate regions, especially Canada. |
| 66 | EA | 1,000,000 | Especially E Africa and other African countries. |
| 67 | IBSC | 1,000,000 | China, especially tropical and subtropical parts. |

**Table 3.** North American Herbaria with more than 550,000 specimens and the origin of their collections. Herbaria that are combined are indicated with an *.

| Rank | Code (in Index Herbariorum) | Number of specimens and their origin, strength |
|---|---|---|
| Group 1 | | |
| 1 | NY | 7,800,000 (50% tropical; most from Americas) |
| 2 | MO | 6,500,000 (70% tropical; Americas, Africa, Asia) |
| Group 2 | | |
| 3 | US | 5,100,000 (60% tropical; most Americas, Pacific) |
| 4 | GH | 5,005,000 (25% tropical; World Wide, strong in North America and Europe, and excellent in Asia) |

Group 3

| | | |
|---|---|---|
| 5 | F | 2,700,000 (66% tropical; most from Americas) |

Group 4

| | | |
|---|---|---|
| 6 | UC | 2,100,000 (40% tropical; CA, Mexico, Pacific) |
| 7 | CAS | 2,000,000 (20% tropical; CA, Western North America, Madagascar) |
| 8 | DAO* | 1,850,000 (Mainly North America especially Quebec) |
| 9 | MICH | 1,750,000 (30% tropical; Regional, Mexico, some SE Asia & Pacific) |
| 10 | PH* | 1,675,000 (25% tropical; WW, North American, some Pacific) |

Group 5

| | | |
|---|---|---|
| 11 | RSA | 1,183,000 (50% tropical; CA, also Mexico) |
| 12 | WIS | 1,078,000 (50% tropical; North America and tropical America) |
| 13 | CAN* | 1,010,500 (North America and Europe) Toronto |
| 14 | BRIT | 1,010,000 (10% tropical; most from USA; recently Pacific and Peru) |
| 15 | TEX | 1,006,000 (50% tropical; most Texas and Mexico, also tropical Americas) |

Group 6

| | | |
|---|---|---|
| 16 | BPI | 950,000 (Fungi WW, most temperate) |
| 17 | MIN | 880,000 (10% tropical; Regional and Pacific) |
| 18 | BH | 845,000 (10% tropical; Cultivated/economic, some China and Old World) |
| 19 | RM | 806,800 (Temperate; Inter-mountain flora region) |
| 20 | DUKE | 800,000 (35% tropical; Regional, West Indies, MesoAmerica) |

Group 7

| | | |
|---|---|---|
| 21 | QFA | 770,000 (North America) |
| 22 | BISH | 750,000 (100% tropical, Pacific) |
| 23 | MT | 745,000 (Regional, Canada) |
| 24 | NCU | 665,000 (Regional, Carolinas) |
| 25 | BRY | 661,100 (Regional, Utah) |
| 26 | UBC | 660,000 (Regional, some Pacific) |
| 27 | MU | 650,000 (35% tropical; North America, some South America and Pacific) |

| | | |
|---|---|---|
| 28 | WTU | 650,000 (Regional, W-USA, North Pacific rim) |
| 29 | ISC | 640,000 (Regional, North America) |
| 30 | NA | 600,000 (25% tropical; WW cultivated/economic, ethnobotanical) |
| 31 | ALTA | 570,500 (10% tropical; Arctic and cordilleran Canada; Bryophytes of New World and Australia) |
| 32 | MSC | 560,000 (20% tropical; WW especially North America, Mexico, Guatemala, Borneo, Patagonia) |
| 33 | TENN | (10% tropical mostly bryophytes; Regional, Mexico and Guatemala |

second largest herbarium in the world (Group 1: 7,800,000) after P (8 million). Others in this top group include LE and K. The next North American herbarium (MO) is found in Group 2, along with G and L, and they each have ca. 6 million. Group 3, with ca. 5 million specimens, contains two North American herbaria (US, GH). So one third of the top 12 herbaria are found in North America, and they all house large collections from the tropics. This is followed by a large gap, and it is not until number 24 in Group 6 and number 28 in Group 7 that we find two more North American herbaria (F: 2,700,000 and UC: 2,100,000), both with large collections from North America and the tropics. These herbaria complete the list of the largest 34 herbaria in the world, only six of which are in North America.

Where on the list do we find herbaria that are actually located in the tropics? The two largest are BO (#30) and CAL (#31), both with 2 million specimens and both focused on regional diversity (Indonesia and India respectively). The largest herbarium in Asia is PE (#26, with a focus on China), and in Australia it is MEL (#51) and NSW (#52), both with 1,200,000, also with a regional focus. The sequential list in Table 2 includes all herbaria with 2,000,000 or more collections.

The excel file shows that in herbaria with an estimated size of 1–2 million specimens, there are two additional ones in North America (both in Canada with a north temperate focus), and three in Australia (with a national and/or regional focus; Table 2, Miscellaneous Group). There are five herbaria from tropical areas of the world in the Miscellaneous Group ranging from MEXU at 1,400,000 (focus on Mexico and Central America) to EA (East Africa) and IBSC (tropical and subtropical China) each with 1,000,000. Most of these tropical herbaria have a broad regional interest.

There are very few really large herbaria (Fig. 2): in North American size quickly falls to 1 million or less where it begins to taper off more gradually. There are six herbaria with 2 million or more specimens (less than 1% of the total number of herbaria in North American herbaria) and 16 with 1 million or more (2.4%). Globally, it drops to 2 million specimens before it begins to taper: there are 22 herbaria with 3 million or more (less than 1% of WW herbaria) and 34 with 2 million or more (1.26%).

The content of the collections in North American herbaria is based on past interests of the staff and/or administration or in some cases the interests of the Federal Government. Most herbaria in North America began by exploring local and regional plant diversity. However, there are exceptions, for instance, the US National Herbarium (US; Smithsonian Institution) was founded on the collections from the *United States Exploring Expedition* (under the command of Navy Lt. Charles Wilkes) which collected in western North America, South America and the Pacific in 1838–1842 and was charged with exploring the physical and biological diversity of the areas visited. It resulted in, among other items, 10,000 plant collections that became the foundation of the US National Herbarium. Over time, some herbaria became research centers with broader interests and greatly increased their holdings by diversifying into other areas of the world. In North America, nearly all of these large institutions were founded in the mid-1800's and have a large percentage of their collections from the Neotropics. Some have additional collections from the Pacific, Africa, Madagascar, and Asia. Most are weaker in Asia, Eurasia and Australasia, however there are exceptions such as GH (including AA) which has a long tradition of Asian exploration, MO with its collaboration with floras in Asia and Madagascar, and US with its history of work in the Pacific and the Philippines.

## What is the Origin of the Collections in North American Herbaria?

Some herbaria have a good idea of the source of their collections. For instance, Field Museum estimates that 31% of their collections are from South American, 29% from Mexico and Central America, and 24% are from North American (M. Dillon pers. com.). Some herbaria have a partial record: US knows how many collections we have added starting in the early 1990's but prior to that it is more difficult. Other herbaria are using estimates that are closer to a guess. But most research staff have a sense of where their collections originated and are willing to share that information and those data are reflected in Table 3.

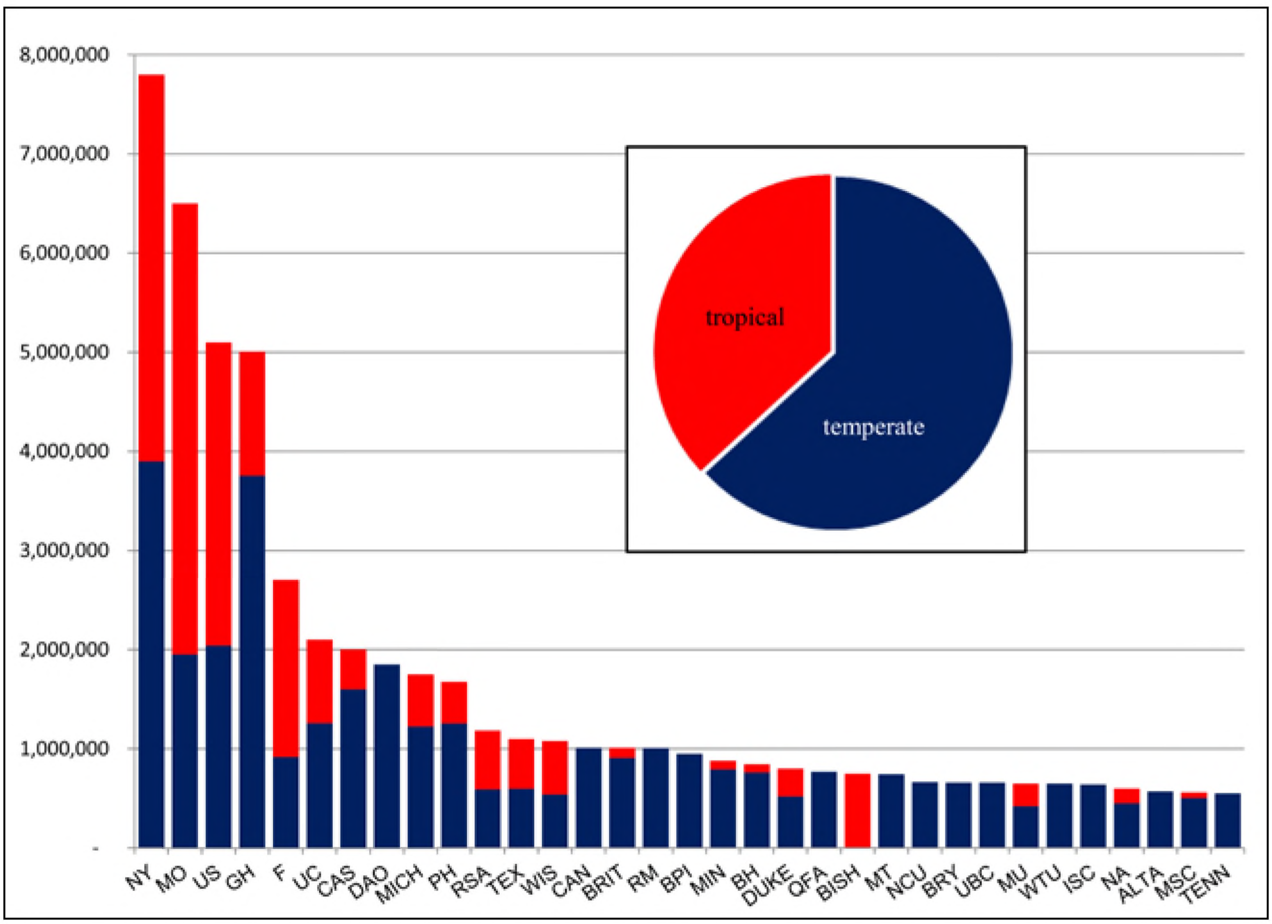



Fig. 3. Estimates of the number of specimens (Y axis) from the tropics in the 33 largest herbaria in North America. The pie-diagram shows the sum for these 33 herbaria.

There are 33 herbaria in North America with 550,000 or more specimens (Table 3). An examination of the list shows that beginning with MT (number 23) most of the collections are mainly regional with little tropical representation. There are exceptions, for instance MU (#27), NA (#30), and MSC (#32) have 20-35% of their collections from the tropics. And, even some of the larger herbaria do not have much in the way of tropical plants, for instance most Canadian herbaria have long focused on North American, mainly Canadian, plants in order to secure funding.

The vast majority of tropical specimens in North American herbaria are found in the largest herbaria. Table 3 and Figure 3 show that once herbaria have fewer than 1 million specimens they often have only a small percentage of specimens, if any, that are tropical, unless, of course, they are located in a tropical environment (e.g. BISH).

Approximately 20 million specimens from the tropics are in North American herbaria. This represents about 37% of the collections in the 30 largest herbaria and about 50% of the specimens in those with significant tropical holdings. These data show that the biggest impact on tropical research can be made by focusing on improving access to the 17 herbaria (out of 33) that have substantial holdings of tropical plants (Table 3).

## How do we Evaluate the Importance/health of an Herbarium? Or indeed of the disciplines of plant taxonomy or systematics?

In looking at tropical plants housed in temperate herbaria, it is tempting to try and evaluate the health of herbaria that hold these important collections. How secure are these collections? Possible measures of success could be longevity, rate of increase in collection size, activity of faculty, staff, and students, or even number of grants and publications.

**Table 4.** Age of herbaria: North American herbaria founded before 1899 that are among the 33 largest herbaria in North America (Table 2). They are ranked by the date they were founded. **Red bold** indicates herbaria that are part of a university. Herbaria that were combined are indicated with an *.

| Code (in 'Index Herbariorum' | Date of founding |
|---|---|
| PH | 1812 |
| **MICH** | **1837** |
| **GH** | **1842** |
| US | 1848 |
| **WIS** | **1849** |
| CAS | 1853 |
| MO | 1859 |
| **MSC** | **1863** |
| BPI | 1869 |
| **ISC** | **1870** |
| RSA | 1872 |
| **UC** | **1872** |
| CAN* | 1882 |
| **WTU** | **1882** |
| DAO* | 1886 |
| **TENN** | **1888** |
| **MIN** | **1890** |
| NY | 1891 |
| F | 1893 |
| **RM** | **1894** |

### *Longevity*

In North America 18 herbaria were founded before 1899 and are part of the list of North American Herbaria with more than 550,000 specimens (Table 3, 4).

**Table 5.** Age of herbaria in North America founded before 1850 with date of their founding and the current size of the collection. **Red bold** indicates the herbarium is one of the 30 largest in North America.

| Code (in Index Herbariorum | Date | Number of specimens |
|---|---|---|
| SC | 1771 | 1,500 |
| CHARL | 1773 | 25,000 |
| MID | 1800 | 2,500 |
| **PH** | **1812** | **1,675,000** |
| PHIL | 1821 | 13,000 |
| DWC | 1826 | 20,000 |
| NYS | 1836 | 278,662 |
| **MICH** | **1837** | **1,700,000** |
| TRT | 1838 | 370,000 |
| UNB | 1839 | 60,000 |
| UCS | 1840 | 8,000 |
| **GH** | **1842** | **5,005,000** |
| **US** | **1848** | **5,100,000** |

PH is the oldest (1812) and remains an important herbarium. The largest herbarium in North America, and the second largest in the world (NY) had a relatively late starting date (1891) but it has continued to prosper. It is interesting to note that Asa Gray, who was important in the founding of GH, was also important in the founding of MICH where he was located prior to moving to Harvard University. These two herbaria were founded five years apart. Three of the oldest large herbaria (MICH, GH, WIS) are university herbaria followed by those with a slightly later starting dates (ISC, UC, WTU, MIN, RM). So eight of the oldest large herbaria in North America are found at universities, a concept that is under siege in many places. Given the declining support for university herbaria one has to wonder if the administrators of herbaria at colleges and universities are aware of the importance of these herbaria, not only in housing irreplaceable collections but also in the training of undergraduates and preparing the next generation of systematists and biodiversity specialists, something museums often have difficulty in doing.

Thirteen herbaria in North America – that are still in existence – were founded before 1850 (Table 5). It is interesting to note that the age of an herbarium seems to have no correlation with its overall growth and current activity. For instance, in Table 5, the Herbarium codes in bold indicate presence of that herbarium in the list of largest 33 herbaria in North America: there are only four. Two of the earliest ones are both from South Carolina (USA) and remain small. In fact, although South Carolina has 12 herbaria in IH all but two are small and only two university collections, CLEMS (100,000 specimens) and USCH (122,000), have substantial holdings.

The age of North American herbaria pales in comparison to those in Europe. KASSEL, the oldest herbarium in the world – that is still in existence – was founded in 1569 (Table 6). The oldest one in North America (SC) is 22nd globally and the four largest herbaria in North America are far down the list with NY, the largest herbarium in North America and the second largest in the world, ranking 368. PH, the oldest large herbarium found in North America (Table 2), is 60th. However, like the herbaria in North America, the age of an herbarium globally is no predictor of continued growth as only six of the largest herbaria (Table 2) are found on the list of oldest herbaria (Table 6).

### *Number of herbaria founded*

The largest growth in herbarium science in North America took place over a 50-year period from 1925 to 1974 (Fig. 4). Between those years, 365 herbaria were established all over North America. That is an average of 7-8 per year for 50 years. The largest gain was from 1950 to 1974 with 244 founded in 25 years, a rate of nearly ten per year. This increase is no doubt the result of the large amounts of government funding

**Table 6.** List of oldest herbaria world wide. **Red bold** indicates the herbarium is one of the 34 largest herbaria in the world (Table 2). **Blue bold** indicates North American herbaria. Herbaria that were combined are indicated with an *.

| Rank | Code (in *Index Herbariorum* | Date | Number of specimens | Country |
|---|---|---|---|---|
| 1 | KASSEL | 1569 | 30,000 | Germany |
| 2 | BOLO | 1570 | 130,000 | Italy |
| 3 | BAS | 1588 | 220,000 | Switzerland |
| 4 | OXF | 1621 | 500,000 | UK |
| **5** | **P*** | **1635** | **8,000,000** | **France** |
| 6 | ARG | 1675 | 10,000 | Malta |
| 7 | AMD | 1700 | at L | Netherlands |
| 8 | PARMA | 1722 | 20,000 | Italy |
| 9 | LINN | 1730 | 33,800 | UK |
| **10** | **S** | **1739** | **4,570,000** | **Sweden** |
| 11 | TO | 1750 | 1,000,000 | Italy |
| **12** | **H** | **1751** | **3,290,501** | **Finland** |
| **13** | **BM** | **1753** | **5,200,000** | **UK** |
| 14 | MA | 1755 | 1,400,000 | Spain |
| **15** | **C** | **1759** | **2,707,000** | **Denmark** |
| 16 | TRH | 1760 | 430,000 | Norway |
| 17 | KRMS | 1761 | 28,000 | Austria |
| 18 | CGE | 1761 | 1,000,000 | UK |
| 19 | MW | 1765 | 989,240 | Russia |
| 20 | LR | 1770 | 77,000 | France |
| 21 | LD | 1770 | 2,500,000 | Sweden |
| **22** | **SC** | **1771** | **1,500** | **USA** |

End of consecutive numbers
Four largest North American Herbaria and PH (the oldest large herbarium).

| | | | |
|---|---|---|---|
| 60 | PH | 1812 | USA |
| 131 | GH | 1842 | USA |
| 139 | US | 1848 | USA |
| 177 | MO | 1859 | USA |
| 368 | NY | 1891 | USA |

(both state and federal) that were directed toward education and science during those years. But the following 25-year period (1975-1999) saw an unprecedented decline with a drop to a rate lower than the one for 1875-1899 and the most recent 15-year period produced only nine new herbaria. It is difficult to determine what caused this drop. It could be that the 'market' for herbaria in North America was saturated

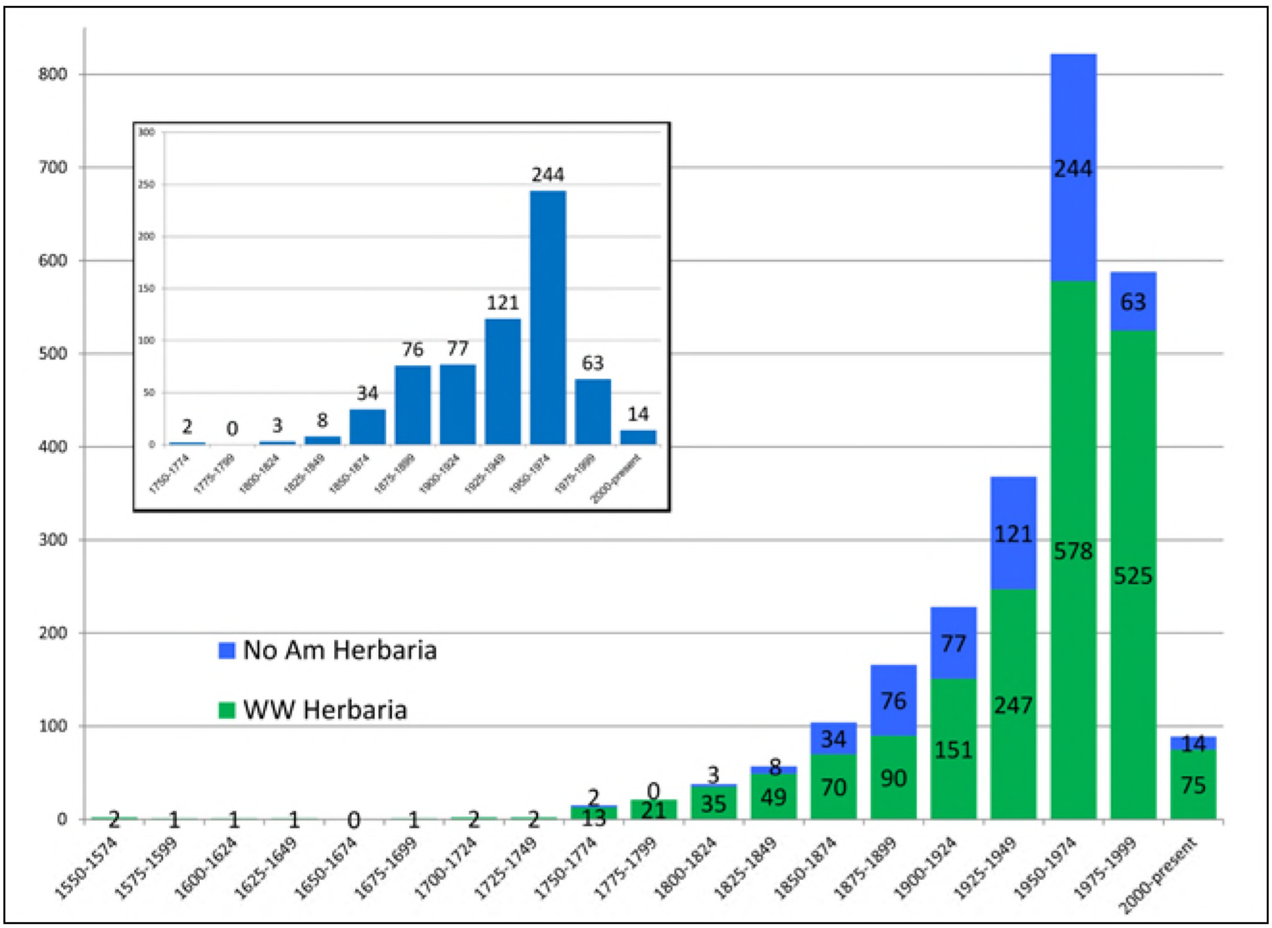



Fig. 4. The number of new herbaria (Y axis) founded in North America ('No Am Herbaria') in 25-year increments and the number of herbaria established world wide ('WW Herbaria').

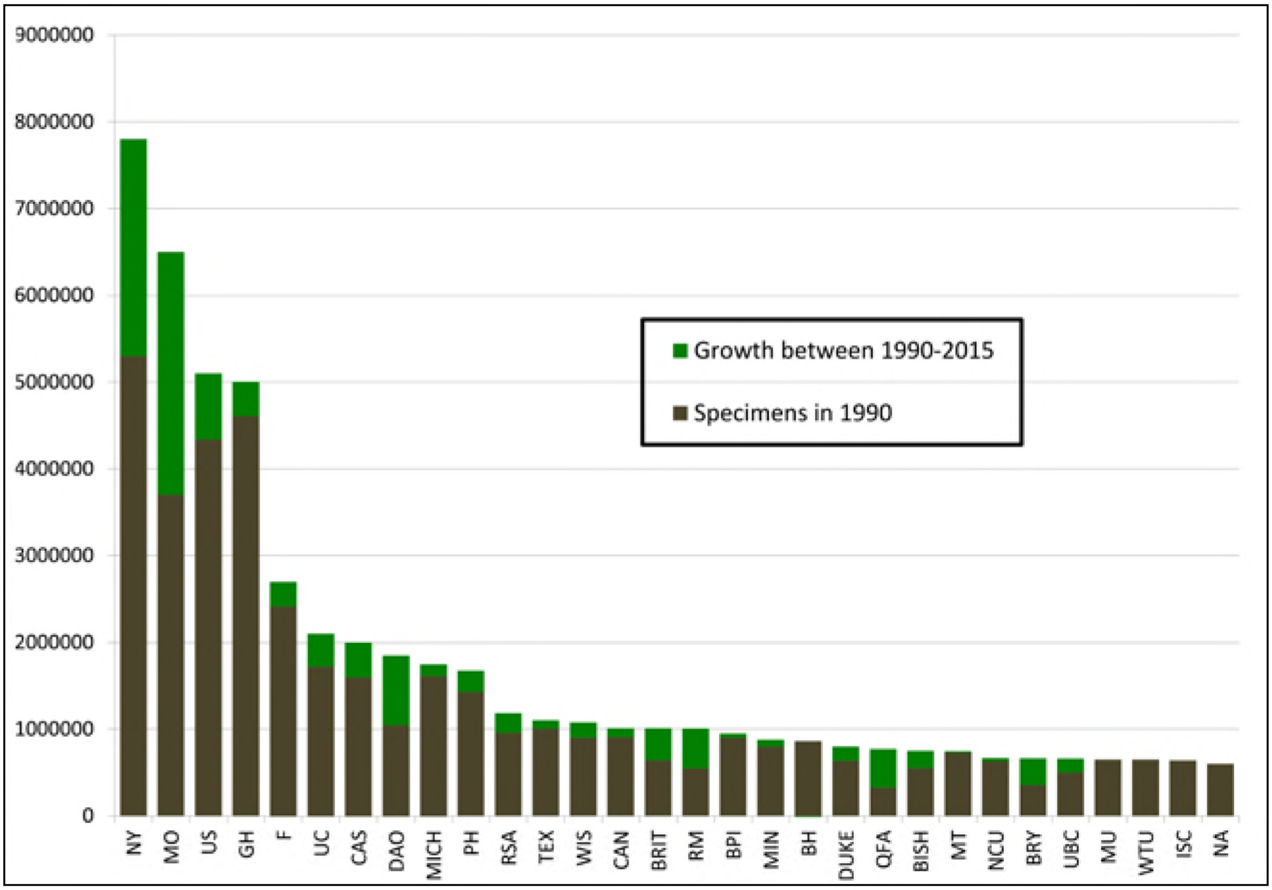



Fig. 5. Size of herbaria (measured by number of specimens – Y axis) in North American in 1990 and their growth between 1990 and 2015.

but it could also be a delayed response to more methods-driven research such as the modern synthesis (Huxley 1942) followed by phylogenetics (Hennig 1966) and the surge of molecular methods in the1990's.

How does this compare with the global rate of founding of new herbaria? The pattern is much the same, but the surge lasted longer (Fig. 4). The biggest increase took place 1950–1974 (nearly 33 per year), but non-North American herbaria continued to increase at nearly the same level for another 25 years while North American herbaria dropped off considerably (see above). This sustained growth seems to reflect new herbaria in the tropics, in fact, a rough count shows that the gains in the tropics were impressive: Tropical Americas 189, Asia-Pacific 170 (includes all of China), and Africa 48. So, a total of 407 of the total 588 new herbaria were in the tropics, corresponding to about 70%. But this too declined as we moved into the new century. The tropical countries with the largest gains were China (110 new herbaria), Brazil (47), Mexico (41), India (20), South Africa (17), and Argentina (14).

### *Increase in collection size through time*

Perhaps the best way to judge how successful herbaria are is by looking at their productivity: how many collections are added, how many publications and grants, and how many students are trained. Most of these are elusive, but we can use the last published version of IH (Holmgren *et al.*, 1990) to evaluate growth in the collections.

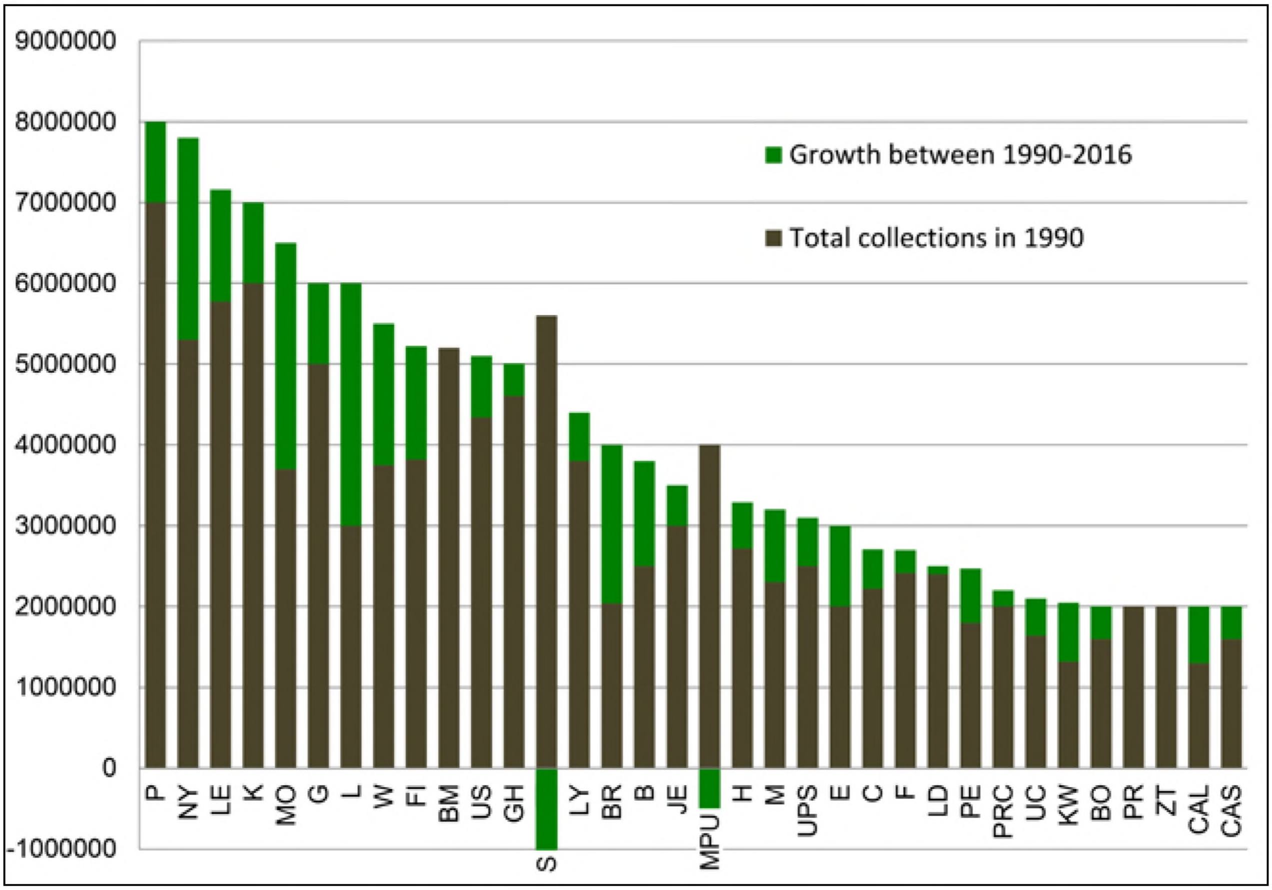



Fig. 6. Size of 34 largest herbaria world wide in 1990 (indicated by number of specimens – Y axis) and their growth in the number of herbarium specimens between 1990 and 2015. Note that several herbaria show no growth (BM, PR, ZT) and others show a negative growth (S, MPU); this is mostly caused by the current, more accurate, count of the existing specimens.

The last hard copy of *Index Herbariorum* was published in 1990 (Holmgren *et al.*) and information was taken from this publication to compare the size of institutions in 1990 versus their size now. The two largest institutions (NY and MO) generally increase their holdings by 80,000 to 100,000 per year (Fig. 5). They are in a league by themselves in regard to collections growth. Some of the growth comes from rescuing orphaned collections, but both herbaria have strong collecting and exchange programmes. US continues to add about 30,000 specimens per year mostly by processing the backlog and gift collections and a few collecting programs. Most other herbaria in North America add substantially less. One reason is the cost of staff to do the collecting and processing, because, to be useful, specimens must be collected, labeled, identified, mounted, and filed. As funding decreases or shifts to other priorities some major herbaria now add fewer specimens than smaller ones. This can be compared with the global herbarium community (Fig. 6) where MO and NY still stand out as having the largest average yearly increase but several others have added a million or more specimens in the last 25 years, including BR, FI, G, K, LE, P, and W. How much of this increase is the result of expeditions and how much comes in as exchange or gifts (e.g., for determination) or even the incorporation of other once independent herbaria (e.g., L), is yet to be determined. Some institutions show a decrease in size or zero increase which is often caused by doing an exact count of all the collections.

In order to discuss growth we need to examine the question: What drives growth? After talking to fellow museum and garden scientists about this question it seems that there are a number of factors:

1. Focus of the director of the institution (e.g. K, NY)
2. Participation in floras and surveys (e.g. K, L, MO, P, US)
3. Availability of funding (e.g. NSF)
4. Availability of jobs for students during degree process and upon graduation
5. Acknowledged importance of expeditions and systematics by scientific community and the government

As an example of the importance of leadership, we can cite the first two directors of K (William Jackson Hooker and Joseph Dalton Hooker) who set the stage for the institution we see today. They were scholars, explorers, and tireless promoters of their institution. Joseph Dalton Hooker took part in several years-long expeditions. On one, the Antarctic voyage of the Erebus and Terror under the command of Captain Sir James Clark Ross (1839-1843), Hooker studied the flora of the circumpolar Antarctic region and developed hypotheses that influenced the discipline of biogeography. They were not just administrators, they were visionary leaders in the scientific community and the development of their institution reflected their dedication and knowledge (Allan 1967). An example from North America is Peter Raven, who became director of MO in 1971 and retired in 2011. During his tenure, he transformed a good mid-western herbarium into a powerhouse of specimen based plant science. Currently, systematists do not run most major herbaria although there are exceptions (e.g. M, MO, RSA). All of the large herbaria organized floras and surveys for tropical areas such as the Amazon (NY), Asia (GH, L), Madagascar (P, MO), MesoAmerica (BM, MO), and the Pacific (P, US).

Equally important in successful herbaria is the ability to generate funding to help offset the cost of expeditions and infrastructure. In the USA, the National Science Foundation (NSF) has had several programs to accomplish this, but sadly, this has all but stopped, and recently it even canceled the call for biological infrastructure proposals. Many other countries are also cutting back on their funding for collections and expeditions that supply new material, leaving institutions with less funding and hence slower growth. Infrastructure includes the training of students and postdocs, but this is limited by the availability of jobs when they graduate. Perhaps the biggest problem is the lack of recognition of the importance of collections in shaping our view of the world.

## Relationships between Temperate and Tropical Herbaria

The development of larger North American herbaria (those that hold most tropical collections) seems to follow a common trajectory (with exceptions to all steps):

**Step 1:** The herbarium founder(s) have a goal of establishing an herbarium to document local and regional diversity.

**Step 2:** The director and staff become interested in how their flora compares to plants from other parts of the world, and they begin to expand their geographic sphere of interest to gain a better idea of global plant diversity. Most specimens are brought back to the country of the collector. In the case of collections supported by federal governments a herbarium may be asked to take specimens from government-backed expeditions (e.g. the US Exploring expedition funded by the US government helped found the National Museum of Natural History).

**Step 3:** The development of a local scientific community results in scientists in the tropics asking questions about why all of the biodiversity samples are being removed from the country. Without adequate libraries and access to historical collections, they are hard pressed to study their own biodiversity. Naturally, this creates a tension between the scientists in tropical countries and the large temperate herbaria.

**Step 4:** Exchange of information starts, students are trained, resources are shared, field trips are joint ventures, etc. which is certainly a great progress. But nearly all of the historical materials remain in temperate herbaria (e.g. publications and type specimens).

**Step 5:** Global and local efforts are initiated to share the information (in both directions). These began gradually, but in recent years, with the advent of big data and global programs, they have transformed the way we work.

Botanists have always worked as a group, and as a result they consistently have been better organized than other fields of research. Many of these still-active projects were begun under the auspices of the International Association for Plant Taxonomy (IAPT), then housed in Utrecht (U); sadly this herbarium no longer exists as an independent unit having been integrated into L. But, because of their foresight we have many resources that are useful to botanists around the world. Index herbariorum: Part I. The Herbaria of the World (Theirs continuously updated), was started in 1952; the International Plant Names Index (IPNI, http://www.ipni. Org; Croft *et al.* 1999), is a collaboration among the Royal Botanic Gardens, Kew (the Index Kewensis was first published in 1885), the Harvard University Herbaria (The Gray Cards Index), and the Australian National Herbarium (Croft *et al.* 1999; Lughadha 2004); *Index Herbariorum II Collectors* (Lanjouw & Stafleu) was first published in 1954; *Taxonomic Literature*, a compendium of taxonomic publications, was first published in 1967 (Stafleu) and is now an amazing online resource (http://www.sil.si.edu/digitalcollections/tl-2/).

More recent efforts have build on this foundation of sharing knowledge and the community now has TROPICOS, developed by MO over the past 30 years, that gives us lists of specimens and localities as well images and references and more (http://www.tropicos.org/Home.aspx). Later the Global Biodiversity Information Facility (GBIF) was established (1999; http://www.gbif.org/). It provides locality information for all of life. This was (and is) an amazing concept and one that most scientists can support. Although the data in GBIF are not curated in a consistent manner (see Goodwin *et al.* 2015), it is a useful tool and one that the community should work to improve (see the recent survey published on line as http://www.gbif.org/newsroom/news/fitness-for-use-report-distribution-modelling). Other efforts to share information are the Biodiversity Heritage Library (BHL) that makes older literature available (http://www.biodiversitylibrary.org/bibliography/48631-/summary) and JSTOR Global Plants, which hosts images of type specimens (http://about.jstor.org/content/global-plants).

In addition, museums, gardens, and universities around the world strive to make the collections they house and their associated data available to the global community. There are many examples of these efforts such as the well-known *Australia's Virtual Herbarium* (Council of Heads of Australasian Herbaria 2013; http://avh.chah.org.au/ ). Some countries are working hard to make their herbarium collections available globally including France, the Netherlands, the United States, and China, where progress has been made in digitizing herbarium collections and in disseminating the information. In fact, the world's largest herbarium (P) was mostly digitized during its recent physical renovation (https://science.mnhn.fr/). Concerning North America, the US Virtual Herbarium project (USVH, http://usvhproject.org/; Barkworth & Murrell, 2012) is underway, and, if successful, it will make available most of the large tropical collections in North America (Beaman & Cellinese 2012), although federal collections are excluded.

Finally, the way we disseminate our data has changed. The years-long wait for publications to be freely available has given way to rapid publication and 'open access'. A few new journals have been designed to rapidly publish the taxonomic work. Pioneered by Pensoft (http://www.pensoft.net/; e.g. *Phytokeys*), a leading publisher of open access cybertaxonomy, this effort really became practical after changes made in the International Code of Nomenclature for algae, fungi and plants (McNeill *et al.* 2012) began to allow electronic publication and the use of English in descriptions of new taxa (Miller *et al.* 2011). These journals disseminate biodiversity data in both traditional and innovative ways, and register all new nomenclature with databases such as the International Plant Names Index (IPNI) (http://www.ipni.org/).

The result of all of these innovations (and more that are not mentioned here) is the empowerment of our colleagues from tropical countries. They now have the ability to view the types and much of the literature that they need. Their herbaria have grown to the extent that they have much better access to recent material, and they are able to interact globally. The future will bring many additional online resources (i.e. more specimens and literature) as these data sharing efforts continue. As a result much of the tension has dissipated, and botanists from temperate and tropical areas are working together and separately to achieve our common goal of understanding the botanical diversity of Earth. One definition of a friend is "someone who accepts your past, supports your present, and encourages your future" and I think temperate and tropical botanists are now, and really have been for some time, friends.

## Afterward

This paper is an outgrowth of my longstanding interest in the health and utility of biodiversity collections (especially herbaria) and their ancillary collections (Funk 2003a, 2003b, 2006, 2014). Mine is not the only voice on this topic, and the literature is littered with the efforts of many (see citations in the Introduction and use Google Scholar to find many additional ones) to stem the receding tide of funding that sucks away our ability to mount expeditions, conduct research, maintain collections, and train the next generation of systematists. This is especially true in most temperate areas, but also in Australia and the Pacific. Although there are some successes, largely these efforts have failed, and the number of herbaria that drastically reduce their staff and store or give away their collections grows at an ever-increasing pace. Despite the overall lack of success, we must not quit because it is possible that eventually, if it is said often enough, the importance of biological collections and the research that results from them will be recognized for its relevance to understanding and preserving life on our planet. It is now time for the herbaria of the topical and temperate areas of the world to work together using our newfound unity to demonstrate the power of herbaria to administrators and funding agencies (Conniff, 2016).

For surely "We must all hang together, or we shall surely all hang separately." (Benjamin Franklin, at the signing of the Declaration of Independence).

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**Appendix.** Location of the ca. 100 herbaria mentioned in this paper (alphabetical by code) and an indication of the ones that were combined for calculations in this study. For more information see *Index Herbariorum* (Thiers (continuously updated)). Herbaria that were combined are indicated with an *.

| Abbreviation | City | Country |
|---|---|---|
| AD | Adelaide | Australia |
| ARG | Floriana | Malta |
| ALTA | Edmonton, Alberta | Canada |
| AMD (housed at L) | Leiden | Netherlands |
| B | Berlin | Germany |
| BAS | | Switzerland |
| BH | Ithaca NY | USA |
| BISH | Honolulu HI | USA |
| BM | London | UK |
| BO | Bogor | Indonesia |
| BOLO | Bologna | Italy |
| BP | Budapest | Hungary |
| BPI | Beltsville MD | USA |
| BR | Meise | Belgium |
| BRIT | Ft Worth TX | USA |
| BRY | Provo UT | USA |
| C | Copenhagen | Denmark |
| CAL | Howrah, Kolkata | India |
| CAN+CANA+-CANL+CANM* | Ottawa QC | Canada |
| CANB | Canberra | Australia |
| CAS | San Francisco | USA |
| CGE | Cambridge | UK |
| CHARL | Charleston SC | USA |

| Abbreviation | City | Country |
|---|---|---|
| CLEMS | Clemson SC | USA |
| DAO+DAOM* | Ottawa QC | Canada |
| DUKE | Durham NC | USA |
| DWC | West Chester PA | USA |
| E | Edinburgh | UK |
| EA | Nairobi | Kenya |
| ENCB | Mexico City | Mexico |
| F | Chicago IL | USA |
| FI | Florence | Italy |
| G | Geneva | Switzerland |
| GH | Cambridge | USA |
| H | Helsinki | Finland |
| HBG | Hamburg | Germany |
| IBSC | Guangzhou | China |
| ISC | Ames IA | USA |
| JE | Jena | Germany |
| K | Kew | UK |
| KASSEL | Kassel | Germany |
| KRMS | Kremsmunster | Austria |
| KUN | Kunming | China |
| KW | Kiev | Ukraine |
| L | Leiden | Netherlands |
| LD | Lund | Sweden |
| LE | Leningrad (St Petersburg) | Russia |
| LINN | London | UK |

| Abbreviation | City | Country |
|---|---|---|
| LR | La Rochelle | France |
| LY | Lyon | France |
| M | Munich | Germany |
| MA | Madrid | Spain |
| MEL | Melbourne | Australia |
| MEXU | Mexico City | Mexico |
| MICH | Ann Arbor MI | USA |
| MID | Middlebury VT | USA |
| MIN | Saint Paul MN | USA |
| MO | Saint Louis MO | USA |
| MPU | Montpellier | France |
| MSC | East Lansing MI | USA |
| MT | Montreal QC | Canada |
| MU | Oxford OH | USA |
| MW | Moscow | Russia |
| NA | Washington DC | USA |
| NCU | Chapel Hill NC | USA |
| NSW | Sydney | Australia |
| NY | New York NY | USA |
| NYS | Albany NY | USA |
| O | Oslo | Norway |
| OXF | Oxford | UK |
| P+PC* | Paris | France |
| PARMA | Parma | Italy |
| PE | Beijing | China |
| PH+ANSP* | Philadelphia PA | USA |
| PHIL | Philadelphia PA | USA |

| Abbreviation | City | Country |
|---|---|---|
| PR | Prague | Czech Republic |
| PRC | Prague | Czech Republic |
| PRE | Pretoria | South Africa |
| QFA | Quebec QC | Canada |
| RM | Laramie WY | USA |
| RSA | Claremont CA | USA |
| S | Stockholm | Sweden |
| SC | Winston-Salem SC | USA |
| TENN | Knoxville TN | USA |
| TEX | Austin TX | USA |
| TI | Tokyo | Japan |
| TNS | Tsukuba | Japan |
| TO | Torino | Italy |
| TRH | Trondheim | Norway |
| TRT | Toronto ON | Canada |
| UBC | Vancouver BC | Canada |
| UC | Berkeley CA | USA |
| UCS | Schenectady NY | USA |
| UNB | Fredericton NB | Canada |
| UPS | Uppsala | Sweden |
| US | Washington DC | USA |
| USCH | Columbia SC | USA |
| W | Vienna | Austria |
| WIS | Madison WI | USA |
| WTU | Seattle WA | USA |
| ZT | Zurich | Switzerland |

# Sub-Saharan Botanical Collections: Taxonomic research and impediments

*Sebsebe Demissew, Henk Beentje, Martin Cheek and Ib Friis*

## Abstract

Many historical specimens from sub-Saharan Africa are only found in European herbaria, but a higher number of newer specimens than widely assumed are kept in African herbaria, with a concentration in eastern and southern parts of the continent. Many of these herbaria were initiated in connection with independence of former European colonies in Africa, fewer were built on well-established herbaria from the colonial period. There are many gaps in collecting coverage, not least with regard to areas of high plant diversity; this is often caused by poor access or political instability. High species diversity exists in both humid and arid parts of Africa. Lack of collections from and knowledge about areas of high species diversity makes it difficult to prioritise conservation efforts. Gaps in taxonomic knowledge exist in certain large families, such as Rubiaceae, or in large genera, such as *Cyphostemma* (Vitaceae), *Euphorbia* (Euphorbiaceae), *Ipomoea* (Convolvulaceae), *Polystachya* (Orchidaceae), and *Barleria* (Acanthaceae). Newly collected specimens are now mainly kept in African herbaria, but lack of training and resources in tropical African herbaria are important challenges to prevent African botanists from continuing a somewhat declining European activity, partly caused by the downgrading in priority given to herbaria in European universities and research institutions. Encouraging examples of progress are the many regional African floras that have now been finished or nearly finished in collaboration between African and European herbaria, and the increasing digitization of herbaria and the general development of relevant services on the Internet, which provides new possibilities for botanical studies in Africa.

**Key Words**: biodiversity hotspots, conservation, field work, herbaria, historical collections, tropical Africa, South Africa

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At the 4th congress of Association pour l'Étude Taxonomique de la Flore d'Afrique Tropicale (AETFAT) held at Lisbon and Coimbra, Portugal in September 1960, early sub-Saharan collections were intensely discussed during the session *Histoire de l'Exploration botanique de l'Afrique au Sud du Sahara* and the proceedings include a series of overviews that cover most of the region (Aubreville 1962 [W Africa]; Cufodontis 1962 [NE Tropical Africa]; Exell 1962a,b [islands in the Gulf of Guniea]; Fernandes & Fernandes 1962 [Mozambique]; Gillett 1962 [E Africa]; Hepper 1962 [W Africa]; Keay 1962 [W Africa]; Mendonça 1962a,b [Angola, Mozambique]; Siméon & Tourney 1962 [Congo]; Wild 1962 [Zimbabwe, Malawi]; White 1962 [Zambia]). Later historical reviews include Beentje and Smith (2001) and Beentje (2015) for Tropical East Africa, Friis (2007, 2011) and Sebsebe Demissew (2011, 2014) for Ethiopia and Thulin (2006) for Somalia.

## Historical Collections

The oldest sub-Saharan plant collections date back to the 1670–1690s, with early collectors such as Patric Adair (Johanna Island = Anjouan), Edward Bartar (Ghana), Charles Coombs (Calabar in Nigeria), and John Kirckwood (Angola and Cabinda: Cabo Verde in Cape Verde Islands and Calabar in Nigeria), but most of the early collections come from the Cape of Good Hope in South Africa and were collected by Adair, William Dampier, John Fox, Paul Hermann, George Lewis, Frederick Ruysch, George Stonestreet

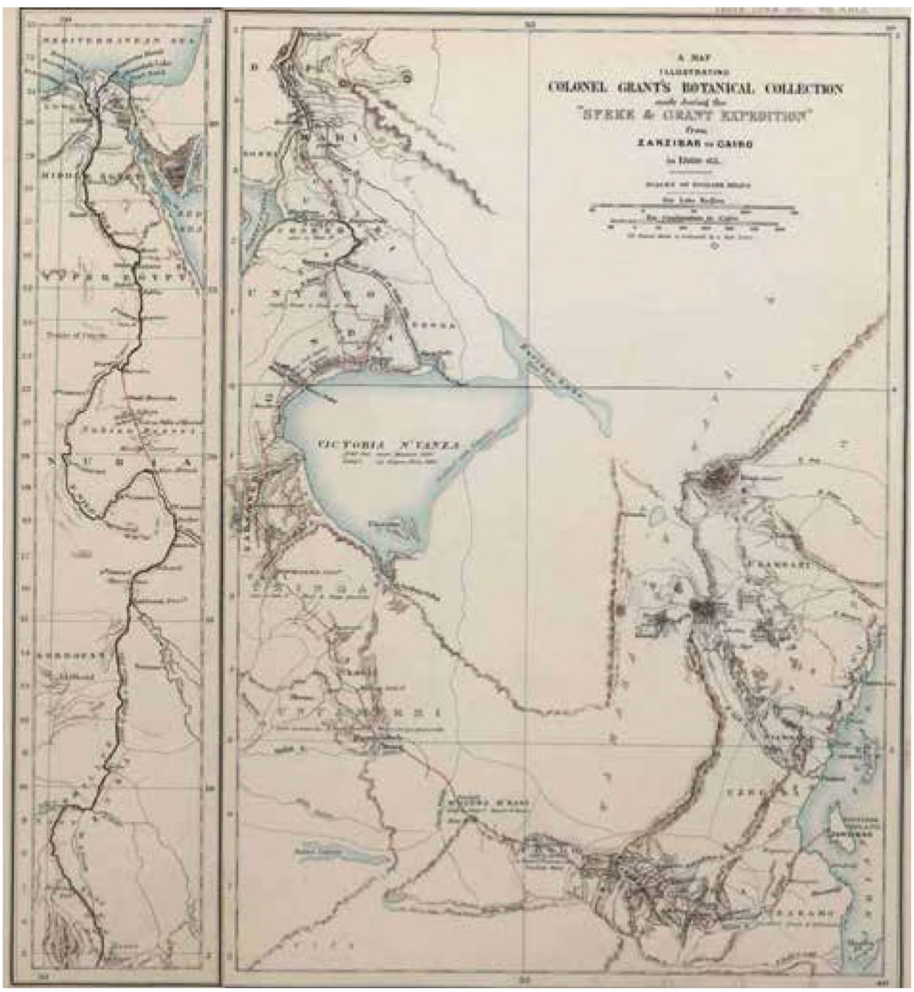


Fig. 1. The route of the travels of J.H. Speke and J.A. Grant from Zanzibar through Tanzania and Uganda in 1860-1863. Map published with Grant and Oliver (1872).

Fig. 2. Friedrich Martin Josef Welwitsch (1806–1872). Lithograph with facsimile signature, 19th century. In the collections of the Royal Botanic Gardens, Kew (published with permission).

Fig. 3. The only known portrait of Georg Heinrich Wilhelm Schimper (1804–1878; lived in Ethiopia from 1837 to his death). Detail from a series of group portraits of Emperor Tewodoros' European hostages, with their wives and children, taken after their release in 1868 by Sergeant John Harrold, a member of the British army. Schimper wears a turban-like headgear and is dressed in an Ethiopian silk cloak with embroidered edge. The people portrayed in the British photographs of the hostages have been identified by Gräber (1999a, 1999b). From Friis (2007).

(Exell 1962a). Most of the early collections were made along the coast. Apart from travels in Ethiopia and South Africa and attempts to cross the Sahara from the North (see for example Onana *et al.* 2017) the first long inland journey that involved collecting of plants was that in 1860–1863 of J.H. Speke and J.A. Grant from Zanzibar along the Nile to Cairo (Fig. 1).

In the 18th and 19th centuries most collections of plants in sub-Saharan Africa were done by naturalists funded by European countries, institutions, or by individuals with the intention to explore territories unknown to Europeans. All collections of these travellers were deposited in institutions in Europe (Table 1). There were no academic institutions dealing with botany, or indeed any herbarium collections, in sub-Saharan Africa before 1870.

Three 19th century collectors deserve special mentioning because of their particularly large output of collections made during long residences or extended travelling in Tropical Africa: Schimper, Welwitch and Schweinfurth. Not only did they make many collections in tropical Africa, their collections included

**Table 1.** Examples of historical collections of tropical African plants made before the 20th century and the herbaria where these specimens are deposited. Based on information from *Index Herbariorum* (Thiers continuously updated) and the index of collectors in *Index Herbariorum, Part II* (Lanjouw & Stafleu 1954, 1957; Chaudhri *et al.* 1972; Vegter 1976, 1983, 1986, 1988), updated with http://plants.jstor.org/. Schweinfurth's data have been supplemented from Wickens (1972). Most of the material brought out of Ethiopia by Bruce were drawings and seeds and bulbs; the few extant herbarium specimens were prepared from plants cultivated in various gardens in Europe (Hulton *et al.* 1991). Speke and Grant, Hildebrandt and Schweinfurth collected during travels in East and in North-East Africa; Hildebrandt's field trip to Madagascar in 1879-1891 is not included.

| Region | Collector | Year | No. of collections | Countries | Herbaria where the collectors' specimens are deposited |
|---|---|---|---|---|---|
| North-East Africa | James Bruce | 1769-1771 | Low | Ethiopia | LINN, P |
| | G.H.W. Schimper | 1837-1863 | 2600+ | Ethiopia, Eritrea | B (main), BM (main), P (main), PC (main), A, AWH (currently BR), BERN, BHU (currently B), BP, BR, BREM, C, CAL, CAS, CGE, CN, CORD, DBN, DPU (currently NY), DR, E, E-GL, ETH, F, FI, FT, G, G-BOIS, GE, GH, GOET, GRO, H, HAL, HBG, HOH, JE, K, KIEL, KR, L, LE, LG, LV, LY, LZ, M, MANCH, MO, MPU, MW, NA, NCY, NEU, NH, NMW, NY, OXF, PAL, PR, PRC, REG, RO, S, SAM, STR, STU, TCD, TO, TUB, U, UPS, US, VT, W, WAG, WB, WRSL, WU, Z, ZT |
| | G. Schweinfurth | 1867-1897 | 4000 | Egypt, Sudan, Ethiopia, Eritrea | B (main, partly lost), AAR (currently HUJ), BAS, BM, BO, BP, BPI, BR, C, CAIM, CORD, DBN, E, FI, FT, G, GE, GOET, GZU, H, HBG, HUJ, K, KIEL, L, LE, LY, M, MO, MPU, MW, NH, NMW, NY, OXF, P, PC, PH, PR, S, SAM, US, W, WIR, WRSL, WU, Z |
| East and North-East Africa | J.M. Hildebrandt | 1872-1877 | 1650 | Ethiopia, Somalia, Kenya, Tanzania | B [main set, partly lost], BM, BR, CORD, GOET, K [important set], KIEL, L, LY, MO, P, PC, W |
| | J.H. Speke & J.A. Grant | 1860-1863 | ?650 | Tanzania, Uganda | K |

| Region | Collector | Year | No. of collections | Countries | Herbaria where the collectors' specimens are deposited |
|---|---|---|---|---|---|
| West Africa | A.M.F.J. Palisot de Beauvois | 1786-1788 | hundreds | Benin, Nigeria | FI-WEBB, G, GH, P [main set], P-JU |
| | J. Heudelot | 1835-1837 | 1000 | Senegal | A, B, BM, BR, CN, DS, FI, G, K, NY, OXF, P [main set], P-JU, PC, W |
| | G. Mann | 1859-1863 | 3000 | Sierra Leone, Nigeria, Cameroon, Bioko, Sao Tomé | A, B, BM, E, G, GH, H, K [main set], L, LE, P, S, U, W |
| Southern Africa | F.M.J. Welwitsch | 1853-1861 | 3000+ | Angola (mainly), Namibia | B, BM [second of two main sets], BOL, BR, C, COI, G, H, K, LE, LISU [first of two main sets ], M, MO, MPU, NU, P, TUR, W |
| | J. Kirk | 1861-1886 | 2800+ | Mozambique, Malawi, Zanzibar | B, CAL, E, F, FHO, GH, K [main set], LE, MO, OXF, W |

more duplicates than the other early collectors, and their collections are represented at more European and North American herbaria than any of the other 19th century collectors (Table 1), thus bringing many plant specimens into herbaria and spreading the knowledge of African plants. Schimper's and Welwitsch's collections include significantly more type specimens of African plant species than all other collectors in tropical Africa, both earlier and later (Gillett 1972; Albuquerque *et al.* 2009). Also a high proportion of Schweinfurth's collections are types. Friedrich Welwitsch (1806–1872; Fig. 2) carried out expeditions in Angola for over seven years (1853-1860). Two almost equivalent sets of his collections are housed at the Natural History Museum, London, UK (BM) and at the University of Lisbon (LISU), but his duplicates are widespread (Vegter 1988; Albuquerque *et al.* 2009). Georg Heinrich Wilhelm Schimper (1804-1878; Fig. 3) lived in Ethiopia for more than 40 years, from 1837 to his death (Gräber 1999a,b; Gestrich & McEwan 2015; McEwan 2015). Over the 40 years of his collecting activity, his first set were placed at different herbaria, mainly P and B, where most of it was lost in World War II, but numerous of his duplicates are widely deposited in European and North American herbaria and now partly also in ETH, Addis Ababa (Friis 2007). Georg August Schweinfurth (1836-1925) went to Egypt in 1863, from where he travelled along the Red Sea coast of Africa and through northern Sudan in 1863-1865, including a stay in the border region between Sudan and Ethiopia. Having returned to Europe in 1866, he explored in 1869-1871 the western parts of South Sudan and the north-eastern parts of todays' Democratic Republic of Congo. From 1874 to 1888 he was based in Cairo and travelled widely in Egypt and to Socotra, and, after his return to Germany, he explored Eritrea in 1891 and 1894 (Wickens 1972).

Later in the 20th century, after European countries had established colonies in Africa, there was an interest to continue the exploration of botanical resources by documenting them in the form of floras and to establish colonial or national herbaria in Africa (Table 2; Fig. 4). The regional survey in Table 2 shows a high

**Table 2.** Richness of collections in sub-Saharan Africa, based on regionally accumulated number of collections in herbaria in sub-Saharan Africa. Data from *Index Herbariorum* (Thiers continuously updated).

| Region | Countries | Number of herbaria | Collections in national herbaria | Associated major herbaria in Europe or USA |
|---|---|---|---|---|
| Horn of Africa | Djibouti, Eritrea, Ethiopia, Somalia and the Sudan | 6 | 160,000 | P, FT, K |
| Eastern Africa | Burundi, Kenya, Malawi, Mozambique, Rwanda, South Sudan, Tanzania, Uganda and Zambia and Zimbabwe | 23 | 2,396,000 | BR, LISC, K, MO |
| Central Africa | Angola, Cameroun, Central Africa, Chad, Republic of the Congo, Democratic Republic of Congo, Equatorial Guinee, Gabon, São Tomé and Príncipe | 23 | 685,000 | BR, COI, LISC, P |
| Western Africa | Benin, Burkina Faso, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo | 24 | 626,000 | P, K |
| Southern Africa | Botswana, Lesotho, Namibia, South Africa, Swaziland | 48 | 3,153,000 | |
| Total | | 124 | 7,020,000 | |

concentration of herbaria in South Africa and a high concentration of large herbaria with many collections in eastern and southern Africa. Figure 4 shows the foundation of many new herbaria after World War II and around the end of the colonial era in the 1960s.

## African Collections in Africa and Europe

*Index Herbariorum* (Thiers continuously updated) has recorded 172 herbaria and a total of 7,171,888 collections in sub-Saharan Africa (Table 3). These herbaria are found in 38 out of 49 countries. The establishment of these herbaria, which started in 1864 in South Africa, has continued up to today (Figs. 4), but the size and distribution of these herbaria are extremely variable (Figs. 5, 6). The largest number of specimens are found in herbaria in South Africa (PRE in Pretoria with 1.2 million and NBG Compton Herbarium with just over ½ million) and tropical East Africa (EA in Nairobi with 1 million and SRGH in Harare >½ million; Fig. 6) . The herbaria in sub-Saharan Africa have a total of more than 7 million specimens (Table 3). Only Eritrea, South Sudan, Chad, Gambia and Guinea Bissau have no herbaria recorded in the *Index Herbariorum.*

In comparison, the herbarium of the Royal Botanic Gardens, Kew (K), is assumed to have about 2.5 million collections from sub-Saharan Africa out of their total holding of about 7 million. The herbarium of the Museum national d'histoire naturelle at Paris (P) seems to hold slightly more than 700,000 collections from tropical Africa (and slightly more than half a million from Madagascar), to judge from the database https://science.mnhn.fr/institution/mnhn/col-

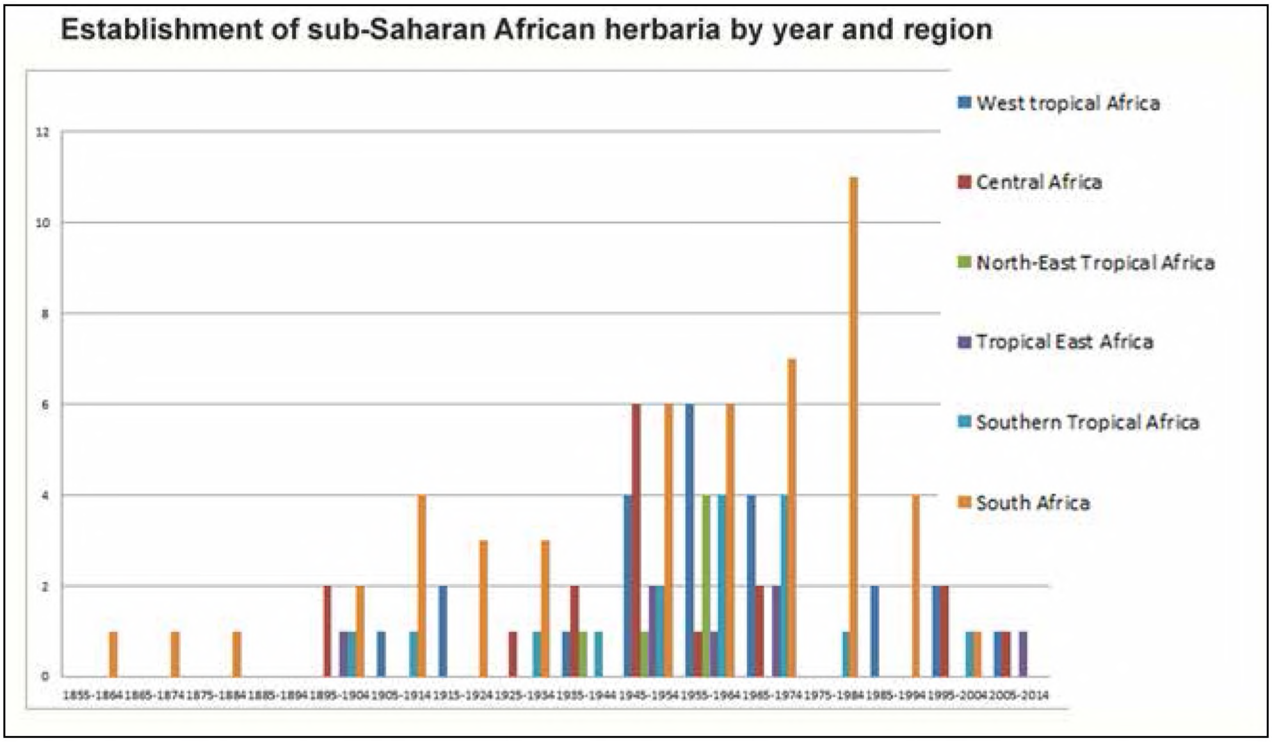


Fig. 4. Number of herbaria established in sub-Saharan Africa by year and region. Based on information from Thiers (continuously updated).

lection/p/item/list?secteur=AFM. Thus, the number of herbarium specimens held in sub-Saharan Africa institutions is significant and, as it would seem, at least as many herbarium collections must be held in herbaria in sub-Saharan Africa as in temperate institutions, which is contrary to the commonly held belief that vastly more African herbarium specimens are deposited in northern institutions than in Africa.

## Gaps in Collecting Coverage

The gaps in plant-collecting in sub-Saharan Africa have many causes. During pre-colonial times it was difficult to make collections in most parts of tropical Africa (Fig. 7A). Plant collectors suffered from diseases such as malaria and were hampered by poor infrastructure; Luigi Balugani, the Italian illustrator who accompanied James Bruce, died of dysentery or malaria in Gondar in Ethiopia in 1771 (Hulton *et al.* 1991), the two French botanical collectors sent on a collect-

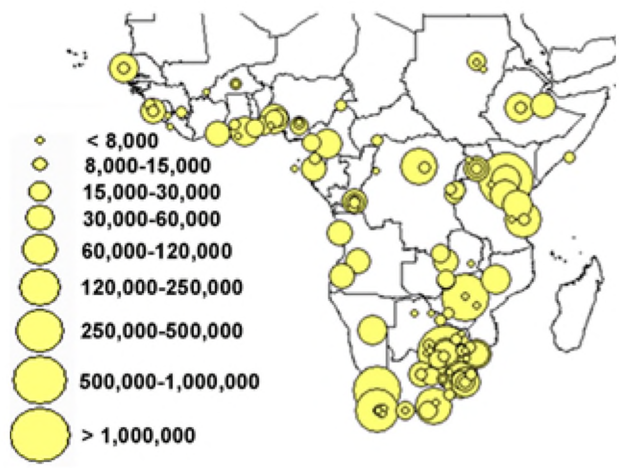


Fig. 5: Size and distribution of herbaria in sub-Saharan Africa. Based on information from Thiers (continuously updated).

ing trip to Ethiopia in 1838 newer returned from their journey, and Richard Quartin-Dillon died in 1840 in northern Ethiopia from an unknown disease. Some

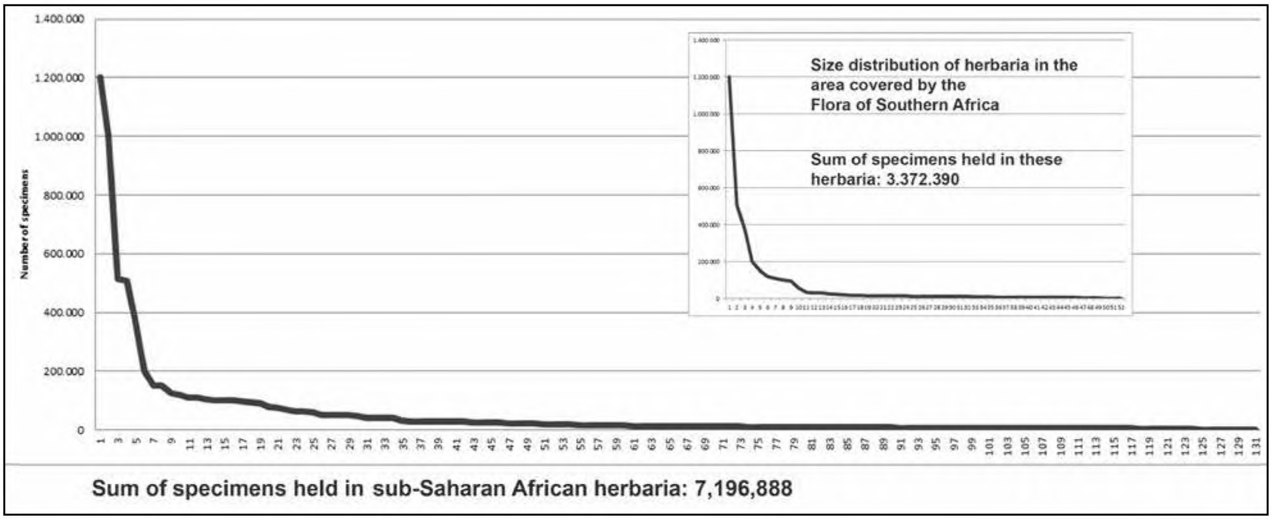


Fig. 6. Size-distribution of herbaria in sub-Saharan Africa and southern Africa. Few herbaria have many specimens, many herbaria have few specimens. Based on information from Thiers (continuously updated).

**Table 3.** Richness of collections by country in sub-Saharan Africa, based on estimated number of higher plant species, area in km², estimated number of species per 1000 km², number of herbaria, number of collections, collections per 1000 km² and collections per estimated number of species. Data on estimated number of species from Beentje and Smith (2001), with modifications from the checklist of Sudan and South Sudan (Darbyshire *et al.* 2015), other data from *Index Herbariorum* (Thiers continuously updated). Countries for which no herbarium has been recorded in the *Index Herbariorum* are marked with a zero.

| Country | Estimated number of species | Area (in 1000 km²) | Estimated number of species/ 1000 km² | Number of herbaria | Number of collections | Collections per 1000 km² | Collections per estimated number of species |
|---|---|---|---|---|---|---|---|
| South Africa | 23,400 | 1223 | 19.1 | 55 | 3,218,590 | 2631.7 | 137.5 |
| Congo (Kinshasa) | 10,000 | 2345 | 4.3 | 12 | 302,894 | 129.2 | 30.3 |
| Tanzania | 10,000 | 940 | 10.6 | 6 | 292,300 | 311.0 | 29.2 |
| Cameroon | 8300 | 475 | 17.5 | 5 | 137,000 | 288.4 | 16.5 |
| Gabon | 7200 | 267 | 27.0 | 1 | 40,000 | 149.8 | 5.6 |
| Ethiopia and Eritrea | 6600 | 1184 | 5.6 | 4 | 137,000 | 115.7 | 20.8 |
| Kenya | 6500 | 583 | 11.1 | 3 | 1,100,000 | 1886.8 | 169.2 |
| Congo (Brazza-ville) | 6000 | 267 | 22.5 | 1 | 40,300 | 150.9 | 6.7 |

| Country | Estimated number of species | Area (in 1000 km²) | Estimated number of species/ 1000 km² | Number of herbaria | Number of collections | Collections per 1000 km² | Collections per estimated number of species |
|---|---|---|---|---|---|---|---|
| Mozambique | 5700 | 783 | 7.3 | 5 | 125,350 | 160.1 | 22.0 |
| Zimbabwe | 5500 | 389 | 14.1 | 5 | 540,636 | 1389.8 | 98.3 |
| Uganda | 5400 | 243 | 22.2 | 4 | 84,767 | 348.8 | 15.7 |
| Angola | 5200 | 1247 | 4.2 | 4 | 90,000 | 72.2 | 17.3 |
| Zambia | 5000 | 746 | 6.7 | 8 | 86,000 | 115.3 | 17.2 |
| Nigeria | 4700 | 924 | 5.1 | 8 | 194,500 | 210.5 | 41.4 |
| Côte d'Ivoire | 3700 | 322 | 11.5 | 3 | 40,000 | 124.2 | 10.8 |
| Ghana | 3700 | 238 | 15.5 | 5 | 102,052 | 428.8 | 27.6 |
| Central African Republic | 3600 | 617 | 5.8 | 2 | 10,000 | 16.2 | 2.8 |
| Equatorial Guinea | 3300 | 28 | 117.9 | 1 | 8000 | 285.7 | 2.4 |
| Namibia | 3200 | 824 | 3.9 | 1 | 94,000 | 114.1 | 29.4 |
| South Sudan | 3100 | 620 | 5.0 | 0 | 0 | 0 | ? |
| Guinea | 3000 | 246 | 12.2 | 7 | 19,800 | 80.5 | 6.6 |
| Somalia | 3000 | 638 | 4.7 | 1 | 10,000 | 15.7 | 3.3 |
| Burundi | 2500 | 28 | 89.3 | 1 | 20,000 | 714.3 | 8.0 |
| Togo | 2500 | 57 | 43.9 | 1 | 21,000 | 368.4 | 8.4 |
| Rwanda | 2300 | 26 | 88.5 | 1 | 16,702 | 642.4 | 7.3 |
| Benin | 2200 | 116 | 19.0 | 1 | 18,000 | 155.2 | 8.2 |
| Liberia | 2200 | 111 | 19.8 | 1 | 7000 | 63.1 | 3.2 |
| Senegal | 2100 | 197 | 10.7 | 2 | 122,000 | 619.3 | 58.1 |
| Sudan | 2100 | 1886 | 1.1 | 3 | 40,500 | 21.5 | 19.3 |
| Swaziland | 2100 | 17 | 123.5 | 1 | 7200 | 423.5 | 3.4 |
| Botswana | 2000 | 30 | 66.7 | 5 | 31,000 | 1033.3 | 15.5 |
| Sierra Leone | 2000 | 72 | 27.8 | 4 | 64,857 | 900.8 | 32.4 |
| Chad | 1800 | 1284 | 1.4 | 0 | 0 | 0 | 0 |
| Malawi | 1800 | 119 | 15.1 | 1 | 100,000 | 840.3 | 55.6 |
| Mali | 1700 | 1204 | 1.4 | 1 | 6400 | 5.3 | 3.8 |

| Country | Estimated number of species | Area (in 1000 km²) | Estimated number of species/ 1000 km² | Number of herbaria | Number of collections | Collections per 1000 km² | Collections per estimated number of species |
|---|---|---|---|---|---|---|---|
| Lesotho | 1600 | 30 | 53.3 | 3 | 21,600 | 720 | 13.5 |
| Niger | 1200 | 1189 | 1.0 | 1 | 0 | 0 | 0 |
| Burkina Faso | 1100 | 280 | 3.9 | 3 | 20,940 | 74.8 | 19.0 |
| Gambia | 1000 | 10 | 100.0 | 0 | 0 | 0 | 0 |
| Guinea Bissau | 1000 | 36 | 27.8 | 0 | 0 | 0 | 0 |
| Saõ Thomé e Principe | 900 | 1 | 900.0 | 1 | 1500 | 1500 | 1.7 |
| Djibouti | 600 | 22 | 27.3 | 1 | 0 | 0 | 0 |
| | | 21864000 km² | | 172 herbaria | 7,171,888 collections | Average for total area and total number of collections: 328 collection per 1000 km² | Average for all countries 6.4 collections per estimated species |

were even killed by wild animals; Antoine Petit was seized and drowned by a crocodile when crossing the Blue Nile in 1843 (Stearn 1982) and the Italian collector and big-game hunter Emanuele Ruspoli was trampled to death by an angry, wounded elephant near Burgi in Sidamo, southern Ethiopia, in 1893 (Settesoldi *et al.* 2005).

Even after the colonial period, many problems have persisted in spite of vast improvements in the infra-structure. Gaps in collecting activities persist, as seen in Fig. 7C, because collectors follow the main roads or because access to remote areas remains difficult and dangerous due to political instability. Current areas of instability include those where armed political conflicts are on-going, as widely reported in the international news-media, for example in South Sudan, Eastern Congo and northern Mali. Religious fundamentalism is also seriously destabilizing large areas, such as the activities of Al-Shabab in Somalia, which is making large areas of the neighbouring territories in the Ogaden in Ethiopia and North-Eastern Kenya inaccessible. The activities of Boko Haram impede access to parts of northern Nigeria, and the Lord's Resistance Army has seriously hampered studies in northern Uganda and north-eastern Congo. And also today diseases may make field work difficult or impossible, for example the outbreaks of ebola in Guinean Republic, Liberia and Sierra Leone in 2014–2016.

Conversely, there are areas that are well-collected, and such areas often figure on high-diversity lists, and therefore, they are studied again and again, and their inclusion becomes a self-fulfilling prophesy. But studying lesser-known areas can pay off. For example, Mt Kupe, Mwanenguba and the Bakossi Mountains in Cameroun were virtually unknown (with 123 plant species known from the area in 1993) until a team from Yaoundé and Kew explored them in 1995-2004 and found 2440 plant species, of which 82 were nar-

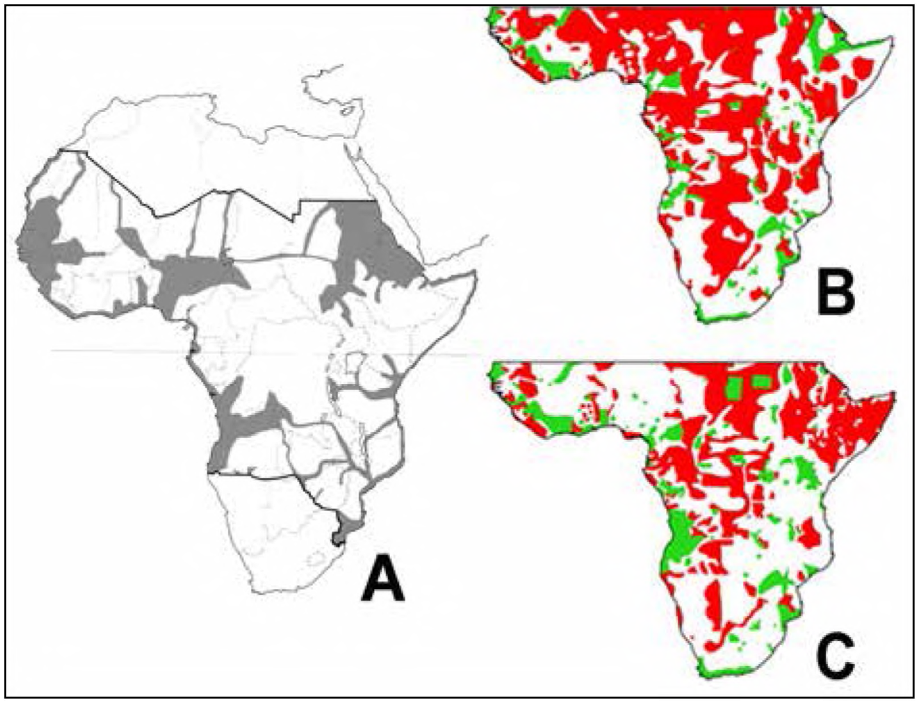


Fig. 7. The degree of floristic exploration of Africa from ca. 1860 to ca. 1980. (A). Parts of tropical Africa visited by European travellers by 1860 (grey); by this time the entire Cape Region is indicated as visited. (B). Degree of floristic exploration at ca. 1965. (C). Degree of floristic exploration at ca. 1980. Poorly known areas are indicated with red, moderately well-known areas with white, and well known with green. (A) From map on p. 16 in Vol. 1 of Lebrun and Stork (1991–1997), redrawn from Plate 10 in Supan (1888). (B) Redrawn from Léonard (1965). (C) Redrawn from Hepper (1979).

row endemics, and 232 were threatened taxa (Cheek *et al.* 2004). These data catapult this area into one of the most important and richest plant diversity spots in tropical Africa, which emphasizes the importance of studying under-explored areas. A similar case is the Makueni area of less than 200 km$^2$ of wooded grassland in Kenya, which was virtually botanically unknown until an inventory organized by the National Museums of Kenya showed that it housed 847 species, including 758 vascular plants, 20 bryophytes, and 69 lichenized fungi (Malombe *et al.* 2015).

It is difficult to state much with certainty about what plants are not known or represented in herbaria, but some attempts have been made in Table 3. First we have tried to look at the number of collections per 1000 km$^2$, for which the average is 328. Some countries seem to have a reasonably good coverage of collections per 1000 km$^2$, with 3–9 times the average. This relates in particular to South Africa (2632 collections per 1000 km$^2$), Kenya (1887 collections per 1000 km$^2$), Zimbabwe (1390 collections per 1000 km$^2$) and Botswana (1033 collections per 1000 km$^2$). These figures do indeed indicate well stocked herbaria, but it should be noted that South Africa, Zimbabwe and Kenya have old herbaria which have acted as central institutions for what is now several separate countries; the EA herbarium in Nairobi, for example, was for long time a central herbarium for Kenya, Uganda and Tanzania, and received also collection from other neighbouring countries. But the fact that more than 25 countries are below the average would seem to suggest serious gaps.

Also the number of collections per estimated number of species for the countries may indicate serious gaps in collecting in many sub-Saharan African countries. Gabon, a species-rich country that covers biodiversity hotspots (Fig. 8A) has only 5.6 collections per estimated species, which is below the average of 6.4.

## Gaps in Collecting Activity and Knowledge about Areas of High Diversity

As it seems to be the case with Gabon, many of the high-diversity areas in sub-Saharan Africa, popularly known as biodiversity hotspots, are under-studied and collections from these areas poorly represented in

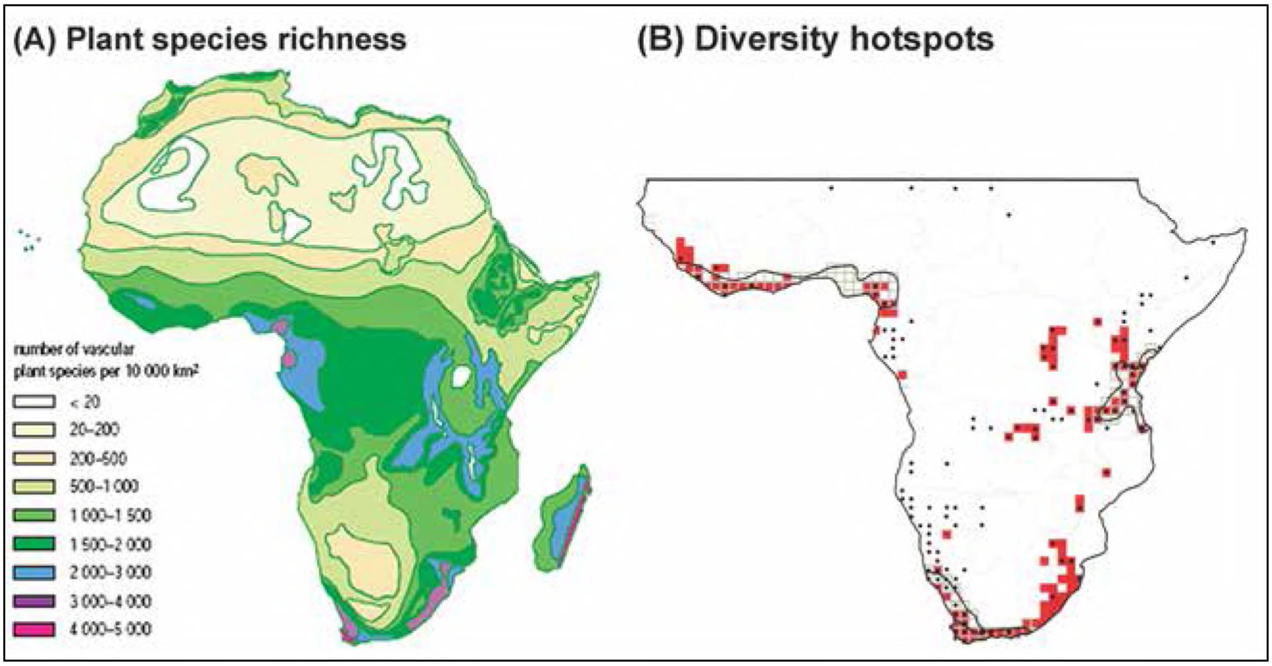


Fig. 8. Diversity of the African flora, biodiversity hotspots and need for conservation and in some cases more collecting activity and exploration (compare with Fig. 6 and 8). (A) Map showing estimated number of vascular plant species per 10,000 km² in sub-Saharan Africa. (B) Sub-Saharan areas estimated to be of high conservation value. The diversity hotspot areas defined by Myers *et al.* (2000) are indicated by solid black lines. Open cells surrounded by grey lines are one-degree squares covered by the hotspots of Myers *et al.,* while the redefined hotspots by Küper *et al.* (2004) are indicated with red cells. The map also shows (black dots) the 125 cells of the 'near-minimum-cost'-set where the most species can be protected at lowest cost. (A) Part of map of estimated plant diversity of the world by Mutke and Barthlott (2005). (B) From Küper *et al.* (2004).

herbaria, African as well as European. This makes it difficult to prioritise these areas with high diversity even though they may be threatened. The original and well-known Myers-Mittermeier hotspots (Myers *et al.* 2000) were painted with a very broad brush, and the resulting picture was geared towards public relations for the conservation of areas characterized by the presence of particularly spectacular species, often outstanding species of animals, so-called 'flag-ship-species.' We are not denying the need for conservation in many of these areas, but such hotspots as 'Horn of Africa' or 'Madagascar' are defined too broadly to be informative. Some of the high-diversity areas within these 'hotspots' are pretty small and discrete, such as the Nogaal Valley in Somalia, the Uluguru and Udzungwa Mountains in Tanzania, or the Bakossi Mountains in Cameroon.

Areas with more than 3000 species per 10,000 km² are quite small. The map only shows the diversity on a continental scale, but even these relatively small areas can sometimes, on a finer scale, be broken up into smaller centres of high diversity, for example the Monts de Cristal in Gabon, which was not included in the map of Myers *et al.* (2000). Because of their small size these areas are particularly important to focus upon for conservation purposes. In 2004 one of us contributed to the redefinition of the African hotspots on a much finer scale and more linked to hard facts than Myers' areas (Küper *et al.* 2004) (Fig. 8B). The map also shows where to protect the most species at lowest cost; that often (but not always) means least human impact, so these are not hotspots, which are defined by having lost at least 70% of their primary vegetation (Myers *et al.* 2000).

When areas with high diversity and high conservation value are under-collected, then these areas represent high-priority gaps that need addressing. Some such areas may be 'invisible' both on distribution and diversity maps and in herbaria because of under-collecting, as proven by the Bakossi Mountains in Cameroon and the Makueni wooded grasslands in Kenya. This points to the need for more fieldwork in as many suspected or potential hot-spots as possible. The study of undiscovered hot-spots may also provide taxonomically interesting new species, such as *Ancistrocladus tanzaniensis* Cheek & Frimodt-Møller, *Diospyros uzungwaensis* Frimodt-Møller & Ndang., *Lijndenia udzungwarum* R.D. Stone & Q. Luke, *Asplenium udzungwense* Beentje, *Coleotrype udzungwaensis* Faden & Layton, *Pauridiantha udzungwaensis* Ntore & Dessein, all described, with many others, within the last fifteen years from humid habitats in the Udzungwa Mountains in Tanzania. The Udzungwa Mountains was a poorly known, but in fact a floristically and faunistically very rich part of the Eastern Arc Mountains, which only became well known after the 1990s (Lovett 1993, 1998).

Equally high and hitherto unnoticed diversity might be seen in dry habitats, for example the 137 new species described from Somalia since ca. 1990 (Thulin 2006). Recent examples of undiscovered floristic richness in dry habitats in the Horn of Africa are a range of striking new species in Acanthaceae, Apocynaceae, Euphorbiaceae, Leguminosae and Solanaceae from the Ogaden in eastern Ethiopia and adjacent parts of Somalia (Thulin *et al.* 2008; Thulin 2008, 2009a,b,c; Thulin & Vollesen 2015), to which has recently been added two extraordinarily tall, woody and large-flowered species of *Commicarpus* from an arid high-diversity part of south-eastern Ethiopia (Friis *et al.* 2016) This also points to the need to study potential hot-spots in order to fill taxonomic gaps.

## Gaps in Taxonomic Knowledge

While gaps in collecting activity in high diversity areas mean that the herbaria are not representative, the gaps in taxonomic knowledge mean that collections in herbaria are not updated and properly utilised. Gaps in taxonomic knowledge are twofold: gaps in the broader understanding of taxonomy at the level of genera and species, and gaps in the production of floras and lacking flora-coverage (Sebsebe Demissew 2011, 2014; Beentje 2015). Taxon-knowledge gaps in sub-Saharan Africa itself are especially vexing in the larger families: Poaceae, Fabaceae, and Asteraceae. But larger genera also need their own specialists; although not belonging in the previously mentioned mega-diverse families several large genera are understudied in Africa, such as: *Cyphostemma* (Vitaceae), *Euphorbia* (Euphorbiaceae), *Ipomoea* (Convolvulaceae), *Polystachya* (Orchidaceae), *Barleria* (Acanthaceae), and *Pavetta* (Rubiaceae).

Although there are now reasonably good estimates of the size of the floras of nearly all African countries, the actual coverage with published floras for the continent is still full of gaps (Table 4). The total area of sub-Saharan Africa is 24.2 million km$^2$ of which 36% are covered by complete floras (Sebsebe Demissew 2011, 2014; Beentje 2015). Another 34% have incomplete floras, ranging from only very partially complete to almost finished. The *Flowering Plants of the Sudan* (Andrews 1950–1956), now covering both Sudan and South Sudan and encompassing a sizeable part of sub-Saharan Africa north of the Equator, is based on few collections and does not have much in the way of identification keys, but has been supplemented with check-lists (Friis & Vollesen 1998, 2005; Darbyshire *et al.* 2014). Finally, some countries do not have scientific floras at all: Chad, Central African Republic, Equatorial Guinea and Congo-Brazzaville, and Gambia, Guinea Bissau, Chad and South Sudan do not seem yet to have established a national herbarium, indeed any herbarium in their countries. For a few areas of high plant diversity field guides have been published, or guides dealing with selected taxa; mostly, these overlap with published floras.

All of this shows the continued need for fieldwork and the subsequent storage and treatment of the collected material in herbaria. Our printed floras are based on existing specimens in herbaria, but work in the field may both add new records and new species

**Table 4.** Coverage of published floras in sub-Saharan Africa. Data updated from a presentation by H. Beentje at the conclusion of the *Flora of Tropical East Africa* project in 2012. The *Flora of Tropical East Africa* is the largest modern tropical flora ever completed. The species in the *Flora of Southern Africa* area are covered by much other information. The recent checklist of Sudan and South Sudan (Darbyshire *et al.* 2015) includes 3969 species.

| | Completion % | (approx.) # species |
|---|---|---|
| *Flora of West Tropical Africa* (in 2nd ed.) | 100 | 7072 |
| *Flora of Tropical East Africa* | 100 | 12,104 |
| *Flora of Somalia* | 100 | 3165 |
| *Flora of Ethiopia and Eritrea* | 100 | 7,000 |
| *Flora Zambesiaca* | 90 | 10,000 |
| *Flore de l'Afrique Centrale* | 60 | 10,000 |
| *Flore du Cameroun* | 40 | 9,000 |
| *Flore du Gabon* | 40 | 7,000 |
| *Flore de Madagascar* | 35 | 12,000 |
| *Flora of Southern Africa* | 13 | 23,400 |

(Friis 2014); and, moreover, add information useful in making conservation assessments, such as population sizes and threat levels.

## Gaps in Resources and Taxonomic Impediment

The taxonomic impediment, which is caused by shortage of herbarium material and taxonomic information, of floristic coverage, and of taxonomic practitioners, is often the main reason for big gaps. Quite frequently the reasons for gaps are financial – fieldwork the establishment and maintenance of herbaria and the employment of herbarium scientists and curatorial staff comes pretty low on most governments' and institutions' priority lists. As a result there is a world-wide shortage of vital taxonomic information to manage/conserve/use our biodiversity. The importance of the taxonomic impediment was recognized by the Convention on Biological Diversity (CBD), signed at the 1992 Rio Earth Summit, but the initiatives taken have not yet solved the problem. The number of practicing taxonomists has been shrinking for several decades, and many taxonomists are now quite advanced in years or practicing in their retirement (Ingrouville 1989; Buyck 1999; Drew 2011).

An important reason for the underfunding of taxonomy is that the discipline is looked upon as old-fashioned, stagnant and not producing economically important results. Far too often it is taken for granted that plants are easy to name, which in very many cases they are not. Increasing funding can only come out of more general awareness of how vital a function taxonomists fulfil. More appreciation of what we do is needed, and it has to be made clear that taxonomists provide vital baseline data utilised by a host of other researchers, from scientists involved in DNA-barcoding and -phylogeny to biochemists, pharmacologists, conservationists, ecologists, ethnographers and even forensic scientists in the service of the police, at times.

There is also an access problem: much of the information provided by taxonomists is locked up in herbaria only accessible to scientists, in obscure publications, or in peoples' heads. The production of floras is one way to synthesize such data. But to improve and streamline the accessibility of our scientific results we need more training, more staff, and this equates to more money. It is vital that a new generation can take over, using modern methods in communication to (maybe) speed up the completion of floras and the popularization of the importance of wild plants. In the meantime, we can work on making our data more easily accessible, in more user-friendly formats as e-floras, overview databases and field guides.

## Positive Development

Taxonomists are slowly closing some of the gaps mentioned above. We are still collecting, at least in certain parts of Africa, naming the collections and incorporating them in herbaria, we are tackling large genera and problem groups, through collaboration and through using both classical and modern methods. We are making our data more accessible by publishing on the web as well as in hardcopy, by making databases available, by sharing and by teaching.

Collections, revisions and monographs are what powers taxonomic progress. They build on fieldwork, herbarium studies and accumulated expertise, and solve problems of taxonomic interrelationships; they provide the floras with the hard-core science on which to build floras, field guides, ecological studies, etc. Floras synthesize all existing knowledge and make it accessible in a unified format. Formats of printed floras themselves may vary quite a bit, but they should ideally all provide solid contributions to our understanding of the African plant world, an understanding on which future generations can build. And some flora projects are also excellent capacity-building taxonomic projects, based on close collaboration between taxonomists in the South and in the North: a shining example is the *Flora of Ethiopia and Eritrea* (Hedberg 2011; Sebsebe Demissew 2011, 2014). Once a flora for a country or a region has been completed, it may give rise to spinoff products like field guides, which are both more restricted in scope than the original flora and more user-friendly. There is also the important category of overview websites that build on floras and monographs. One can mention the International Plant Names Index (IPNI), a database of plant names and associated basic bibliographic information (www.ipni.org ), TROPICOS, with information on 4.3 million specimens, many of which are from Africa, and bibliographic data (www.tropicos.org ); the Biodiversity Heritage Library (BHL), through which much taxonomic literature is made available on-line (www.biodiversity-heritagelibrary.com), JSTOR, with on-line access to historical journals (www.jstor.org) and the Global Plants Initiative (GPI), Global Plants on JSTOR, with scanned high-resolution images of more than two million type specimens (plants.jstor.org).

A number of partially linked and unique resources for plant taxonomists and other interested users deal specially with the plants of sub/Saharan Africa: (1) a number of volumes in two series, entitled *Énumeration des plantes à fleurs d\Afrique tropicale* and *Tropical African Flowering Plants* by Lebrun and Stork (1991–1997; 2003–2015). The two series list all the species of vascular plants occurring in tropical Africa, the later series with ecological information and generalized distribution maps. (2) The extremely accessible and useful African Plant Database (http://www.ville-ge.ch/musinfo/bd/cjb/africa/recherche.php ) in which one can search for any African plant name (199,873 in total in May, 2017) and find bibliographical data, synonymy, notes on ecology and distribution, a generalized map, and links to other sites such as (Global Plants on JSTOR). (3) Photo guides with images of many species, such as http://www.africanplants.senckenberg.de/root/index.php. All these aid both herbarium curation and taxonomic research in sub/Saharan Africa.

## Conclusions

We have seen that plant collections in sub-Saharan Africa are more and more kept in Africa itself, and the collections are spread widely over the continent. These plant collections do not cover all areas equally, and collecting gaps remain in high diversity hotspots, as seen from a comparison of Table 3 with Fig. 9. The hotspots should be investigated before it is too late, but it is important to remember that not all high diversity areas have been localised or can be predicted.

The taxonomic impediment is strong in Africa, mainly due to underfunding. This causes a shortage of trained taxonomists and curators. We need to address this, as a community, by making it clear that we fulfil a vital role, on which many other disciplines rely. In the post-colonial time and until the present, collaboration between taxonomists in the South and in the North has been very productive (Beentje 2015; Hedberg 2011; Sebsebe Demissew 2011, 2014; Onana 2017), resulting in national or regional floras of high standards. The number of taxonomists in the North who can take part in future collaborative efforts is declining, adding to the taxonomic impediment in the South. African taxonomists cannot change this development in Europe and North America, but one can hope that increasing South-South collaboration, and the increasing ability of African botanists to attract their own funding, might alleviate some of this impediment in the future.

As shown in this paper, many of the areas of high plant diversity in tropical Africa remain under-collected and under-studied. Where such areas are rich in species and coincide with threats to the habitats, they should become priority areas for collecting and study, in order to give a strong basis for coming conservation proposals.

There is a current need in many countries in sub-Saharan Africa to complete their national botanical inventories for conservation purposes, for sustainable use of their plant resources, and to fulfil their obligations to the Aichi Biodiversity Targets (https://www.cbd.int/sp/targets/) by 2020. This will require more alpha level taxonomic research to in under-explored areas in sub-Saharan Africa, despite the progress made in specimen collections, flora documentation, and in the fields of molecular systematics.

While large gaps remain in flora coverage, we urgently need more specialists in large families, both for the curation of herbaria and for the many practical uses of taxonomic treatments. There is good progress in making our work more accessible, and therefore in collaboration between colleagues, both inside the discipline and with colleagues in other fields. Much remains to be done, both with the plant collections of Africa and with their utilisation, and continuing threats to the biodiversity all over the continent make this urgent – but there is hope for the future, too, with much already accomplished.

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# The North-South Synergy: The National Herbarium and Limbe Botanic Garden experience

*Jean-Michel Onana, Julie Mbome Mafanny and Yves Nathan Mekembom*



## Abstract

The North-South synergy for plant collections in Cameroon began in 1869 when K sent the first botanist to collect on Mount Cameroon. The colonial administration of Germany created the Victoria [Limbe] Botanic Garden in 1924, and the Herbarium (SCA) was established in the garden during he British rule in 1959 as a databank for the Mount Cameroon area. The 'Section de Recherches Forestières du Cameroun' (YA) was created in 1948 during the French rule and it later became the National Herbarium of Cameroon. Many Herbaria in Europe and USA have sent taxonomists to Cameroon for collecting. Thanks to assistance from the North, the synergy has produced about 65,000 specimens in the working collection in YA and with many duplicates in international herbaria, a floristic database, 42 volumes of the series *Flore du Cameroun*, a vegetation map and nine checklists for conservation. Also the capacity building for Cameroonian taxonomists was effective thanks to workshops in P and training at the University of Yaoundé and School of Forestry. But still there are gaps for collection and lack of plant taxonomists. The challenges for the future are to keep improving the skills of taxonomists, improve the collection and complete the publication of families for the *Flore du Cameroun*. Thanks to the institutions of the North, the flora of Cameroon is one of the best known in tropical Africa.

**Key Words:** Cameroon, collections, flora, *Flore du Cameroun,* publications, legacy, future

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The North-South collaboration with regard to plant collecting and the building of collections in Cameroon is linked to the political history of the country. The beginning was made by very active German botanists from 1892 to the World War I, after which the originally German colony of Kamerun was divided between Britain and France under a 1919 League of Nations mandate. The territory of the German colony was divided into two mandated territories, the British Cameroon in the smaller south-western part, and the French Cameroon (Cameroun) in the much larger eastern part. In 1960, the French part of Cameroon became independent, and the British part became federated with it in 1961. In 1972 the federal status of the two parts was abandoned, and the country became the United Republic of Cameroon and the Republic of Cameroon in 1984. Each of the two countries that were responsible for the mandated territory assisted Cameroon in the creation, operationalization and management of institutions housing botanical collections. The Limbe Botanic Garden Herbarium was supported by the British (United Kingdom) and the National Herbarium (of Cameroon) in Yaoundé was supported by France. Thus the two herbaria benefited from partnership with scientist from both countries, both before and after independence. The work of and collaboration with botanists from the North in Cameroon will be evaluated in the following, as well as major challenges to complete the publication of the series *Flore du Cameroun*.

## Historical Overview of Botanical Collections in Cameroon

Cameroon, a nation like most African nations, is a creation of the colonial period beginning in the late 19$^{th}$ Century, although the name 'Rio dos Cameroes' (river of prawns) had been given to the river Wouri by the Portuguese as far back as the 15$^{th}$ century, and in the following century or longer, the Portuguese continued coastal contacts with Cameroon by the estuary of the river Wouri. For many centuries, long before the Portuguese, there had been contacts between Cameroon and northern Africa through caravan routes across the Sahara. Contact by sea with the Mediterranean may possibly first have been made as early as in the fifth century BC by the Phoenician admiral Hanno, who travelled along the west coast of Africa and near the coast he observed a phenomenon which by night looked as if the land was covered by flames and in one place there was a very tall flame, but by day that could be seen to be a very high mountain called *Theo Oekema* (Greek for 'Chariot of Gods'); the fires on the coast have been interpreted as grass fires, rather common during the dry season in many parts of tropical Africa, and the tall flames from a high mountain may possibly be a reference to the volcano Mount Cameroon during an eruption. Not far beyond that place, Hanno reported on savage people with hairy bodies, which the interpreter called 'gorillae' (Schoff 1912).

Letouzey (1968a) described the history of botanical collections in Cameroon in detail. The story goes back to contact with the first European explorers from Portugal in 1472. But no botanical collections or botanical illustrations are known from this early date. The first known collections were obtained from the caravan routes across the Sahara by the Scottish medical doctor or surgeon Walter Oudney (1790-1824), who travelled with the explorer Dixon Denham and Hugh Claperton during the years 1822-1824. Having travelled from Tripoli in present-day Libya since January 1823, the expedition reached the town of Kousseri near Lake Chad in February/March 1823 and then part of the Bornu empire. There Oudney collected about 300 plants, but he died in January 1824 near the town of Katagum, now in northern Nigeria. His plants from the expedition came to the British Museum (BM) (Holmgren *et al.* 1990), but the specimens were poorly preserved. This material was published by Robert Brown in an appendix to the report of the expedition (Brown 1826).

After the journey by Oudney, Denham and Clapperton followed other missions by explorers from England or Germany, still focusing on the area around Lake Chad, but most of the material from these journeys has disappeared. The authors of this paper are not aware of any collections made during these explorations and cited in floristic study of northern Cameroon.

The history of botanical exploration of Cameroon began in earnest with the expedition of Gustav Mann (Fig. 1) in 1861 to Mount Cameroon. The work of botanical collecting in Cameroon continued intensively with a number of active German collectors, for example Friederich Reichardt Rudolph Schlechter (collected 1899–1900), Paul Rudolf Preuss (associated with the Victoria Botanical Garden, collected 1889–1892) and Georg August Zenker (collected 1889–1913). During the time of the British and French mandates collecting continued, but perhaps less intensively than during the German colonial period. Until 1967, about 52,000 specimens from Cameroon collected almost entirely by European collectors had been deposited in different herbaria in northern institutions, essentially in Europe at B, BM, G, K, MO, P and WAG, but also at FHI in Nigeria and SCA in Cameroon.

In assessing the state of knowledge about the flora of Cameroon, Letouzey (1968a: 27) indicated the gaps in collections, by identifying areas that are very little known or not explored. It is to these areas that most of the field botanists will continue go to document the floristic richness of Cameroon. And it is significant to note that 1968 is the starting point of a period of intensive botanical collections in Cameroon, almost certainly the most intensive in the history of botanical exploration of Cameroon, and that this was led by institutions and botanists from the North.

Comparing the amount of collectors and collections in different parts of the country, the largest number of collections was carried out by Dutch botanists, who have collected a total of 22,329 plant samples in the Littoral, Central and South administrative Regions (Letouzey 1980; Bruijn 1980). From 1980 to 1992 approximately 3000 samples were collected by Cameroonian nationals from the National Herbarium at Yaoundé (Onana 2010). From 1992 to 2004, nearly 37,850 were collected in the Southwest Region, including 18,350 during the implementation of the Mount Cameroon project financed by the Government of the United Kingdom (Gosline 2004). About 3000 specimens were collected in the Dja Biosphere Reserve under the ECOFAC (Forest Ecosystems of Central Africa) project, funded by the European Union. About 3000 were collected in the Operational Technical Unit of Campo Ma'an (Tchouto 2004). In total, about 155,000 plant specimens have been collected from all over Cameroon between 1869 to 2007 (Onana 2010).

These intense collecting efforts have been performed by 648 field botanists. Of these, 634 (98%) were from Europe and USA, including volunteers and team-leaders from organizations such as Earthwatch. Most of these collections have been distributed to some 55 herbaria worldwide, mainly in Europe, where they have gone to B, BR, BRLU, G, HBG, K, P and WAG, or to the US, where they have mainly gone

Fig. 1. Gustav Mann (1836–1916). A Hanoverian, he was first a Kew gardener and then a plant collector. Mann was the first to collect on Mt Cameroon, which he visited three times during 1861–1862, staying several months in total and collecting many hundreds of specimens. He concentrated on the upland flora at the instruction of Kew's director, Sir William Hooker. Source: Cable & Cheek (1998).

to MO, or to other countries in Africa, such as IFAN, FHI and EA, but duplicates were always left at YA (Onana 2010).

## History of the Main Herbaria in Cameroon and North-South Cooperation

The Limbe Botanic Garden Herbarium (SCA) and the National Herbarium at Yaoundé (YA) were established by the colonial Government of Germany and the mandate-administrations of the Britain and France for specific purposes, including basic botanical research. After independence, bilateral separate conventions between the Britain, France and Cameroon has enabled the development of these herbaria.

### *The Limbe Botanic Garden Herbarium (SCA) – cooperation with Kew (K)*

The Limbe Botanic Garden was established by the German colonial government as the Victoria Botanic Garden in 1892. It was initially to be an agricultural research station and forestry school under the directorship of Paul Rudolf Preuss.[1] The purpose of the station was the importation, acclimatization center for the introduction, development of exotic tropical crop species of economic and medicinal potential such as coffee, tea, palm oil, quinine, rubber, banana and coconut, teak and sugar cane. These were among the many plants evaluated at the garden before being planted in commercial plantations in Cameroon and other German colonies in Africa, and the botanical garden introduced up to 400 species annually from the tropics around the world. In addition, experimental plots to evaluate the yield of tea were set up. Some of the first introductions are still growing in the garden, but the majority of the species have now disappeared and are known only thanks to botanical collections, for example *Canarium zeylanicum* (Retz) Blume, the Ceylon almond, endemic to Sri-Lanka, which is known to have been introduced in the garden thanks to a specimen, *Maitland* 426 (K), that was collected in the garden in 1929.

The botanical garden at Limbe has had a varied history. By 1916, it occupied an area of nearly 200 hectares, extending along the coast from the village of Bota to the present-day New Town and inland for about one mile. The botanic garden formed the hub of a larger research station, which was composed of a network of research facilities, laboratories, an agricultural college, a museum and a library, staff accommodation, trial plantations and vegetable and animal farms. In addition, the station also established a number of tea, coffee and quinine plantations on and around the slopes of Mount Cameroon.

After 1916, during World War I, the funding for the station was reduced, and the botanic garden entered several years of decline. At the end of World War I, in 1918, all German properties, plantations and assets were seized and put into the trusteeship of the Allied Governments of Britain and France. As a result, funding for the garden dwindled and it entered a period of severe decline. In 1924, concerns about this decline were raised, and it was decided to bring in two specialists from the Royal Botanic Gardens (RBG), Kew, in Great Britain to assist with the renovation of the garden. It was during this period that research on cocoa, citrus, mango and other important fruits began and continued until the early 1930s when the global recession made it impossible for the Royal Botanic Gardens, Kew, to continue to provide staff for the garden. Funding again became scarce, and the number of staff working at the garden fell from 100 to around 30. While work continued, it was impossible to maintain the entire garden, and large areas were abandoned to return to forest, or were taken over for homes and farms. This situation continued until 1954, when British funds permitted increased staff and a renovation of the garden.

The Herbarium, Victoria Botanical Garden (SCA:

1. Part of the information about the general history and possibilities of the Limbe Botanical Garden has been obtained from home pages consulted on 16 February, 2014: http://www.bgci.org/worldwide/article/127/; http://www.globeholidays.net/Africa/Cameroon/Limbe/Limbe_Botanic_Garden1.htm Limbe Botanical and Zoological Gardens (LBZG); http://www.africanconservation.org/explorer/limbe-botanical-and-zoological-gardens-lbzg.

Southern Cameroon) was founded in association with the garden in 1959 (Lanjouw & Stafleu 1964: 194) with 1400 specimens. The exact state and size of the garden when the herbarium was established in not known. The aim of the herbarium was to serve as a databank to preserve plant material from the Mount Cameroon area until the Republic of Cameroon was formed in 1962. The government of Cameroon managed the garden and the herbarium unassisted until 1988. The garden came into its present size during the period 1962–1988, with an area reduced from its original size to about 48 hectares. Due to the lack of trained personel to manage the specimens at the herbarium, the dried collections were moved to YA.

In 1989, the Governments of Cameroon and the United Kingdom entered into a new bilateral agreement to renovate the Limbe Botanic Garden as a center for the conservation of biodiversity in the Mount Cameroon region. During the first five years of the project, the garden, its infrastructure, plant collections and herbarium were largely restored. Then, in 1995, the garden became a component of the Mount Cameroon Project, the herbarium re-opened and collections began to be deposited in the herbarium again, with duplicates sent to YA in Yaoundé.

During the period of the project, attention was increasingly focused on forest conservation and the protection of the rich biodiversity and resources within the Mount Cameroon region. Hence, the role of the garden shifted from solely serving agriculture to playing roles in research, education, tourism, recreation and conservation in order to meet the demands of the Convention on Biological Diversity (CBD). The Cameroon Government and the British Overseas Development Administration (ODA) then collaborated to:

- encourage the conservation of Cameroonian forests by the local people for sustainable use;
- encourage scientific studies of the natural resources for the benefit to humankind;
- develop environmental awareness at different levels of society for a better future;
- promote tourism and recreation in the region.

Fig. 2. Réné Letouzey (1918–1989). From a photograph by F.J. Breteler, reproduced with permission and thanks.

The first achievement of the field work was the botanical survey report of the Mabeta-Moliwe proposed forest reserve forest (Cheek 1992). This report served as the basic document for the first checklist for conservation in Cameroon (Cable & Cheek 1998). This first checklist, with a red data list, lead to the classification of this forest into a protected area named Bimbia-Bonadekombo council forest, with the incomes from tourism going to the Limbe Council. Later, the checklist of Mount Cameroon (Cable & Cheek 1998) was used as a basic document with the creation of the Mount Cameroon National Park by the Ministry of Fauna and Forest of Cameroon. The joint British-Cameroonian funding of the garden continued until March, 2002.

Today (in 2015), the Limbe Botanic Garden is an institution under the Ministry of Forestry and Wildlife (MINFOF), recognized as a Technical Operational Unit (TOU). This status recognize the Limbe Botanic Garden as part of a larger protected area with various activities including research and conservation of plants at all levels. The herbarium (SCA), with over 22,000 herbarium specimens (of which over 32 types), and more than 13,000 ecological (sterile) specimens, includes 1400 species, 700 genera and 260 plant families; 46 species represent endemics. This herbarium will serve as the center of studies and research for the flora of the Cameroon mountains. However, the collections at SCA are in bad state due to the lack of funding for curation.

### *The National Herbarium (YA) – cooperation with European and American herbaria*

Réné Letouzey (1918–1989; Fig. 2) was a young French engineer in forestry when he arrived in Cameroon in 1945, appointed conservator of the natural resources of the forests, with responsibility for both plants and animals. Because logging of tropical timber from the forests of Cameroon was an important economic resource for France, he decided that it was high time to improve the knowledge of the flora and vegetation of Cameroon before too much was converted to secondary vegetation. To achieve this, he soon moved from the administration in charge of the management of forests (the Ministry of Forestry) to the Centre National de la Recherche Scientifique (CNRS). The herbarium in Yaoundé, was initially established in 1948 in conjunction with the European herbaria P and WAG. It first specialized in the collection of timber specimens, called 'Section des Recherches Forestières du Cameroun' (SRFCam or SFRKam [=Kamerun]). A provisional house was built to store the specimens. The herbarium was then recognized as 'Service des Eaux et Forêts du Cameroun, Section des Recherches Forestières', recorded as YA (Lanjouw and Stafleu 1964: 202) with a holding of 2000 specimens. From 1960, YA was assisted by the herbarium of the Museum national d'Histoire naturelle de Paris, Laboratoire de Phanérogamie' (P). Taxonomists from P came to Cameroon to collect specimens, describe new species and teach at all levels, from the School of Water and Forestry of Mbalmayo to the Faculty of Science of the University of Yaoundé. The Herbarium was then expanded to include all vascular plants and attached to the Forestry Administration after independence. By then, three principal objectives were assigned to the National Herbarium:

1. Constitute a basic botanical reference collection of the national floristic patrimony;
2. Produce a phytogeographic map of Cameroon or at least increase the knowledge of the vegetation and the phytochoria of the country;
3. Describe species and publish the series *Flore du Cameroun* for the country's vascular plants.

To achieve the first objective, field work and collecting began in the western part of the country now Northwest, West and Southwest Regions, then in the eastern part in the East Region and later in the north in the Adamaoua, North and Far North Regions. Until 1967, 8964 collections were made and incorporated in YA, comprised largely of nearly 7000 collected by Letouzey.

Thanks to the joint cooperation between the French cooperation agency (Fonds d'Aide et de Cooperation) and the Government of Cameroon, the present building of the YA was constructed to replace the preliminary one, which had been built in wood. In 1971, the name Herbier National Camerounais was made official. According to the then director, Bernard

**Table 1.** Number of specimens in the working collection in the National Herbarium of Cameroon according to Satabié (1981, 1999) and a query in the database in YA

| Type of collection/Number of samples | 1981 | 1999 | 2015 |
|---|---|---|---|
| Sheets of mounted specimens | 50,000 | 70,000 | 65,680 |
| Wood samples | 800 | 800 | 800 |
| Fruits and seed | 500 | 500 | 500 |
| Flowers in spirit | 100 | 100 | 100 |
| Pollen slides | 1200 | 1200 | 1200 |

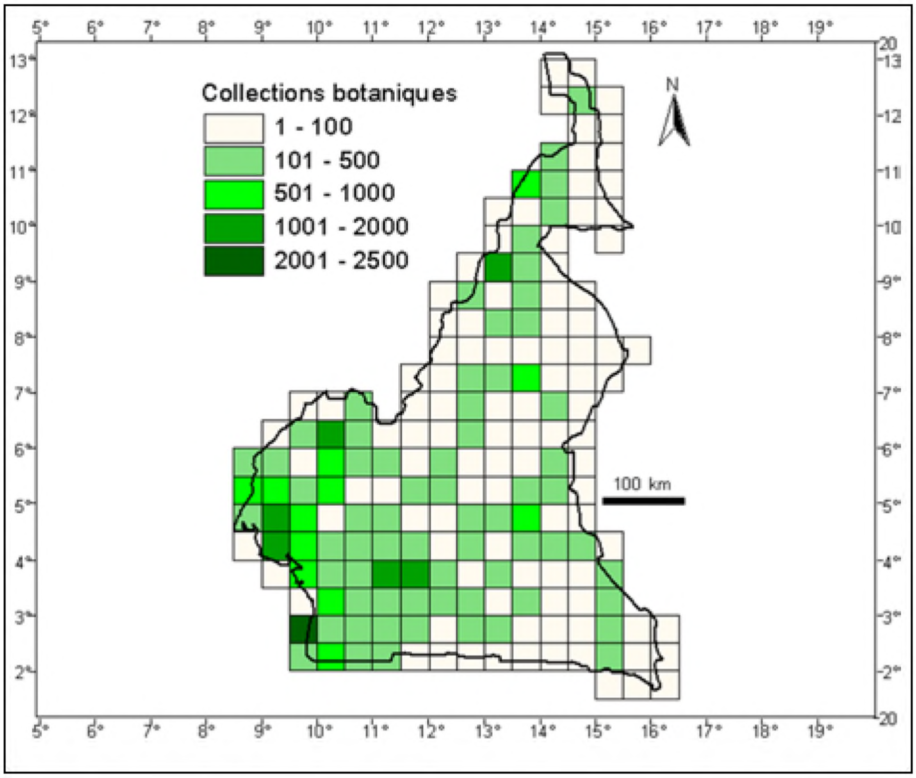


Fig. 3. Results of botanical collecting efforts in Cameroon based on the distribution of 36,588 specimens at YA using half degree cells. Map by C.K.Ngembou & J.M. Onana: Source: Onana (2011).

Satabié (1981), the working collections was the approximately 50,000 specimens. About 20,000 had been added to the herbarium 19 years later (Satabié 1999; see also Table 1). The collection of specimens continued with field botanists collecting all over Cameroon (Fig. 3). In 2015, according to the database of the herbarium, the number of specimens had reached exactly 65,680. So from 1967 to 2015, 56,893 collections were added to the working collection of YA. About 20,000-35,000 specimens are still waiting to be mounted.

The plant species of Cameroon are not all represented at the collections of the National Herbarium. The number of species not represented by specimens at YA, are about 5% of the expected total number (Onana 2010).

At present, YA has status as Specialized Station in Botanical Research (with international interest) as part of the Biodiversity Program under the Institute of Agricultural Research for Development (IRAD) of the Ministry of Scientific Research and Innovation (MINRESI). New objectives have been added to original ones of conservation and sustainable management, and climate change is at the moment an important issue. For that purpose, the collections of YA provide essential material for research in bio-indicators for conservation (endemism, assessment of potential species for a Red List of the flora of Cameroon), studies of ecological niches, locating areas for plant conservation and acting as tools for land use mapping. As an overview of the collections, the series *Flore du Cameroun* is a main key to assess the level of the taxonomic knowledge of the flora of Cameroon.

## Legacies from the Past and Gains of the North-South Synergy

The gains of the North-South collaboration and the synergy in the botanical research in Cameroon can be observed through the increased level of collections, the description of new species, taxonomic revisions, publication of the volumes of the series *Flore du Cameroun*, the publication of checklists, training of botanists and participation in international initiatives.

### *Collections*

The collections in the National Herbarium (YA) are recognized to be the best managed in central and west African countries. In addition to the collections, almost 97% made by field workers from abroad, there are about 400 high quality images of historical specimens, including some collected by Mann in 1869, which have been sent to YA by the Royal Botanic Gardens, Kew.

Through the scientific cooperation between the Institute of Research for Development (IRD), the Museum national d'Histoire naturelle in Paris in France and the Cameroon National Herbarium, and with funding from the Fonds Francophone des Inforoutes (FFI), an initiative of La Francophonie to have more data from French speaking countries on the Web, the digitization of the data labels has been going on since 2002 with the RIHA database (Chevillotte *et al.* 2006). The aim was to set up a network of herbaria of the French speaking countries. The collection of the YA was then chosen as a model. At the end of the financing of FFI, there was a period without funding, but scientific cooperation continued informally on the basis of the strong relationships that was built during the initial phase. Thus, by December 2006, the database had 40,078 specimens recorded (61% of the expected total), representing 71 (30%) families in 1178 (67%) genera and about 5000 species. In 2007, the initiative Sud-Expert-Plantes (SEP), funded by the Government of the Republic of France, the digitization has been accelerated, so that in December, 2010, the entire collection of work, 65,000 entries are already registered in the database. Updates started and continue for localities and will follow for scientific names.

Moreover, from 2006–2009, the National Herbarium participated in the international collaboration named the African Plant Initiative (API), aiming to upload high resolution images of types of African plant species. This participation was organised by Royal Botanic Gardens, Kew, through the Memorandum of Understanding that existed between the two organizations. This participation enabled the YA to record online 1002 items, including 150 types (mostly isotypes), and specimens of endemic and near-endemic species. In addition to these images produced at the National Herbarium, several other images of type specimens from Cameroon have been posted by various other herbaria in countries, where they had been deposited (Darbyshire *et al.* 2010). This makes it easier for taxonomic work, which in the past required long travels to study the types in the herbaria where they are kept. A case study is the review of the genus *Vepris* Comm. ex A.Juss. (Rutaceae); in this study almost all types were downloaded from the site JSTOR Global Plants (http: //www.plants.jstor.org), and this exercise allowed the description of four new species from Cameroon (Onana & Chevillotte 2015). Perhaps even more interesting is the case of *Toddaliopsis ebolowensis* Engl. Mziray (1992) had not seen the types for his taxonomic work, and consequently had not transferred the name to the genus *Vepris*. Thanks to the image of the type sent by HBG, demonstrating that the type was not lost, as had been assumed, the transfer of this taxon to *Vepris* was seen necessary, and the new combination *Vepris ebolowensis* (Engl.) Onana could be validly published (Onana & Chevilotte 2015; image of the recovered type, Mildbraed 5494 (HBG), reproduced as Fig. 5 on p. 113).

Also noteworthy in the context of North-South collaboration is the Royal Botanic Gardens (RBG), Kew western Cameroon database (Gosline 2004), set up by the Wet Tropical Africa-team at Kew and including all collections made during field works from the Mount Cameroon project to north-west and south-west of Cameroon (Cable & Cheek 1998; Cheek *et al.* 2000, 2004, 2010, 2011; Harvey *et al.* 2004, 2010), with addition of the material from Cameroon cited in the five volumes of the *Flora of West Tropical Africa* (Keay 1954, 1958; Hepper 1963, 1968, 1972). With respect to the commitment of the Royal Botanic Gardens, Kew, in the MOU signed in 2005 to send back data available in K to YA, a copy of the database was handled

**Table 2.** Some material identified or found to be new to science long after its collection

| Collection | Collection date | Identification | Date of identification | Duration between collection and first description or identification (years) |
|---|---|---|---|---|
| *Raynal J. & A.* 9959 (YA, P) | 1963 | *Vepris araliopsoides* Onana | Onana & Chevillotte (2015) | 52 |
| *Letouzey* 5249 (K, P, YA) | 1963 | *Gnetum latispicum* Biye | Biye *et al.* (2013) | 50 |
| *Letouzey* 8475 (YA)<br>*Letouzey* 10862 (YA). | 1966<br><br>1971 | *Pradosia spinosa* Ewango & Breteler | Lachenaud *et al.* (2013) | 45<br>Known first from Congo (Ewango & Breteler 2001) |
| *Nemba & Thomas* D.W. 335 ( YA) | 1986 | *Vepris letouzeyi* Onana | Onana & Chevillotte (2015) | 29 |
| *Thomas & Namata* 7663 (MO, YA) | 1988 | *Memecylon korupense* R.D.Stone | Stone (2015) | 27 |

to the Head of YA. It is available at the National Herbarium in Yaoundé (YA) and will be incorporated in the database of the entire country.

Moreover, with the support of France for the node of the Global Biodiversity Information Facility (GBIF), Cameroon was admitted as associate participant in 2005. The achievement of a pilot project in April 2011 was the publication online of 9337 plants records relative to primary data of aquatic plants, data for the Convention on Trade in Endangered Species of Wild Fauna and Flora (CITES), and endemic species from Herbaria of Cameroon (www.gbif.org).

The specimen collected many years ago are still used as the source of description of new species (Bebber *et al.* 2010) and for taxonomic revisions by Cameroonian botanists (Biye *et al.* 2013; Onana 2015) or taxonomists abroad (e.g. Ewango & Breteler 2001; Lachenaud *et al.* 2013; Stone 2015) (Table 2).

Thanks to the collection in different parts of Cameroon, our knowledge of the distribution of species has improved. This has been the key data for the red list assessment of plant species with the publication of the sole Red Data Book of flowerings plants at the global level in tropical Africa (Onana & Cheek 2011).

### *The Vegetation Map of Cameroon*

Because of the variety of ecosystems found in Cameroon, Letouzey set a second research strategic goal for the National Herbarium producing a vegetation map. All through his research career in Cameroon, he was focused on this objective. After his doctoral thesis (Letouzey 1968b), he continued to work on the description of Cameroonian vegetation, which resulted in the publication of the vegetation map of Cameroon at scale 1:500,000 (Letouzey 1985; Fig. 4). This document, remains one of the most detailed vegetation maps of any tropical African country, and it is the basis for all subsequent research in plant ecology in Cameroon (Amougou 1986; Sonké 2004; and the unpublished theses by Sonké 1998; Tchouto 2004 and Kouob 2009), biogeography (e.g. Achoundong 1996;

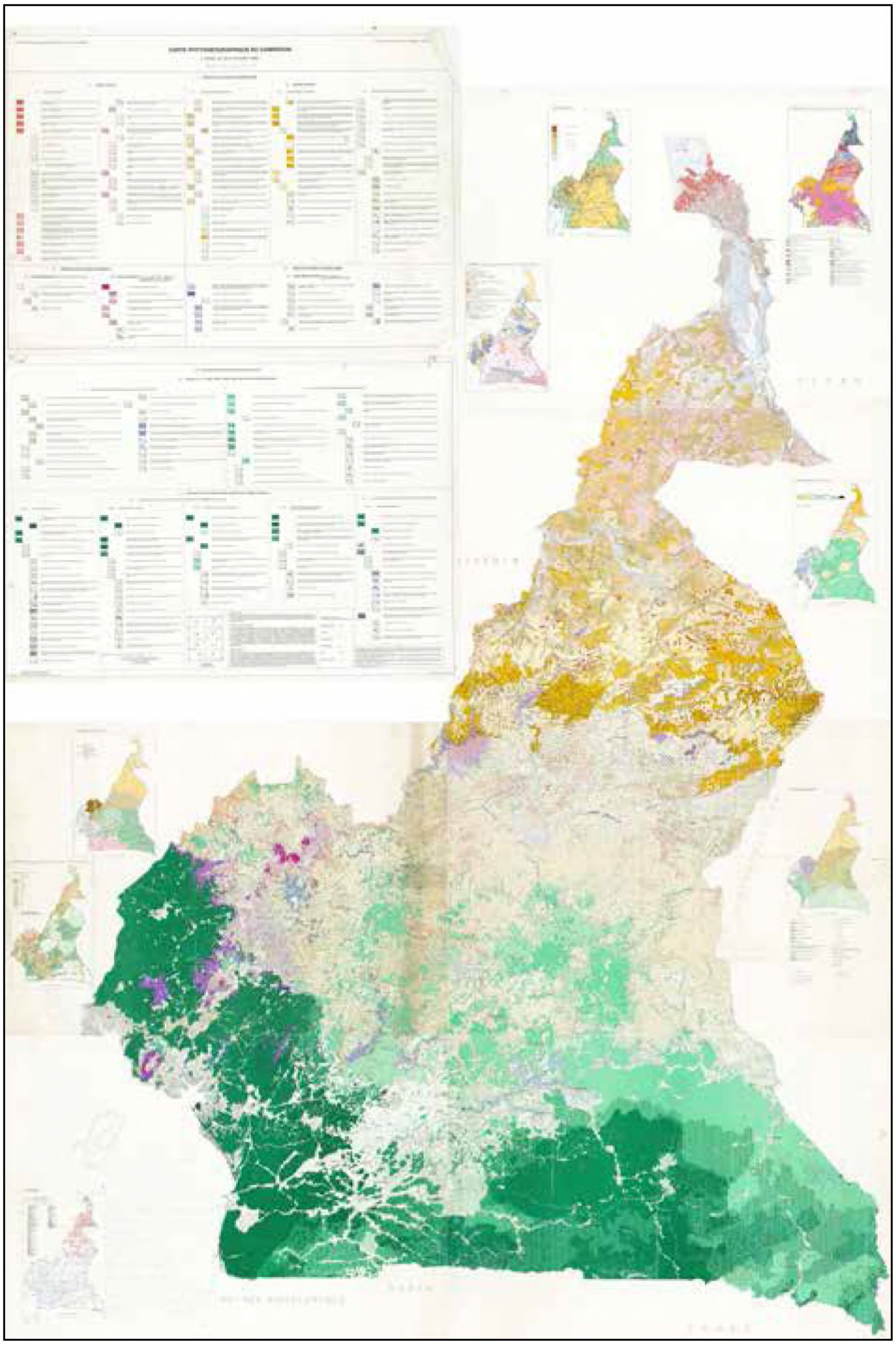

Fig. 4. Overview of the vegetation map of Cameroon. The eight sheets of the printed maps have been combined by Justin Moat, Royal Botanic Gardens, Kew. From Letouzey (1985).

Amiet, 1987), paleoecology (Maley 1987; Ngomanda *et al.* 2009) or phytogeography (Achoundong 1994; Cheek *et al.* 2001).

*Publications*

The main achievement of the collaboration and synergy North-South for floristic research in Cameroon is the publication of new species, volumes of the series *Flore du Cameroun* and cheklists for conservation.

***Taxonomic novelties and revisions:*** Nearly 1200 collections from Cameroon have been designated as type material for new taxa (Onana 2010: 563), but the number of those which are types of accepted taxa is not known at present. Many other specimens are still to be described as new species. Before 1980, the publication of new species was sporadic. According to Cheek *et al.* (2006) during the period 2000-2004 and thanks to the Darwin Initiative project, 41 new species were described and 12 others were submitted or in preparation; also among the proposed 78 new species of *Psychotria* accounted for in Lachenaud unpublished thesis (see Appendix with List of Unpublished theses), 54 are based on material from Cameroon. The work with these findings is not yet concluded, but new species from West Africa have been published (Lachenauld *et al.* 2013; Lachenauld & Jongkind 2013)

In total 210 species new to science have been described in Cameroon from 1980-2006 (Onana 2010). From 2006-2015, nearly 77 new additional species were described, in total of 287 new species in 35 years, with reference to the specimens in YA and other herbaria worldwide.

This taxonomic work was conducted by nearly 180 taxonomists from 17 different countries mainly from Europe (France, Belgium, United Kingdom, Scotland, Poland, Spain, Netherlands, Switzerland, Portugal, Denmark , Norway) and the USA but also from other African countries (Nigeria, Kenya, Gabon, Malawi) working in the laboratories and herbaria of countries in the North and in South Africa. Among the most prolific contributors are Martin Cheek, UK (57 publications), Franciscus Jozef Breteler, the Netherlands (31 publications), Réné Letouzey, France (23 publications), Anthonius Josephus Maria Leeuwenberg, the Netherlands (9 publications) and Elmar Robbrecht, Belgium (8 publications).

Thanks to this and other floristic and taxonomic work, Cameroon is now believed to be the tropical African country with most plant species per degree square (Barthlott *et al.* 1996) with more than 5000 species per degree square in parts of the southwest of the country (Fig. 5), and it is the fourth richest in plant diversity in all of Africa, after South Africa (with c. 23,000 species), the Democratic Republic of Congo and Tanzania (with c. 10,000 species each).

***Flora series and checklists for conservation:*** The series *Flore du Cameroun* was initiated by Réné Letouzey in order to describe all genera and species of all plant families of Cameroon. He was also the author of the first volume (Letouzey 1963) (Table 3). After 54 years of floristic study, 2726 species (estimated 34% of the total) for 115 families have been published in 40 volumes (excluding volumes 39 and 40 which are checklists) by 41 different authors (Onana 2011: 10). Of these authors, only one is from Cameroon (Ntépè-Nyame 1988), while the 40 others are from the North, representing 11 different countries (Belgium, Denmark, France, Germany, Netherlands, Poland, Sweden, Portugal, Norway, United Kingdom of Great Britain, and United States of America)(Table 3). In comparison, according to Poncy and Labat (1996), among the 53 botanists who participated in the description of 9377 species (2/3 of the estimated total) in the *Flore d'Afrique Centrale*, 35 were Belgian and one from Zaire [Republique Démocratique du Congo]. This shows that, in tropical Africa, taxonomists from the North are still the ones who describe plants from the South.

The production of a series of checklists (beta taxonomy) is the main result of projects for the conservation of plants in Cameroon. Given the state of conservation of specimens at the herbarium of the Limbe Botanic Garden (SCA), and also the rate of destruction of the forest in western Cameroon, and thus the urgent need to implement the Global Strategy for Plant Conservation, the Government of the United Kingdom had launched several projects in the context of Memoranda of Understanding with Cameroon. This resulted in series of nine checklists documenting the richest areas in plants of Cameroon and Africa (Cable & Cheek 1998; Cheek *et al.* 2000, 2004, 2010, 2011; Harvey *et al.* 2004, 2010; Onana & Cheek 2011), and two other thematic taxonomic works thanks to the Darwin Initiative II (Onana 2011, 2013). Cheek *et al.* (2004) has been the baseline study which led to the creation of the Bakossi National Park in 2007 (Décret no. 2007/1459/ PM du 28 Novembre

**Table 3.** Authors of the plant families in the series *Flore du Cameroun* and their country of origin.

| Volume | Year | Family | Author | Country of origin |
|---|---|---|---|---|
| 1 | 1963 | Rutaceae, Zygophyllaceae, Balanitaceae | Letouzey, R. | France |
| 2 | 1964 | Sapotacceae | Aubréville, A. | France |
| 3 | 1964 | Pteridophytes [31 families] | Tardieu-Blot, M.L. | France |
| 4 | 1965 | Scitaminales : Musaceae, Strelitziaceae, Zingiberaceae Cannaceae, Maranthaceae | Koechlin, J. | France |
| 5 | 1966 | Thymeleaceae | Aymonin, G. | France |
| 6 | 1967 | Cucurbitaceae | Kéraudren, M. | France |
| 7 | 1968 | Les botanistes au Cameroun | Letouzey, R. | France |
| 8 | 1968 | Ulmaceae, Urticaceae | Letouzey, R. | France |
| 9 | 1970 | Leguminosae – Caesalpinioideae | Aubréville, A. | France |
| 10 | 1970 | Umbellales (Alangiaceae, Apiaceae) | Jacques-Félix, F. | France |
| 11 | 1970 | Ebenaceae, | Letouzey, R., White F. | France, UK |
| | | Ericaceae | Letouzey, R. | France |
| 12 | 1972 | Loganiaceae | Leeuwenberg, A.J.M. | Netherlands |
| 13 | 1972 | Vitaceae, Leeaceae | Descoings, B. | France |
| 14 | 1972 | Malpighiacceae , Linaceae, Lepidobotryaceae, Ctenolophonaceae, Humiriaceae Erythroxylaceae, Ixonanthaceae | Badré, F. | France |
| | | Santalaceae | Lawalrée, A. | Belgium |
| 15 | 1973 | Icacinaceae, Olacaceae, Pentadiplandraceae, Opiliaceae, Otocknemataceae | Villiers, J.-F. | France |
| 16 | 1973 | Sapindaceae | Fouilloy, R. Hallé, N. | France |
| 17 | 1974 | Amaranthaceae | Cavaco, A. | Portugal |
| 18 | 1974 | Lauraceae, Myristicaceae, Monimiaceae | Fouilloy, R. | France |
| 19 | 1975 | Celastraceae (excl. Hippocrateoidae), Aquifoliaceae, Salvadoraceae, Pandaceae, Avicenniaceae, Bixaceae, Cannabaceae, Bombacaceae | Villiers, J.-F. | France |

| Volume | Year | Family | Author | Country of origin |
|---|---|---|---|---|
| 20 | 1978 | Scytopetalaceae, Rosaceae | Letouzey, R. | France |
| | | Chrysobalanaceae | Letouzey, R.<br>White, F. | France<br>UK |
| 21 | 1980 | Cruciferae | Jonsell, B. | Sweden |
| | | Dipsacaceae | Lawalrée, A. | Belgium |
| | | Cochlospermaceae | Poppendieck, H. | Germany |
| 22 | 1981 | Balsaminaceae | Grey-Wilson, C. | UK |
| | | Xyridaceae | Lewis, J. | UK |
| 23 | 1982 | Loranthaceae | Balle, S. | Belgium |
| 24 | 1983 | Melastomataceae | Jacques-Félix, H. | France |
| 25 | 1983 | Combretaceae | Liben, L. | |
| 26 | 1984 | Alismataceae, Limnocharitaceae, Hydrocharitaceae, Aponogetonaceae, Potamogetonaceae, Najadaceae, Triuridaceae | Symoens, J.J. | Belgium |
| | | Flagellariaceae | Villiers, J.-F | France |
| 27 | 1984 | Gesneriaceae | Burtt, B.L. | UK |
| | | Bignogniaceae | Gentry, A.H. | USA |
| 28 | 1985 | Moraceae (incl. Cecropiaceae) | Berg, C.C.,<br>Hijmann, M.E.E.<br>Weerdenburg, J.C.A. | Netherlands |
| 29 | 1986 | Capparidaceae | Kers, L.E. | Sweden |
| 30 | 1987 | Podostemaceae, Tristichaceae | Cusset, C. | France |
| | | Amaryllidaceae | Nordal, I. | Norway |
| | | Hypoxidaceae | Nordal, I.,<br>Iversen, J.L. | Norway |
| 31 | 1988 | Araceae | Ntépè-Nyamè, C. | Cameroon |
| 32 | 1990 | Celastraceae (Hippocrateoidae) | Hallé, N. | France |
| 33 | 1991 | Balanophoraceae | Hansen, B. | Denmark |
| | | Rhamnaceae | Johnston, M.C. | USA |
| | | Dipterocarpaceae | Villiers, J.-F. | France |

| Volume | Year | Family | Author | Country of origin |
|---|---|---|---|---|
| 34 | 1998 | Orchidaceae I | Szlachetko, L., Olszewski, S. | Poland |
| 35 | 2001 | Orchidaceae II | | |
| 36 | | Orchidaceae III | | |
| 37 | 2001 | Dichapetalaceae | Breteler, F.J. | Netherlands |
| 38 | 2011 | Eriocaulaceae | Phillips, S.M. | UK |
| 39 | 2011 | The vascular plants of Cameroon. A taxonomic checklist with IUCN global assessments | Onana, J.-M. | Cameroon |
| 40 | 2013 | Synopsis des espèces végétales vasculaires endémiques et rares du Cameroun | | |
| 41 | 2014 | Anthericaceae | Bjorå, C.S., Nordal, I. | Norway |
| 42 | 2017 | Polygalaceae | Paviva, J.A.R. | Portugal |

2007 portant création du Parc National de Bakossi), a protected area of the first category. Data from the National Herbarium of Cameroon (YA) is the base of a map of estimated species richness (Fig. 5; Onana 2011), which again is part of the base of a more detailed map of the hotspots for flowering plants in Cameroon (Fig. 6) that might aide conservation of plants in Cameroon (Onana & Cheek 2011).

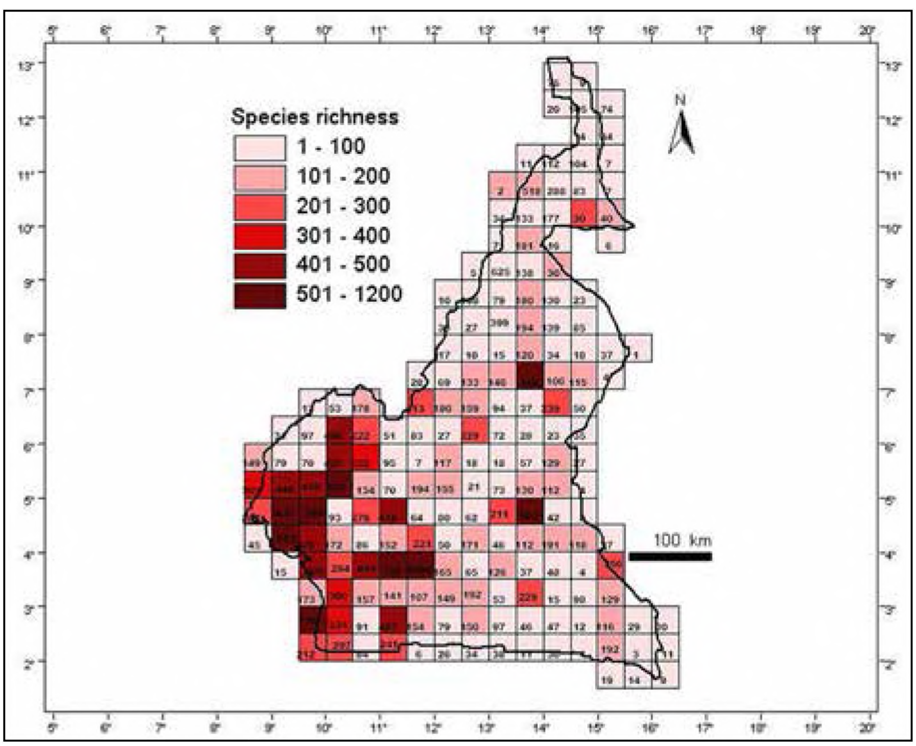


Fig. 5. Richness of vascular plant species in Cameroon, based on the distribution of 36,588 specimens at YA using half degree cells. Map by C.K.Ngembou & J.M. Onana. From Onana (2011).

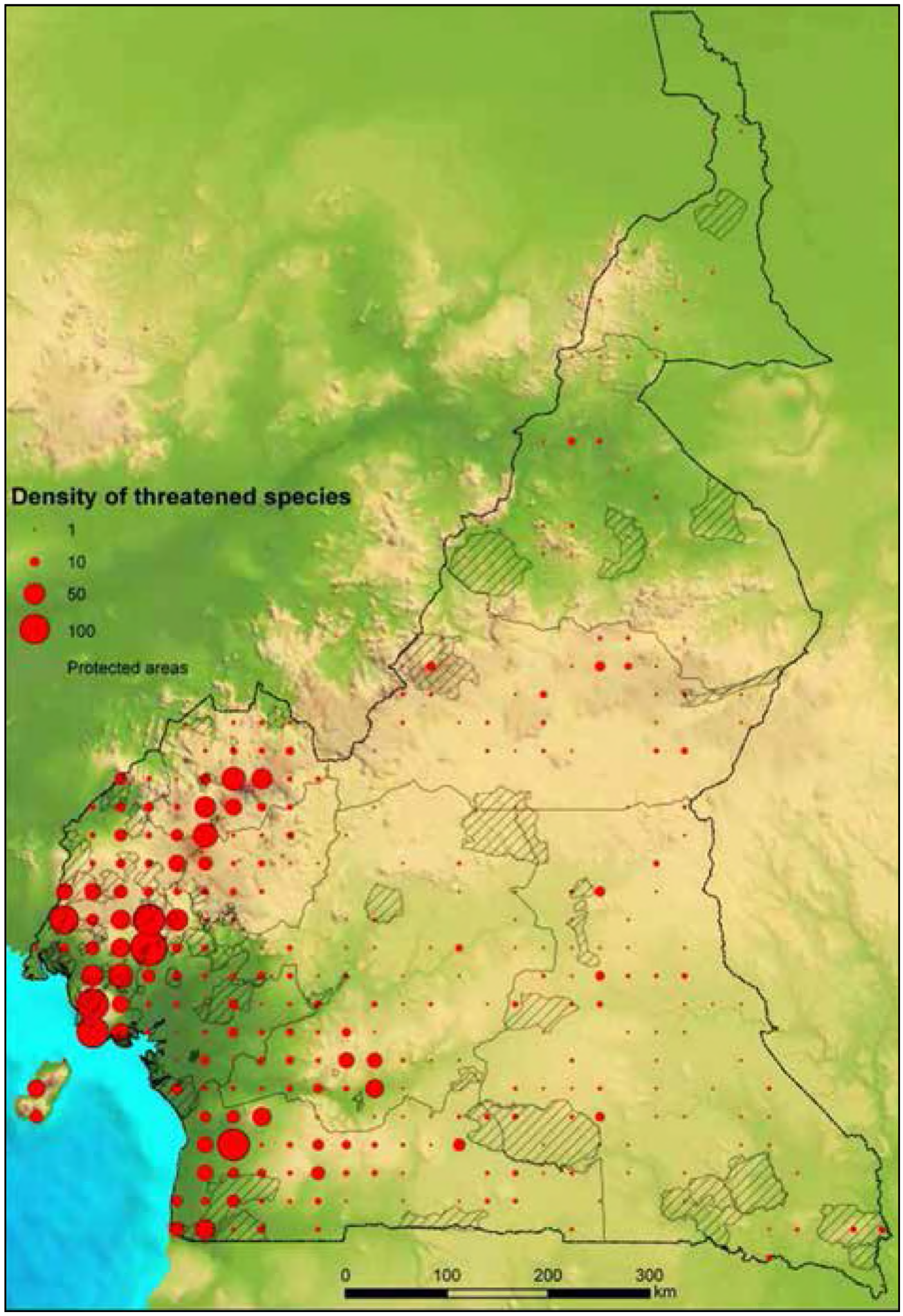


Fig. 6. Overview of hotspots of flowering plants in Cameroon. Map by Steve Bachman, Royal Botanic Gardens, Kew. From Onana & Cheek (2011).

***Capacity building:*** Training of botanists in Cameroon began with Réné Letouzey at the time when he taught forest botany at the School of Water and Forestry in Mbalmayo (Satabié & Villiers 1991). He mainly trained field botanist for the identification of timber. The first of his students was Mpom Benoit, who began studying in 1948, and then technicians from the school of forestry (Paul Mezili in 1961; Daniel Dang in 1965; Anacletus Koufani in 1966; Edmond Bounougou in 1957; Michel Biholong in 1959; Mbamba Ekitiké Dieudonné in 1968; Jean Marie Ottou in 1974) (Paul Mezili pers. comm.) All these field botanists

Fig. 7. Earthwatch team in Tombel (Southwest Region Cameroon) on field work for botanical inventories in Western Cameroon during 1995–2000, sponsored by Earthwatch and Darwin Initiative of DEFRA (UK). From left to right standing (back row) Martin Cheek (principal investigator for Earthwhatch, Royal Botanic Gardens, Kew (Kew), a volunteer from Malawi, Elvire Hortense Biye (National Herbarium, YA, now senior lecturer at the Department of Plant Biology University of Yaoundé I (DPB, UY I), Barbara Mackinder (Kew), a volunteer from United Kingdom, Dieudonné Nwaga (lecturer DPB, UY, in the field to meet B. Mackinder and discuss Legumes), a volunteer from Kenya; a volunteer from Malawi, Victor Nana (field botanist in YA), Fulbert Tadjouteu (technician from YA), guide from Tombel. Line in front (standing): Georges Gosline (Kew), two staff members from the camp, Moussa (technician from YA), Jean Michel Onana (taxonomist from YA, Head of YA), a volunteer, three staff members from the camp. Sitting, from left to right: a local guide employed for the field work, two volunteers from Ethiopia, staff members from the camp, a volunteer from United States of America. At the corner on the left, a tent for a volunteer. Photo by Martin Cheek (1999).

formed a strong and effective team that accompanied not only Letouzey, but also the foreign botanists, who came to Cameroon for floristic research. These are also the technicians, who worked on setting up and operationalize the young National Herbarium (YA).

In the 1970s, the capacity building of Cameroonian researchers who would do research in taxonomy and give practical courses, were organized under the supervision of botanists of P. Asonganyi Nchiendia Joseph was supervised in 1984 by Henri Jacques-Félix in his study of Graminae which resulted in the description of a new species, *Pennisetum felicianum* Asong. (Asonganyi 1985). Bernard Aloys Nkongmeneck was supervised in 1986 by Réné Letouzey which led to the description of *Cola letouzeyana* Nkongm. (Nkongmeneck 1985). Then Réné Letouzey, Jean-Francois Villiers (who should teach plant systematics at the Faculty of Science of the University of Yaoundé), Nicolas

Hallé and Raymond Schnell, Marcel Bodard, Charles Marie Evrard (all from France), Jean Lejoly and Elmar Robbrecht (both from Belgium) or Vernon Hilton Heywood and David Moresby Moore (both from the United Kingdom), supervised theses in systematics, plant ecology or biology (see Appendix with List of Unpublished Theses at the end of this paper).

This training continued during Earthwatch expeditions with Dr Matin Cheek as principal investigator and participation of volunteers from many countries, both from Africa, Europe and North America (Fig. 7). The international publications produced from this are co-authored by taxonomists from Kew (K) and Yaoundé (YA). Thanks to the contribution of the institutions and botanists from the North, the handling of research, education and training of professionals in the field of plants systematics by scientist from the YA is effective. But with the evolution of plant systematics, in particular molecular biology, the need for the skill and partnership for these new methods of investigation that require laboratory equipment more expensive and more specialised supervision is a very good reason to maintain and even increase the North-South collaboration in floristic and taxonomic research.

One major achievements of the capacity building of the botanists of Cameroon was the organising of the congress for the members of the Association pour l'Étude Taxonomique de la Flore d'Afrique Tropicale (AETFAT) in Yaoundé in 2007. According to the report of the congress (Burgt *et al.* 2010), the Secretary General for the 18th AETFAT Congress and the preceding period was Gaston Achoundong, Head of the National Herbarium of Cameroon until June 2005. The congress was co-organised by the National Herbarium of Cameroon, with the then Head, Jean-Michel Onana. The Scientific Committee was presided over by Amougou Akoa, Head of the Department of Plant Biology, University of Yaoundé I. Vice-Presidents were Bonaventure Sonké, University of Yaoundé I and Benoit Satabié, former Head of the National Herbarium of Cameroon.

The 18th AETFAT Congress was attended by 335 registered participants from 50 countries. Of the 335 participants, 165 came from 31 African countries while 170 came from 19 other countries (Table 4). All African participants were sponsored by the Mellon Foundation of the United States of America through the project Afican Plants Initiative (API). The Royal Botanic Gardens, Kew, provided assistance with financial and administrative matters.

**Table 4.** Countries with at least 10 participants during the 18th AETFAT Congress in Yaoundé

| Country | # participants |
|---|---|
| Cameroon | 43 |
| United Kingdom | >25 |
| France and Germany | 22 |
| Belgium | 21 |
| South Africa; United States of America | 20 |
| Netherlands | 12 |
| Switzerland | 11 |
| Benin and Gabon | 10 |

## Perspectives for the Future

The SCA herbarium is almost closed due to the lack of taxonomists to manage the collection. It was thought that good collections with flowers or fruits might be re-deposited at the National Herbarium (YA); however, no action has been taken. To survive, Limbe Botanic Garden reoriented its activities to environmental education, ecotourism, and recreation. It appears that it may be difficult to revive the floristic research at Limbe without a vigorous effort of the international community and continuous training of taxonomists.

On the other hand, at Yaoundé (YA), research activities continue through and with the traditional partners, Royal Botanic Gardens, Kew and the French cooperation including the Institut de Recherche pour le Développement (IRD) (= Institute of Research for

Development, Ministère des Affaires Etrangères (MAE), and the Museum national d'Histoire naturelle (P).

Still, there are notable gaps for further collecting activities (Fig. 3). According to Campbell (in Campbell & Hammond 1989, cited from Poncy & Labat 1996), for a collection with a density index (IDC) 10/100 km² collections and with an increase of 1.38 per 100 km² collections per year, it will take 65 years (up to 2054) to reach the minimum acceptable IDC of 100 collections for 100 km² in Cameroon. Fourteen years after the figure published by Poncy and Labat (1996), the IDC was about 30 collections per 100 km² (Onana 2010). Unfortunately, since 2005, field work making general collections for the National Herbarium has virtually stopped, so it is difficult to say when the minimum acceptable value of IDC could be reached. Fig. 3 is not fully up to date, but it may still give an indication of areas where more collections probably should be carried out to reach the minimum acceptable IDC.

In order to be able to complete the *Flore du Cameroun*, solutions need to be sought for the following major obstacles (Onana 2015): (1) lack of plant taxonomists (Surtcliffe & O'Reilly 2010); the lack of taxonomists is acute in Cameroon at present, with only four taxonomists regularly describing and publishing new taxa or revisions, and an additional two, who have sporadically described new species during the last five years, but are not working on floristic research; (2) taxonomic research is not one of Cameroon's priorities. One of the development challenges for the country with high priority is food security. Floristic research that leads to conservation is regarded as a possible obstacle for the development of agricultural activities, causing plant taxonomy research to be relegated to the lowest rank of priorities, with almost nonexistent funding; (3) it is an increasing challenge to convince taxonomists to produce family accounts; instead they give preference to other types of research such as molecular biology for publications in high impact journals.

The result is neglect of the production of baseline data to improve the knowledge of the flora at local level. The lack of funding allocated to research in the taxonomy of plants of the Cameroon also impacts upon the service and development of collections, laboratories and general working conditions for taxonomists in the country.

Amongst the ways that could be explored is the signing of Memoranda of Cooperation / Understanding between the National Herbarium of Cameroon (YA) and funding institutions that may specifically help to produce more volumes. For example, the incomes from the sale of the volumes could be shared to help meeting specific needs. The Head of the National Herbarium could use the part of the income sent to YA to properly maintain the collections and send more specimen to taxonomists for description, while the part remained in the northern institution could be used to edit and print more volumes.

## Conclusion

The knowledge of the flora and vegetation of Cameroon rests on interest of European countries and institutions in the plants and plant communities of Cameroon in the 19th century. Since the 1860s, it is particularly countries like the United Kingdom, France, Germany and the Netherlands that have actively contributed to the knowledge of the flora and vegetation of Cameroon. The pioneers were undoubtedly driven by economic incentives, but the first European botanists working in the territory that later became Cameroon were surely also driven by a passion for the tropical flora. After independence, the enthusiasm has continued in the framework of bilateral and multilateral agreements and cooperation. The heritage from the pioneers is important and can be summarized in four main points:

- hold collections of nearly 100,000 identified specimens with duplicates in international herbaria constitutes the largest part of the collection at the National Herbarium of Cameroon (YA). These collections allow us to describe and understand the floristic heritage of Cameroon. It is also thanks to these collections that Cameroonian botanists can work as partners in international projects and initia-

tives such as participation in the African Plant Initiative (API) for the establishment of an on-line collection of African type images, in the Global Biodiversity Information Facility (GBIF) for the establishment of a CAM BIF portal, providing primary data on the floristic collections from Cameroon, in the African Herbaria Network (RIHA) which aims at the establishment of a potentially continent-wide database of herbarium sheets; and the Sud-Expert-Plantes (SEP), which allowed the strengthening of national herbaria through international projects to improve management capability.
- produce a vegetation map of Cameroon that allows us to define the main plant communities of Cameroon;
- publish 2709 species of 113 families in 38 volumes of the series *Flore du Cameroun* by 39 taxonomists in the North;

From these examples, it is clear that the principal objectives of the National Herbarium that have been achieved so far are thanks to the North-South cooperation.

- At the same time, training of botanists and foresters has been a powerful lever for local botanists to get involved in the cooperation and take over the legacy. This is illustrated by the number of African botanists from Cameroon, who have attended major meetings on botany in Africa. The congress and general meeting of the Association pour l'Étude Taxonomique de la Flore d'Afrique Tropicale (AETFAT) in 2007 demonstrates this. With the support of the Royal Botanic Gardens, Kew, the AETFAT meeting in Cameroon experienced the largest participation ever of attendants for these congresses, with almost 300 taxonomists from around the world, of which 43 (>20%) were from Cameroon.

This flattering further development of our legacy is now threatened by the lack of funding for tropical collection-related research in the North and by a change of priority from training in biodiversity to education and development with more obvious relation to social issues in Cameroon. For nearly two decades, botanical field campaigns have all but stopped, and the publication of the volumes of the *Flore du Cameroun* has become a very sporadic event in spite of the amount of work, which still needs to be done. It is then a challenge, as well for the international community as for Cameroon, to continue supporting development of our knowledge about plants, which are a heritage for Cameroon as well as for the entire World.

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# From Alpha Taxonomy to Genomics in South Africa: One of the hottest biodiversity hotspots

*A. Muthama Muasya*

## Abstract

South Africa is home to globally important plant diversity, with over 20,000 species of vascular plants among which 57% are endemic, including three biodiversity hotspots. The south western part of the country holds over 50% of the species in the Cape Floristic Region and Succulent Karoo hotspots, comprising Mediterranean vegetation that has been mostly assembled since the Miocene. To the east, the Maputaland-Podoland-Albany hostpot region has summer rainfall and vegetation similar to tropical Africa. Botanical exploration started in the 1700s, with collectors including Carl Thunberg, and species discoveries continue to date. Nearly 3 million herbarium specimens are housed at the South African National Biodiversity Institute (SANBI), at universities, at museums, and in nature reserves. The majority of the specimens within the SANBI and selected large herbaria elsewhere have been databased and images of types and other collections are available online. Relative to other parts of Africa the molecular systematics revolution has been actively adopted with several of the hotspots reasonably studied, more recently as part of the DNA barcoding initiative. Comparative studies, linking the herbarium collections and using DNA (sources include botanic gardens), address questions on the origin and assembly of the unique biodiversity. A recent strategy for plant taxonomic research outlines goals towards achieving targets of the Global Strategy for Plant Conservation, including production of an e-Flora and highlighting priority plant groups for taxonomic study. There are some dedicated funding streams towards achieving these goals, but the plant taxonomy enterprise is frustrated by low numbers of active taxonomists (1 person per 500 species), reduced training in systematics and low uptake of newer approaches.

**Key Words:** herbaria, new species, plant collectors, research strategy, southern Africa, systematics

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Africa's vegetation is diverse and has been grouped into various biomes and up to 18 phytochoria (White 1983). The continent's biota were grouped into four major biogeographical clusters: the Guinea-Congolian, Southern African, Zambezian to Horn of Africa, and the Saharan to Nubian Desert (Linder *et al.* 2012). Within southern Africa four smaller units (i.e., Cape, Natal, Kalahari and Namib elements) were recognized, all represented in South Africa.

South Africa is one of the most biodiversity rich countries in the world. With a size of about 1,214,000 km$^2$ (http://www.worldatlas.com), about twice the size France, the country hosts nearly 20,000 species of vascular plants (Klopper *et al.* 2007). This diversity is structured into five major biomes (Fynbos, Succulent Karoo, Albany Thicket, Grasslands, Savanna; Mucina & Rutherford 2006). There is uneven distribution of vascular plants among these biomes, with the Fynbos biome being most rich and holding about 9000 species in an area of about 90,000 km$^2$ (Manning & Goldblatt 2012). Also the vascular flora has high endemicity, with about 13,300 species restricted to South Africa nearly half of which are restricted to the Fynbos biome.

The high diversity of species in South Africa is linked to its geology, climate and interactions between abiotic and biotic factors. Geologically, the country sits on an old landscape which has been relatively stable except for Palaeozoic processes such as folding leading to the Cape mountains as well as more recent (Miocene) uplifts leading to formation of the Drakensberg mountains (Linder & Verboom 2015). Varying erosion and shifts in drainage system, together with shifts in sea levels, have led to a complex geology especially in the Cape area (Cowling *et al.* 2009). Within the Miocene, upwelling of the Benguela current (Dupont *et al.* 2011, 2013; Hoetzel *et al.* 2013) triggered a shift in rainfall seasonality, with winter rainfall becoming prevalent in the south-western areas whereas the eastern and northern parts of the country experienced summer rainfall. Consequently, the vegetation has shifted from a tropical woodland in early Miocene (Linder & Verboom 2015) to the currently observed biomes which are partitioned into the winter rainfall areas (Fynbos, Succulent Karoo; collectively referred to as the Greater Cape Floristic Regions (GCFR)), and summer rainfall area with no winter snow (savanna), and summer rainfall with winter frost (Grasslands, Nama Karoo).

## Botanical Collections in South Africa

Southern Africa has a rich history of botanical explorations (Glen & Germishuizen 2009). The region attracted botanical collectors since the 16$^{th}$ century, with the first known vascular plant record being an illustration published in Leiden in 1605 of a dried inflorescence of *Protea neriifolia* R. Br. in the *Exoticorum libri decem* (Clusius 1605). The importance of the Cape, as a restocking point for voyages enroute to Asia, encouraged earlier collections and plants from this region gained popularity among pre-Linnaean collectors and gardeners. The publication of the *Species plantarum* (Linnaeus 1753), beginning the binomial naming and seeking to catalogue all know biodiversity, injected impetus to the naming and classification of biodiversity. Carl Thunberg, a student of Linnaeus, arrived in the Cape in 1772 and made three journeys travelling into the interior where he collected about 3100 specimens (kept as part the historical Thunberg Herbarium at the University of Uppsala, UPS-THUNB), and this comprises one of the earliest focussed collections from southern Africa. During the 19$^{th}$ century, specimens were collected and distributed to a number of European institutions, notably by collectors such as C.F. Drège, C.F. Ecklon and C.L.P. Zeyher. With the establishment of colonies (Cape, Natal), collectors based within the region accumulated specimens leading to establishment of precursors of current day herbaria (codes follow Thiers continuously updated) at Cape Town (South African Museum Herbarium, SAM), founded 1825; Bolus Herbarium (BOL, founded 1865), Grahamstown (Selmar Schonland Herbarium, Albany Museum (GRA, founded 1855), and Natal (KwaZulu-Natal Herbarium, Durban (NH, founded 1882). Notable 20$^{th}$ century collectors include E.E. (Elsie) Esterhuysen, who collected over 34,000 specimens with a bias on Cape flora and who is celebrated in over 60 species names. Robert H. Compton collected 35,000 specimens, perhaps the highest number of specimens in Southern Africa, among which 8000 were from Swaziland, and his collection forms part of the Compton Herbarium (NBG, which now also includes the South African Museum Herbarium, SAM). The history of botanical collections were strongly influenced by political history at local to international levels, and are intertwined with personalities wielding power and influence over the last three centuries (Carruthers 2011). It is interesting

**Table 1:** The largest herbaria in South Africa. * Mycological collection.

| Province | Institution | Established | No. of specimens |
|---|---|---|---|
| Gauteng | National Botanical Institute (PRE) | 1903 | 1,200,000 |
| Western Cape | National Botanical Institute (NBG) | 1933 | 500,000 |
| Western Cape | University of Cape Town (BOL) | 1865 | 300,000 |
| Eastern Cape | Albany Museum (GRA) | 1855 | 200,000 |
| KwaZulu Natal | University of KwaZulu-Natal (NU) | 1910 | 120,000 |
| KwaZulu Natal | National Botanical Institute (NH) | 1882 | 100,000 |
| Gauteng | University of the Witwatersrand (J) | 1917 | 100,000 |
| Gauteng | University of Pretoria (PRU) | 1924 | 100,000 |
| Gauteng | Agricultural Research Council (PREM)* | 1905 | 60,000 |
| Northern Cape | McGregor Museum (KMG) | 1908 | 32,600 |
| North West | University of North-West (PUC) | 1932 | 28,000 |
| Free State | National Museum Herbarium (NMB) | 1984 | 25,000 |
| KwaZulu Natal | KwaZulu-Natal Nature Conservation Service (CPF) | 1985 | 23,100 |
| Free State | University of the Orange Free State (BLFU) | 1905 | 20,000 |
| Northern Cape | Grootfontein Agricultural College | 1911 | 20,000 |

to note among the collectors were the two-times Prime Minister of South Africa (Jan C. Smuts), but it is disconcerting that only 1% of the 2000 plant collectors are black Africans.

There are over 70 herbaria in South Africa which together hold about 3.1 million specimens (Smith & Willis 1999; Table 1). The South African National Biodiversity Institute (SANBI) manages several of the largest herbaria (National Herbarium, Pretoria, PRE; Compton Herbarium, Claremont, NBG; KwaZulu-Natal Herbarium, Durban, NH) which hold nearly 60% of the specimens. About 90% of the collections are housed at the top ten largest herbaria which are part of SANBI or at universities, and nearly 50% of the herbaria have less than 10,000 specimens. These collections have varying usages, with the majority of the small collections held at nature reserves and focused on biodiversity within a small region or dedicated to particular kinds of plants, e.g., weeds or agricultural species. In addition to herbarium collections, there are a number of botanic gardens especially under the SANBI network, distributed in all the provinces.

## Recent Trends in Capturing Specimen Data and Images

Information on herbarium specimens is unavailable to wider usage if it only exists as physical specimens in the holdings of a particular institution. Within the last two decades, various efforts have been made to provide such data in alternative forms, ranging from databases to completely searchable images. Specimens held under the SANBI herbaria are databased and information can be searched online with options to compile maps and sieve other details linked to the data. The South African Biodiversity Information Facility (SABIF) is a participant in the global collation of data on various taxa, and there has been concerted effort to capture data from herbaria and other repositories outside the SANBI network. More recently, South Africa herbaria participated in the African Plant Initiative (API) project, contributing immensely to the wealth of type specimens. Outside the SANBI network, the Bolus Herbarium (BOL) at the University of Cape Town, founded 1865, has a large collection of 11,500 types of the Cape Flora, holding one of the oldest and perhaps richest historical collections in the country.

The contribution of citizen scientists in biodiversity information gathering has been recognized widely. There is extensive involvement of the wider public in gathering images and other data on various biota, particularly animals, and such data forms a unique resource in gazetting the occurrence of various taxa. The South African virtual museum (http://vmus.adu.org.za/) has a wide variety of animals, but is rather poor on plants. Better plant content is at iSpot (www.ispotnature.org/communities/southern-africa), a forum used by amateur botanists to deposit images and data. The potential of involving citizen scientists is as yet to be fully exploited.

## Species Discovery, Catalogue of Taxa into Floras

The discovery, description and cataloguing of new taxa to science continues into the 21st century. The earliest catalogues of the southern African flora goes back to Thunberg's *Prodromus plantatrum Capensium* (Thunberg 1794-1800), which was followed by the several volumes of *Flora Capensis* (Harvey, Sonder *et al.* 1860-1933). Unlike tropical Africa where regional floras (e.g. *Flora of Tropical East Africa*) have attempted to provide detailed description of each species, there is no single detailed regional flora for South Africa. Instead there are lists of species in national checklists (e.g., Germishuizen *et al.* 2006), and at a regional scale (e.g. biome or province), the most recent being the two volume conspectus of the Greater Cape Flora (Manning & Goldblatt 2012; Snijman 2013). Various publications on the flora are being collated under the e-Flora of South Africa, which contributes to the mandate on the Global Strategy for Plant Conservation, 2011-2020 (GSPC; https://www.cbd.int/gspc).

Despite the long collecting history, new species are still being recorded due to detailed inventory in previously under-collected areas as well as from specimens already incorporated into herbaria. A survey of publications on new species in the *South African Journal of Botany* (SAJB) for the period 2005-2015 reveals that over 121 species endemic to South Africa were described (Fig. 1). These mostly belong to the Asteraceae (20 species) and Fabaceae (20), Iridaceae (16), Apiaceae (12), and are predominantly from the GCFR (69%) and a third were geophytes. Recent sustained fieldwork in previously under-collected areas, such as the quartz fields of the Namaqualand and Overberg (e.g., Curtis *et al.* 2013), has contributed most to the increased discoveries.

## Adoption of Molecular Data

Molecular phylogenetic approaches, mostly based on Sanger sequencing, have been adopted in the study of the South African flora. These include studies inferring phylogenetic relationships among lineages, origin and biogeographic patterns, and relating to the monophyly and classification of suprageneric taxa. There is evidence of complex radiations leading to the flora in the fynbos, desert, grasslands and woodlands since the Miocene (Linder & Verboom 2015), most notably the shift from tropical/subtropical woodlands to the current temperate flora in the hyper diverse winter rainfall area. There is consensus that observed biogeographic links between the austral-temperate continents has occurred by long distance dispersal since the split of Gondwana (Crisp *et al.* 2009), and there are frequent exchanges of species between similar habitats (Linder & Verboom 2015).

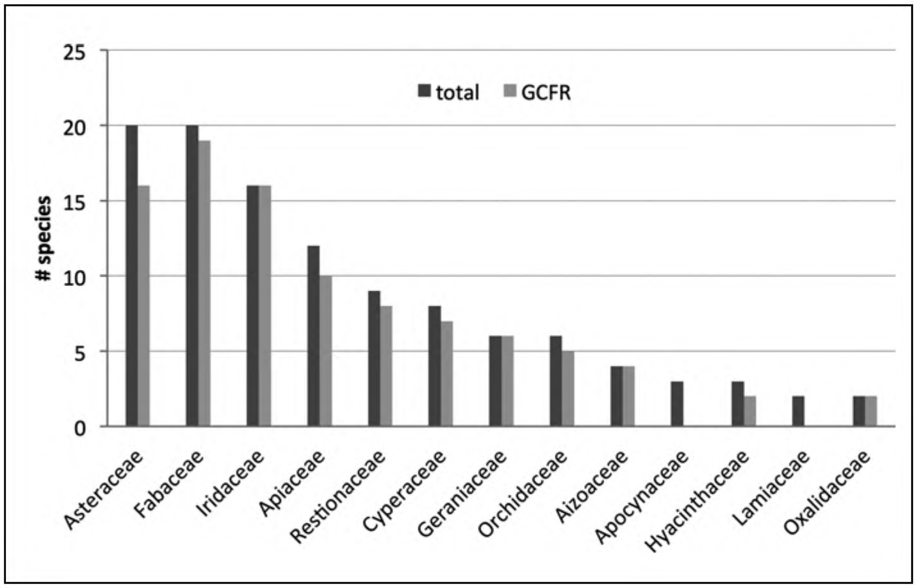


Fig. 1. A summary of new species published in the *South African Journal of Botany* during 2005–2015. GCFR: Greater Cape Floristic Regions.

Adoption of DNA sequencing approaches in taxonomic studies has focused mostly at suprageneric level. There are ongoing revisions of generic circumscriptions, especially among widespread genera, which have been found not to be monophyletic. As a consequence, a number of genera have been enlarged to include previously segregated lineages (e.g., *Cyperus*: Bauters *et al.* 2014; Larridon *et al.* 2011). In several cases, large genera have been split into smaller units in attempts to achieve monophyly by recognizing smaller (and at times charismatic subgroups) especially in economically and horticulturally important taxa such as *Aloe* (Manning *et al.* 2014). Within the last 10 years, four small genera (*Bertilia*: Cron 2013; *Dracoscirpoides*: Muasya *et al.* 2012; *Kappia*: Venter *et al.* 2006; *Wiborgiella*: Boatwright *et al.* 2010) have been described in the SAJB to segregate previously known taxa that had been included in larger (non-monophyletic) taxa, in all four cases based on re-interpretation of morphology in combination with DNA sequence data. More generic changes can be expected as more taxa are included in broader studies especially in transoceanic disjunct genera occurring in austral-temperate areas.

DNA barcording is gaining popularity in the study of the southern African flora. Spearheaded by the African Centre of DNA Barcoding, over 15,000 DNA barcodes (van der Bank *pers. com.*) have been deposited at the global database (Consortium for the Barcoding of Life, CBOL) for the two main plant barcodes (*rbcL*, *matK*). The South African barcodes have targeted groups such as woody and invasive species as well as major plant families such as the legumes and sedges. These DNA barcode data have been used to address questions relating to community assembly processes (e.g., Maurin *et al.* 2014), phylogenetic diversification (e.g., Bello *et al.* 2015), and invasion biology (e.g., Bezeng *et al.* 2015). Despite the perceived utility of DNA barcode data (Kress *et al.* 2015), there is lack of divergence among lineages which have experienced recent and rapid radiation such as Cape legumes (*Aspalathus* L., Edwards *et al.* 2008; Psoraleeae, Bello *et al.* 2015).

The adoption of modern approaches in plant taxonomy is restricted to a handful of institutions, where final steps of the Sanger sequencing are outsourced outside Africa. Next generation sequencing and sequencing of whole genomes is yet to become routine in studies of South African plants. Given the high costs of such approaches and the need for bioinformatics skills to analyse the data, it is unlikely that whole genome and next generation sequencing will be adopted widely in the near future. Furthermore, large proportions of budgetary allocation from government are dedicated to poverty alleviation and policies on the green economy are yet to be fully implemented.

## National Priorities on Biodiversity Studies

The South African National Biodiversity Institute's mandate includes coordinating and promoting taxonomy on indigenous biodiversity as well as managing herbaria (www.sanbi.org). As part of this mandate, SANBI has undertaken a review of the status of taxonomic research in the country, concluding that: (i) there are under 50 active taxonomists (a third of them already retired) and several unfilled posts due to government policies on equity; (ii) there is a decline in number of large revisions but there is steady description of new taxa as stand-alone or in papers revising small groups of species; (iii) the ratio of number of species to taxonomists is about 500 species to one; and (iv) nearly 3800 species are represented by under five specimens in herbaria (Victor *et al.* 2015a). The human resource shortage is exacerbated by low uptake of undergraduate studies in taxonomy, and the unequal distribution of taxonomists (and curricula), with few traditionally black universities offering postgraduate training in taxonomy (Victor *et al.* 2015b).

Regardless of the above, South Africa is committed to meet the targets set by the Global Strategy for Plant Conservation (GSPC; www.cbd.int/gspc/). Objective 1 of the GSPC requires that plant diversity is well understood, documented and recognized by 2020. A recent strategy for plant taxonomic research in South Africa (2015–2020; Victor *et al.* 2015a) identifies strategic objectives and proposes three research programmes. Research programme 1 aims to produce an online (e-Flora) for South Africa, focusing on 13 large families (Aizoaceae, Asphodelaceae, Asteraceae, Campanulaceae, Ericaceae, Fabaceae, Geraniaceae, Lobeliaceae, Oxalidaceae, Santalaceae, Scrophulariaceae and Thymelaeaceae), where capacity for research and curation exists at SANBI and local universities. Additionally, priority was identified for understudied families (Cyperaceae, Hyacinthaceae, Malvaceae, Rhamnaceae, and Rutaceae), in which over 50 taxa have not been revised in the last 50 years. Research programmes 2 and 3 set priorities for further studies to revise plant genera that have not been studied since the World War II; genera that have a high proportion of unidentified specimens or have data deficient taxa; genera with economic important species; and genera with a high proportion of taxa occurring in South Africa. These programmes act as a guide in setting priority for gaps in knowledge, and allow funding opportunities from the National Research Foundation to be harmonized with research needs, as evident from recent 'ring-fenced' opportunities under the Foundational Biodiversity Information Programme.

## Conclusions

Despite the extended history of plant collecting in South Africa, there remains gaps in the knowledge and new species continue to be described. There are rich collections, with over 3.1 million herbarium specimens made over the last 150 years, which have been databased and are widely available. With over 20,000 species of vascular plants and under 50 active taxonomists, innovative approaches are needed to meet the South Africa's targets under the GSPC. The recently published research strategy and dedication of funding to support the activities will contributes towards a better understanding of the flora.

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# Indian Herbaria: Legacy, floristic documentation and issues of maintenance

*Munivenkatappa Sanjappa and Potharaju Venu*




## Abstract

Indian herbaria have a long history of providing data for taxonomic and floristic studies of Indian plants; now they also have a number of other special functions: they act as guiding sources for prioritized field work in unexplored or underexplored areas and for focussed collections of species that are inadequately represented in herbaria. Fresh collections of rare species resulting from such field work may represent rediscovery of species from already known localities or may represent new habitats. New collections may help to bring in clarity on morphology of less known taxa owing to poor or scarce material. In the last 10 years, about 40 species, which were previously only known from the type collections, were located again in the field by the Botanical Survey of India or by other taxonomy research centres or departments in the country. A good proportion of the Indian plants in European herbaria represent type specimens or other authentic material, but many names also have isotypes in or can be typified solely on old collections in Indian herbaria, thus underlining the importance of these old collections in India. Although data from the period 2007–2013 showed that the majority of new species in the Indian flora were described from fresh material resulting from field work, the gathering of some of this material was prompted by the need for further collections of incomplete or poor specimens from the past, specimens that had been left unidentified in Indian herbaria. Here, we survey the wealth of historical and modern specimens kept in Indian herbaria and the multiple implications of conserving this wealth of material, including financial consequences. Recent progressive explorations in unexplored or under-explored areas have added numerous specimens to the holdings of Indian herbaria, which further adds to the financial and practical challenges of herbarium maintenance. New methods pave the way for more effective documentation of the flora and use of the specimens, but also add to the tasks of herbarium curation: High-quality photographs of plants in the field and their habitats; more detailed information about the precise location of specimens, using coordinates obtained with GPS; increased accessibility of specimens by scanning and digitization. Currently, multinational collaborative projects promote joint exploration and facilitate full exposure of specimens, as well as of old literature and correspondence (published and unpublished) relating to the Indian flora. These projects are carried out in collaboration with renowned experts and reputable organizations and will boost our pace of publishing a National Indian Flora with desired excellence.


**Key Words:** digitization, floristics, herbaria holdings, multilateral collaboration, specimens, taxonomic literature

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The earliest literature referring to Indian plants is in the Sanskrit classic, *Charaka Samhita,* probably written 1000–800 BC). This work had been in use for preparing herbal formulations in agreement with Ayurveda ('science of life'), the traditional Indian mind-body health system. Garcia de Orta (1563), a Portuguese physician, published a treatise on medicinal and economic plants of India based on plants grown in his garden at Goa. Hendrik Adriaan van Rheede tot Drakenstein (Rheede 1678–1693) gave a detailed account of Malabar plants (*Hortus Malabaricus*) in 12 comprehensively illustrated folio volumes.

Indian botany according to the principles of Linnaeus began with Royal Danish physicians and explorers. Johann Gerhard König was born in what is now the Baltic state of Latvia, but came early to Denmark. He studied in 1757–1759 with Carl Linnaeus in Uppsala, Sweden, and returned to live in Denmark from 1759–1767 to study pharmacology and medicine and work as an assistant with botanical exploration of Denmark. In 1767, he was sent to work as a doctor at at the Danish trading post at Tranquibar (known in Tamil: *Tharangambadi*), which he reached in 1768. From 1773 to his death in 1785, he worked as a naturalist for the Nawab of Arcot, a state in southern India, and formed an informal botanical association, the 'United Brethren', mostly Moravian and the Lutheran missionaries, but his associates also included British medical officers of the Madras Presidency. König sent duplicates of his collections to Copenhagen and a number of other European herbaria. He published relatively little himself, but sent specimens and descriptions to European botanists, who published them. Examples of this are the descriptions of the new genera *Metroxylon* Rottb. (Arecaceae), *Thottea* Rottb. (Aristolochiaceae) and *Wormia* Rottb. (Dilleniaceae) by the Danish botanist C.F. Rottböll (1783) in the early publications of the Royal Danish Academy of Sciences and Letters, the institution which now organize this symposium. König became a friend of William Roxburgh, a fellow medical doctor, who attended him on his deathbed, where König donated his manuscripts to Sir Joseph Banks in London.

The continued expansion of the British Empire between the 17th and 19th centuries was driven mainly by search for commodities, such as spices and crop plants, and the establishment of new markets for British goods. As a part of this objective, by the late 18th century, the East India Company had established botanic gardens at Samarlakot (now, nonexistent) and Calcutta (now Kolkata, more precisely on the right bank of the Hooghly River at Howrah) in West Bengal, specifically to know and experiment with native plants suitable for cultivation. The Establishment of the Garden at Calcutta was initiated by Col. Robert Kyd (Superintendent of the garden 1787–1793). William Roxburgh was appointed in 1794 as the next Superintendent of the Calcutta Botanic Garden. He was the author of the *Plants of the Coast of Coromandel*, dealing with plants from southern India (Roxburgh 1795–1820), the *Hortus Bengalensis,* a catalogue of the garden at Calcutta (Roxburgh 1814) and the *Flora Indica,* the first attempt at an Indian flora, edited posthumously by the missionary and botanist Willian Carey and Nathaniel Wallich at Serampore (Roxburgh 1820–1824, 1832), and he organized a large collection of illustrations of Indian plants, *Icones Roxburghianae,* 35 volumes, with duplicate sets at the Calcutta Botanic Garden and the Royal Botanic Gardens, Kew, UK, now published by the *Botanical Survey of India* (Roxburgh 1964–1978). His descriptions are remarkably complete, as he grew the plants in his garden and examined them in all stages of their growth.

From 1817–1845 Nathaniel Wallich was superintendent of the botanic garden at Calcutta. At first he acted in a temporary position after Roxburgh, who had retired to Scotland in 1813, was replaced by the Scottish physician Francis Buchanan-Hamilton in 1814–1815, but obtained permanent position as superintendent in 1817. He produced notable works in the flora of India and Nepal. Wallich was born in Copenhagen, Denmark, and had been sent as a surgeon to work at the Danish trading post of Serampore north of Calcutta. Following an expedition to Nepal in 1820, he produced *Tentamen Florae Nepalensis Illustratae* (Wallich 1824–1826), printed at the Missionary Press at Serampore, where Roxburgh's *Flora Indica* had also been printed. From 1826–1827 Wallich studied the nature of Ava and Lower Burma. After a number of years as Superintendent of the Calcutta botanical garden he produced the beautifully illustrated work *Plantae Asiaticae Rariores* (Wallich 1829-1832), with illustrations mainly by Indian botanical artists employed by the Calcutta Botanic Garden: 146 drawings were by Gorachand, 109 were by Vishnupersaud and one by Rungiah. Another of Wallich's most important publications, *A numerical list of dried specimens of plants in the East India Company's museum, collected under the superintendence of Dr. Wallich (1828-49)*, contains in all 9148 species and is known as *The Wallich Catalogue* (Wallich 1828-1849). It is a work of basic importance for the understanding of Indian plants, and was compiled in London by Wallich and a group of collaborators from the specimens in the herbarium of the East India Company which had been sent to England (a set of these plants have remained at CAL).

William Griffith, English, served as superintendent for a short period (1843-1844) during the absence of Wallich; he revived and built the herbarium which he called 'Public Herbarium' (prior to this, the herbarium had been kept in Roxburgh's and later Wallich's official residence). It was during the period (1855-1861) of Thomas Thomson, another Scottish surgeon, as superintendent of the garden, then known as the 'Company *Bagan*', was officially renamed as the Royal Botanic Garden, Calcutta. Thomson associated himself with J.D. Hooker in the publication of *Flora Indica,* of which only vol. 1 appeared (Hooker & Thomson 1855).

Thomas Anderson (Scottish medical doctor, superintendent 1861-1869) was instrumental in the introduction of *Cinchona* from Kew in 1861. After Anderson, Charles Baron Clarke (English) took briefly charge of the garden and contributed to 52 family accounts in the *Flora of British India* (Hooker 1872-1897), a work which was completed, following Hooker and Thomson's unsuccessful *Flora Indica*. Separately, Clarke also produced monographic accounts of Commelinaceae, Gentianaceae, Begoniaceae, Leeaceae and Cyperaceae.

George King (Scottish medical doctor, superintendent 1871-1897) was the founding Director of the *Botanical Survey of India*; during his period, the landscaping of the Calcutta Garden was laid out. In 1882, he was instrumental in the construction of a new building to receive the rapidly growing herbarium, which, by the time he left the Calcutta Botanic Garden in 1897, had risen to contain a million specimens. In 1891, the title superintendent was replaced by the title director, and David Prain (Scottish medical doctor) was promoted to become director of the Royal Botanical Gardens, Calcutta, in 1898, and also in the same time director of the *Botanical Survey of India*, a posts in which he remained until 1903, later to become director of the Royal Botanic Gardens, Kew, in 1905. He produced the work *Bengal Plants* in two volumes (Prain 1903).

Wilhelm Sulpiz Kurz was a German botanist arriving in India from Dutch service in the Dutch East Indies (now Indonesia); he was appointed curator of the garden's herbarium by Anderson in 1864 and worked in that function to his death in 1878. He explored Burma and Pegu and spent three months in the Andaman Islands. The *Forest Flora of British Burma* (Kurz 1877) is his major work and his most representative Burmese collections are at CAL.

By the end of the 19th and early in the 20th centuries, botanical studies continued in Bombay and Madras presidencies and also in the north-western provinces through the gardens at Poona, Madras and Saharanpur. Some of the most renowned naturalists, forest officers and army officers had left behind a rich legacy of specimens to the herbaria as well as inventories for the *Botanical Survey of India*. Thomas Fulton Bourdillon, a Conservator of Forests in the princely state of Travancore, authored a book on *The Forest Trees of Travancore* (Bourdillon 1908).

James Sykes Gamble founded the Forest School Herbarium, now part of the Forest Research Institute in Dera Dun, and produced *A Manual of Indian Timbers* (Gamble 1881) and *Flora of the Presidency of Madras* (Gamble 1915-1936). Colonel Richard Henry Beddome, an army officer, produced *The Trees of the Madras Presidency* (Beddome 1863), *The Ferns of Southern India* (Beddome 1863-1864), *The Flora Sylvatica for Southern India* (Beddome 1869-1874), *The Ferns of British India* (Beddome

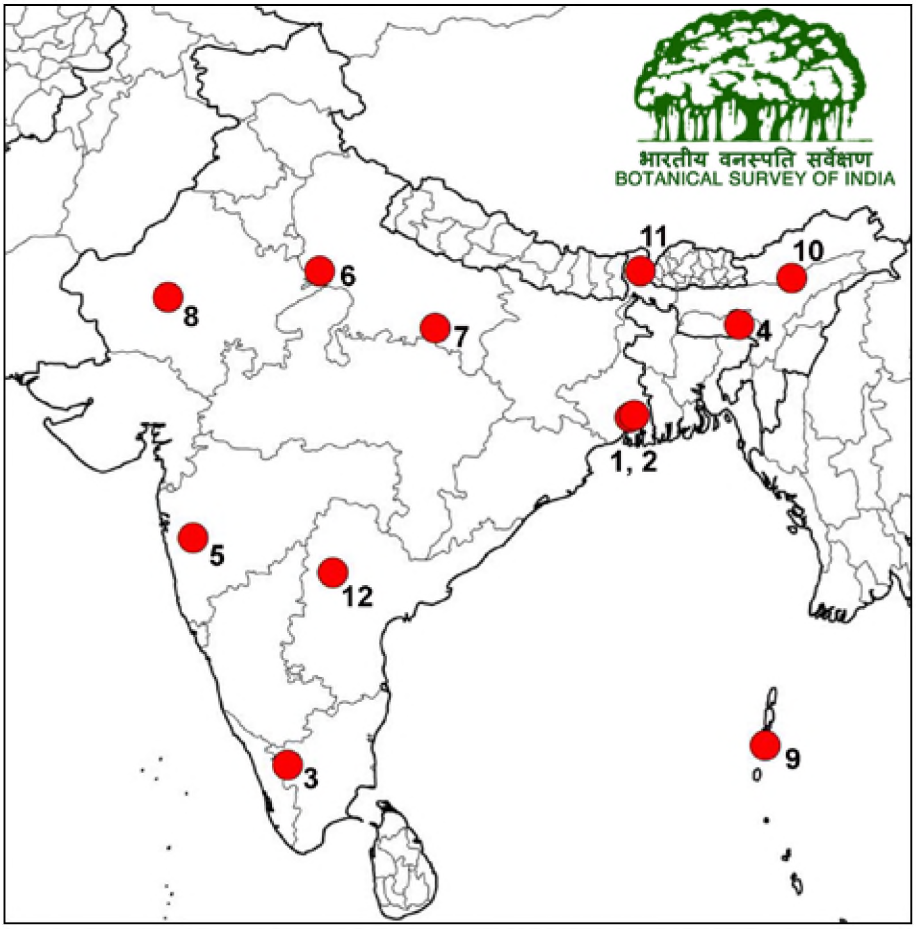


Fig. 1. The locations of the present centres of the Botanical Survey of India. 1. The Central National Herbarium in the Indian Botanic Garden (the Acharya Jagadish Chandra Bose Indian Botanic Garden) in Howrah south west of Kolkata, where the Botanical Survey of India was founded in 1890, and where the Central Botanical Laboratory is now located. 2. The present headquarter of the Botanical Survey of India in Salt Lake City, a north-eastern suburb of Kolkata. Not shown is the Industrial Section, Indian Museum, Kolkata, located in central Kolkata and housing a herbarium of useful plants and samples of their uses. 3. Southern Regional Centre in Coimbatore, Tamil Nadu (established in 1955). 4. Eastern Regional Centre in Shillong, Meghalaya (established in 1956). 5. Western Regional Centre in Pune, Maharashtra (established in 1955). 6. Northern Regional Centre in Dehra Dun, Uttarakhand (established in 1955). 7. Central Regional Centre in Allahabad, Uttar Pradesh (established in 1962). 8. The Arid Zone Regional Centre in Jodhpur, Rajasthan (established in 1972). 9. The Andaman and Nicobar Reginal Centre in Port Blair, the Andaman Islands (established 1972). 10. The Arunachal Pradesh Regional Centre in Itanagar, Arunachal Pradesh (established in 1977). 11. The Sikkim Himalayan Regional Centre in Gangtok, Sikkim (established in 1979). 12. The Deccan Regional Centre in Hyderabad, Telangana (established in 2006). The logo of the Botanical Survey of India is inspired by the more than 250 years old banyan tree (*Ficus benghalensis* L.) in the Indian botanical garden in Howrah; the tree is older than the botanic garden and now more than 450 m in diameter, with ca. 3000 prop roots supporting the canopy.

1883) and the *Icones Plantarum Indies Orientalis* (Beddome 1874), not to be confused with the well-known work by Wight (1840–1853) with the same title. Dietrich Brandis, another forest officer, documented botanical wealth of sacred groves in various parts of India, and produced an important botanical work, *Indian Trees*, dealing with 4400 species of woody plants (Brandis 1911).

## Herbaria in Present Days' India

As mentioned in the historical review, the importance of the classical collections made by the European collectors during the 18th and 19th centuries was recognised with the establishment of the *Botanical Survey of India* in 1890, which was created to document historical, floristic, taxonomic, nomenclatural and environ-

**Table 1.** Herbaria of the *Botanical Survey of India*

| Name of Herbarium & location | Code | Total Holdings | Types |
|---|---|---|---|
| Central National Herbarium, Howrah | CAL | 2,050,000 | 15,000 |
| Eastern Regional Centre, Shillong | ASSAM | 271,000 | 509 |
| Southern Regional Centre, Coimbatore | MH | 275,000 | 2750 |
| Western Regional Centre, Pune | BSI | 170,000 | 571 |
| Northern Regional Centre, Dehra Dun | BSD | 121,500 | 140 |
| Industrial Section, Indian Museum, Kolkata | BSIS | 70,000 | 120 |
| Central Regional Centre, Allahabad | BSA | 69,000 | 28 |
| Andaman Nicobar Regional Centre, Port Blair | PBL | 22,000 | 100 |
| Arid Zone Regional Centre, Jodhpur | BSJO | 24,800 | 18 |
| Sikkim Himalayan Regional Centre, Gangtok | BSHC | 40,000 | 22 |
| Arunachal Pradesh Regional Centre, Itanagar | ARUN | 13,500 | 22 |
| Deccan Regional Centre, Hyderabad | BSID | 30,000 | 30 |

mental aspects of Indian botany. The plant collecting was an activity sustained after India's independence in 1947, particularly after the revival of the *Botanical Survey of India* in 1954 with the continued objectives of (1) undertaking intensive floristic surveys and collecting accurate and detailed information on the distribution, ecology, and economic importance of Indian plants, (2) collecting, identifying and distributing materials of use to educational and research institutions, and (3) acting as the custodian of the authentic collections in herbaria and living collections, as well as documenting plant resources in the form of publications of local, district, state and national floras. The Indian government supports the *Botanical Survey of India* as an exclusively taxonomic and floristic research institution, which organizes more than 100 field explorations on average per year under various action plan programs and in different parts of the country. These programs have a purpose to explore unexplored areas for the discovery and documentation of species and distributions new to science and also to study the range of variations and extent of distribution of all known species with the purpose to build a revised manual of the Indian flora covering all territories within the present Indian political boundaries. This enhanced collecting activity keeps enriching the various herbaria attached to the Survey and other institutions.

## *Herbaria of the Botanical Survey of India*

The *Botanical Survey of India* maintains herbaria in all its regional centres. Its Central National Herbarium is located at Howrah on the right bank of the Hoogli River near Kolkata, and it has the largest specimen holdings in India and is a National Reference Centre. Apart from this, the Survey's 11 Regional Centres maintain herbaria located in different bio-geographical regions (Table 1 & Fig. 1).

Considered together, the Indian herbaria have the most important botanical collections in South Asia. Some of them are known by their exclusive collections of a few explorers, apart from their general collections. Others, such as CAL, MH, ASSAM, BSIS, and BSI, have impressive historical collections representing a many classical collectors (Table 2).

**Table 2.** Important collections in selected *Botanical Survey of India* Herbaria

| Herbarium Code | Important Collectors |
|---|---|
| ASSAM | Bor, N.L., Fischer, C.E.C., Hooker, J.D. & Thomson, T., Kanjilal, U.N., Mann, G., Perry, L.M., Ward, F.K. |
| BSI | Bhide, R.K., Cooke, T., Ritchie, J.C., Talbot, W.A., Thaker, I., Woodrow, G.M. |
| BSIS | Barber, S.A., Burkill, I.H., *Brühl, P.*, Srinivasan, K.S., Watt, G. |
| CAL | Aitchison, J. E.T. , Anderson, T. , Baker, C.F., Barber, C.A. , Beddome, R.H., Biswas, K.P., Blandford, C.F., Bor, N.L., Borthakur, S.K., Bourdillon, T.F. , Brandis, D., Buchanan-Hamilton, F., Burkill, I.H., Calder, C.C. , Campbell, J., Cave, G.H. , Clarke, C.B., Cleghorn, H.F.C., Collett, H., Cooke, T., Craib, W.G., Curtis, C., Dalzell, N.A., Deb, D.B., Debbarman, P.M., Deka, G.K., Dixit, R.D., Drummond, T., Duthie, J.F., Edgeworth, M.P., Ellis, J.L., Elmer, A.D.E., Falconer, H. , Fischer, C.E.C., Forbes, J. , Forrest, G., Gage, A.T. , Gallatly, G., Gamble, J.S., Gammie, G.A., Griffith, W., Haines, H.H., Hance, H.F., Heinig, R.L., Helfer, J.W., Henry, A., Heyne, H. , Hohenacker, R.F. , Hole, R.S., Hooker, J.D., Hooper, D., Hope, C.W.W., Horsfield, T., Hume, A.O., Jenkins, F., Jerdon, T.C., Joseph, J., Kanjilal, U.N. , Kerr, W., King, G., Kingdon-Ward, F., Kittoe, M., Kotschy, C.G.T., Kurz, W.S., Lace, J.H. , Law, J.S., Lawson, M.A., Lister, J.L., Lobb, T., Mackinnon, P.W., Maingay, A.C., Masters, J.W., Maximowicz, C.J.I., Mc Clelland, J., Meebold, A.K., Merrill, E.D., Modder, E.A.C., von Mueller, F.J.H., Pantling, R., Parish, W.H., Parkes, J., Prain, D., Prazer, J., Pringle, C.G., Ridley, H.N. , Rogers, C.G., Rosenberg, W.A.V., Rottler, J.P., Roxburgh, W., Royle, J.F., Schimper, A.F.W., Schlechter, F.R.R. , Schmid, B., Scortechini, B., Scully, J., Simons, K.J., Smith, W.W., Stainton, J.D.A., Stapf, O., Stocks, J.E., Stoliczka, F., Strachey, R., Talbot, W.A. , Teysmann, J.E., Thompson, G., Thomson, T., Thwaites, G.H.K., Vicary, N., Wallich, J. N., Watt, G., White, J.C., Wight, R., Winterbottom, J.E., Wood, J.J., Younghusband, F., Zollinger, H. |

**Table 3.** Herbaria affiliated to other institutions

| Name of Herbarium, Location | Code | Total Holdings | Material and/or collectors |
|---|---|---|---|
| Blatter Herbarium, Bombay | BLAT | 200,000 | Angiosperms, Algae, Mosses and Fungi; seed samples and wood samples from Maharashtra are the other referable collections. |
| Madras Presidency College Herbarium, Chennai | PCM | 100,000 | Flowering plants; Flora of the Presidency of Madras (Barber, C.A., Gamble, J.S., Fisher, C.E.C.) and Flora of Nilgiris and Pulney Hills (P.F. Fyson) have their vouchers/ cited specimens deposited here. |

| | | | |
|---|---|---|---|
| The Rapinat Herbarium, Tiruchirapally | RHT | 225,000 | Flowering plants from Central and Northern Tamil Nadu, Tamil Nadu Coast, the Palni Hills and Sirumalais. Flora of Tamil Nadu and Carnatic (Matthew, K.M.) vouchers and cited specimens deposited here. |
| The Herbarium, Indian Institute of Science, Bangalore | JCB | 17,000 | Flowering plants; specimens of Dr. C.J. Saldanha and his colleagues/students from Karnataka; also collections of others from the Western Ghats including the Nilgiris Biosphere Reserve. |
| The Herbarium, Lucknow University, Lucknow | LWU | 35,000 | Indian bryophytes, lichens, and angiosperms; collections of many recent explorers are in this herbarium. |
| The Herbarium, French Institute of Pondicherry, Pondicherry | HIFP | 24,000 | Flowering plants specially of Western Ghats; important collections include those of Balasubramanyam, K., Blasco, F., Guinet, P., Kostermans, A.J.G.H., Meher-Homji, V.M., Suresh, S.R., Thanikaimoni, G. |
| Forest Research Institute, Dera Dun | DD | 340,000 | Flowering plants; collections of Aitchison, J.E.T., Bahadur, K.N., Beddome, R.H., Bor, N.L., Bourdillon, T.F., Brandis, D., Collett, H., Cooke, T., Dalzel, N.J., Donald, J., Drummond, J.R., Duthie, J.F. , Falconer, H., Fischer, C.E.C., Flemming, R.L., Gage, T.A., Gamble, J.S., Gammie, G.A. , Govan, G., Haines, H.H., Hole, R.S., Jameson, W. , Kanjilal, U.N., King, G., Lace, J.H., Lowrie, A.E., Mamgain, K., Mann, G., Mooney, H.F., Osmaston, B.B., Parker, R.N., Parkinson, C.E., Prain, D., Royle, J.F., Stewart, R.R., Stocks, J.E., Strachey, R., Talbot, W.A., Winterbottom, J.E. |
| Botany Department, University of Calicut, Calicut | CALI | 40,000 | Flowering plants; The herbarium holds specimens from (1) Silent Valley National Park, (2) Wayanad District, (3) Agasthyamala of Southern Western Ghats of Kerala and (4) Pteridophytes of South India and Bryophytes of Kerala. |
| TJawaharlal Nehru Tropical Botanic Garden and Research Institute, Thiruvananthapuram | TBGT | 40,000 | 20,500 specimens of flowering plants and 10,000 fungal specimens. The collections include nearly 2000 specimens collected by Beddome, R.H., Bourdillon, T.F., Narayanaswamy, Sankara Iyer, Venkobarao and many recent explorers. |

### *Herbaria maintained by other institutions*

Even with use of the *Index Herbariorum* (Thiers continuously updated), it is difficult to provide detailed information on all the herbaria outside the *Botanical Survey of India*. However, there is a publication exclusively devoted to this subject, which may be consulted for further details (Singh 2010). There are about 2.5 million specimens of flowering plants in herbaria outside the *Botanical Survey of India*. The authors listed a few of them above (Table 3).

## Herbarium Specimens: Importance and limitations

The utility of herbarium specimens has some limitations. Specimens in dried state will only give clues of how the plants look in their natural habitat: Particularly larger plants that can only be preserved as fragments, and dissections of dried material may fail to give all the information necessary for verification and identification, for example in cases where flowers have complicated coronal processes and unification of staminal and stylar portions into columns, as in the Asclepiadaceae. There are other limitations with respect to water plants, succulents, members of Orchidaceae and bamboo species that do not preserve well as herbarium specimens. Many tropical trees shed leaves prior to producing their flowers, thus making it difficult to obtain complete material unless one returns again and again to the same plant and collect during several seasons. The pressing and drying of fleshy flowers may be difficult, particularly if the flower structure is complicated. Often, the flowers lose their colour in the drying process and quite often the flowers get separated and lost after mounting, leaving the naked stems behind. Monographers are often compelled to complement their work in the herbarium with field studies in order to complete their descriptions and analyses. In spite of these limitations, herbaria remained cardinal in taxonomic research, primarily with regard to reliable identification of specimens and in revisionary and monographic works. The importance of herbaria and other collections of dried and other preserved plant material for focussed floristic exploration and for improved documentation is further discussed and documented below.

### *The need for fresh collections*

A large number of unidentified specimens are often placed at the end of genera and families in Indian herbaria. Some of these specimens are too poor to identify correctly. But fresh collections of such materials may help significantly in arriving at complete understanding of the taxa concerned.

While describing *Polyalthia crassa* R. Parker (Annonaceae) in 1929, the author had quoted his own collection made during 1926 from erstwhile Burma (Myanmar). He also quoted specimens collected by Parkinson (*Parkinson* 213, 584, 880, 1010) from Andaman Islands. Mitra (1999) and Karthikeyan *et al.* (2009) included *P. crassa* based on Parker's report (1929). Rao (1999) and Pandey and Diwakar (2008), in their checklist of the flora of Andaman and Nicobar Islands, included information based on Mitra's authority. But none of the authors managed to make any fresh collections or to improve the original description. Only recent, fresh collections from North Andaman Islands made it possible to draft a complete description and to improve the distribution notes (Venkat Ramana *et al.* 2012).

The unresolved status assigned to *Mitrephora andamanica* Thoth. & D. Das in most plant databases was essentially due to incomplete material and characterization when it was first published (Thothathri & Das 1968), and also due to absence of any other collection than the type from the Middle Andaman Islands. It was recently collected again from North Andaman Islands. Its complete description, with information on population status was reported (Venkat Ramana *et al.* 2015a). Unfortunately, quite a few endemic species reported from the Andaman and Nicobar Islands appear with unresolved status in important plant databases as they are represented by very few collections or poor descriptions, and therefore were treated under different synonyms in different works.

Similarly, fresh collections often help in the reviewing of the identity of earlier collections. The fresh collections of *Suregada* material from the North Andaman Islands helped in establishing the taxonomic identity and diagnosis of *Suregada bifaria* (Roxb. ex Willd.) Baill. (= *Gelonium bifarium* Roxb. ex Willd.). Its earlier place in synonymy under *Suregada multiflora* (A. Juss.) Baill. (= *Gelonium multiflorum* A. Juss.), as found in Indian floras and the *World Checklist of Euphorbiaceae* (Govaerts *et al.* 2000), could be corrected (Venkat Ramana *et al.* 2015b).

Species represented by single collections often prompt explorers to rediscover them again. A good number of species were rediscovered in explorations undertaken with such purposes. Some of them were even introduced in gardens of the *Botanical Survey of India*. Some such species, which have been collected again after having for long been only known from one collection, are reported from various regional centres (Table 4).

### *Undetected novelties*

Indian herbaria have good number of specimens left unexposed for future critical studies. There are many reasons why some specimens representing new species remain undetected in herbaria. Lack of expertise in specific groups is one reason. In many other cases, the specimens are incomplete (lack of flowers or fruits) or the species are represented by fragments with no field data or, in a few cases, with the locality illegibly written.

As mentioned, novelties go unnoticed when there is lack of expertise in specific groups, and the number of experts associated with Indian herbaria is not adequate to secure sufficiently qualified identification. In some instances, some of specimens were recognised as representing new species, and annotated as such on the sheet, but never described or published. Between 1955 and 2000, as many as 500 new species published from India were the results of studies on such collections. Interestingly, most of these were collected again from the localities given on the labels of the older collections, very rarely from different localities with comparable habitats.

Some specimens of *Indigofera* L. (Fabaceae) were collected by C.B. Clarke from Khasia Hills (Meghalaya) and named by him as *I. sesquipedalis,* but also called 'Khasia heterantha' because of its resemblance with *Indigofera heterantha* Wall. ex Brandis of Himalaya. However, several other sheets were erroneously identified by him as *I. dosua* Ham. (*C.B. Clarke* 7296), *I. het-*

**Table 4.** List of rare species rediscovered and introduced in botanic gardens

| Arunachal Pradesh Regional Centre | Name of taxon | First/Subsequent collection |
|---|---|---|
| | *Impatiens laevigata* Wall. var. *grandifolia* Hook. f. (Balsaminaceae) | 1873/ 2012 |
| | *Justicia anfractuosa* C.B. Clarke (Acanthaceae) | 1885/ 2009 |
| Sikkim Himalayan Regional Centre | *Cymbidium whiteae* King & Pantl. (Orchidaceae) | 1890/ 2010 |
| | *Oberonia jenkinsiana* Griff. ex Lindl. (Orchidaceae) | 1859/ 1898, 2013 |
| | *Platanthera biermanniana* (King & Pantl.) Kraenzl. (Orchidaceae) | 1896/ 2013 |

| | | |
|---|---|---|
| Eastern Regional Centre | *Eria lacei* Summerh. (Orchidaceae) | 1938/ 2007 |
| | *Epigenium treutleri* (Hook. f) Ormerod (Orchidaceae) | 1890/ ? |
| | *Appendicula cornuta* Blume (Orchidaceae) | 1890/ 2007 |
| | *Geodorum appendiculatum* Griff. (Orchidaceae) | 1845/ 2012 |
| | *Pyrenaria khasiana* R.N. Paul. (Theaceae) | 1871/ 1983 |
| Central National Herbarium | *Zeuxine reflexa* King & Pantl. (Orchidaceae ) | 1885/ 2013 |
| | *Zeuxine rolfiana* King & Pantl. (Orchidaceae) | 1891/ 2012 |
| | *Taeniophyllum filiforme* J.J. Sm. (Orchidaceae) | 1867/ 2002 |
| Central Botanical Laboratory | *Salix obscura* Andersson (Salicaceae) | 1849/ 2006 |
| Northern Regional Centre | *Corydalis lathyroides* Prain (Fumariaceae) | 1884/ 1958, 2013 |
| | *Trisetum micans* (Hook. f.) Bor (Poaceae) | 1883/ 1892, 1941, 2002 |
| | *Arenaria kumaonensis* Maxim. (Caryophyllaceae) | 1884/ 2002, 2003 |
| | *Parnassia kumaonica* Nekr. (Parnassiaceae) | 1884/ 1974, 2002, 2003 |
| Western Regional Centre | *Canscora stricta* Sedgw. (Gentianaceae) | 1917/ 2007 |
| | *Tillaea schimperi* Fisch. & C.A. Mey. subsp. *schimperi* (Crassulaceae) | ?/ 2007 |
| Southern Regional Centre | *Vanda thwaitesi* Hook. f. (Orchidaceae) | 1861/ 1998, 2011 |
| | *Brachystelma elenaduense* Sathyan. (Apocynaceae) | 1969/ 2012, 2013 |
| Andaman & Nicobar Regional Centre | *Marsypopetalum crassum* (R. Parker) B. Xue & R.M.K. Saunders (Annonaceae) | 1916/ 2012 |
| | *Ginalloa andamanica* Kurz (Annonaceae) | 1872/ 2007 |
| | *Cassine viburnifolia* (Juss.) Ding Hou (Celastraceae) | 1896/ 2006 |

*erantha* Wall. ex Brandis (*C.B. Clarke* 18598), *I. leptostachya* DC. (*C.B. Clarke* 40103) and *I. pulchella* Roxb. (C.B. Clarke 18614). Prain, after scrutiny of all the specimens at CAL, had annotated them as *I. sesquipedalis* C.B. Clarke. Indeed, on critical study of all the above sheets and many other specimens from different herbaria, they were found to represent a distinct species which is allied to *I. heterantha,* as was suspected earlier by Clarke. Because this species had not been validly published by Clarke or by others and was listed as *I. sesquipedalis* C.B.Clarke MSS in Index Kewensis, it was validly published with illustrations by Sanjappa (1984).

### *Typification and standardization of names*

It is difficult to give an overview of older names typified by British and other European collections until type databases of all the herbaria with Indian types are completed. Wood (1994) had lectotypified many older Acanthaceae specimens collected from India by Campbell and Wight available at Edinburgh (E). Eleven names of *Strobilanthes* Blume (Acanthaceae) described in the 19th century by Anderson and Kurz from China, India and Myanmar were typified based on specimens from the CAL herbarium (Albertson & Wood 2012).

What is important is to envisage meaningful collaboration on specific groups with the World's established taxonomic institutions so that monographers can sort, detect, and add authenticity in determinations of these specimens or otherwise establish them as new. CAL has the best set of collections from Myanmar collected when it was under British rule (1824–1948), and these collections have not been much studied by specialists or those who prepared the various editions of the check-lists of that country (latest edition Kress *et al.* 2003). Similarly the collections from Sri Lanka, Malaysia and Indonesia in CAL need critical study as many of them are type-specimens or their duplicates. Some of them could be new species or records.

CAL has also volumes of correspondences and a number of manuscripts that reach back to the establishment of the botanic garden at Calcutta in 1787. Their study has relevance to construct botanical history of India with greater authenticity.

## Herbarium Maintenance

Herbaria require regular attendance particularly in humid tropical situations for their continued survival. This is very important because great pains have been involved in establishing, building and maintaining them, and many specimens represent extremely valuable scientific documentation. Despite herbaria being air-conditioned, specimens are exposed to high humidity during the rainy seasons. Particularly in humid tropical climate there are problems with the continued conservation of important specimens, and without sufficient financial support and manpower, there is no certainty of their continued well-being.

Indeed, specimens in herbaria maintain a necessary link with the floras and other taxonomic works published in the past, and without well preserved herbarium material we cannot be sure that we can maintain scientifically reliable identification of plants. Unfortunately, there is sometimes lack of understanding of this among administrators at various levels and governing agencies of institutions, which are responsible for housing such herbarium collections. Taxonomy in general may be given low priority, and resource allocation towards field collections and continued management of existing collections may be low. Many universities and non-governmental organizations' herbaria have no facilities to maintain large collections. Herbaria, which are outside the Government system of the *Botanical Survey of India,* require support in terms of human resources and capital infrastructure to maintain herbarium collections. The *Botanical Survey of India* has recently drawn up a plan for such assistance.

Fortunately, the herbaria of the *Botanical Survey of India* do have curatorial staff for taking care of specimens on a regular basis. The Central National herbarium of the *Botanical Survey of India* headquarters at Howrah (CAL) has a maintenance expenditure (annual fumigation, annual maintenance and service charges for central air conditioning and electricity charges) amounting to 5 Rupees (≈ 0.06 Euros) per specimen per year. This does not include the salaries of personnel involved in maintenance. The annual earnings from the technical services provided by CAL are significantly less than the expenditure needed for the maintenance of the herbarium.

## Digitization

Many Indian herbaria are now resorting to digitization since this offers easy access and retrieval of specimens for study also outside the institution, where the collections are held. The *Botanical Survey of India* has about three million specimens housed in various herbaria located at its Headquarter at Howrah and in its Regional Centres, Gardens and Museums. A pilot project on digitization of herbarium specimens at Central National Herbarium (CAL) at Howrah was sanctioned by the Ministry and was executed at the Central National Herbarium in 2009-2010 to digitize 20,000 herbarium specimens. A Data Centre was created housing the hardware and software for the establishment of an Indian Digital Herbarium, with high resolution digital images and detailed label data associated with each specimen through a web based application software operating in a local area network environment, and an Indian Virtual Herbarium, with a centralized inventory to provide open single point access to low resolution images and associated label data of the specimens available in BSI's herbaria located at various locations in India through the Internet.

Two Data Production Lines (DPLs), having servers, computers and scanners, were created for digitization, which included scanning and data capturing. Around 10,000 herbarium specimens were digitized by employing the manpower for one data production line on project basis for the duration of one year. The hardware, application software, methodology and work flow and total process of digitization were tested in an initial pilot project.

Now, all the regional centres have also built facilities for scanning and digitisation of specimens. In 2015, nearly 30,000 specimens had been digitized: 1612 sheets (all ferns) from the Sikkim Himalayan Centre in Gangtok (BSHC), 600 type sheets from the Eastern Centre at Shillong (ASSAM), 8000 Types from the Central National Herbarium at Howrah (CAL), 2134 sheets (includes 872 type specimens of Angiosperms and 87 type specimens of ferns) from the Northern Centre at Dehra Dun (BSD), 4336 sheets from Western Centre at Pune (BSI), 800 sheets Deccan Regional Centre, Hyderabad (BSID), 2000 type sheets from the Southern Centre at Coimbatore (MH) and 9922 sheets from the Andaman and Nicobar Centre at Port Blair in the Andaman Islands (PBL). At least 100,000 more specimens will in all probability have been digitized by various centres of the Botanical Survey of India by the time this article appears in print.

## Conclusion

To expedite the production of a comprehensive national Indian flora, multinational projects, involving institutions such as the herbarium of the Royal Botanic Gardens, Kew, the Natural History Museum of London (formerly British Museum - Natural History), the Royal Botanic Garden of Edinburgh and other European herbaria are to be promoted. Joint explorations in all phytogeographic regions and the study of specimens of particularly difficult or poorly known taxonomic groups are to be encouraged and organized in order to understand tropical plant diversity in its totality. Writing a flora at the national level, producing monographs of specific groups with worldwide syntheses are possible only through such collaborations. If properly financed and otherwise supported, such international collaborations are bound to succeed, because in combination the European and Indian herbaria have built up the collections, the expertise and the necessary historical and geographical data. The Indian herbaria represent both rich legacies from the past and are essential tools for the future study of the Indian flora.

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# How to Survive as a Taxonomic Institute: The amalgamation of the large Dutch herbaria and their collections

*Peter C. van Welzen and Christel Schollaardt*

## Abstract

In the late nineties of the last century, the Dutch herbaria of Leiden (L), Utrecht (U), and Wageningen (WAG) were merged to form the National Herbarium of the Netherlands (NHN). The merger was followed by an even larger unification, that with the other natural history collection institutes of the Netherlands to form Naturalis Biodiversity Center in Leiden. Naturalis is now by far the largest natural history museum of the Netherlands and ranks among the world's top 10 largest natural history institutes. While the research programme of Naturalis is still being developed, the digitisation of all herbarium collections and wood and slide collections, together with state-of-the-art facilities for molecular, computational, and (ultra)microscopic imaging put the institute in an ideal position for innovative collection-based biodiversity research and teaching.

**Key Words:** Leiden, National Herbarium of the Netherlands, Naturalis Biodiversity Center, Rijksherbarium, Utrecht Herbarium, Wageningen Herbarium, Zoological Museum of Amsterdam

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Most of the Dutch herbaria originated during colonial times in the nineteenth century (see Table 1 for sizes and foundation dates of the botanical collections in the Netherlands, and Fig. 1 for a map of where they were initially located). Three of the old herbaria were by far the largest, those of Leiden, Utrecht and Wageningen. The herbarium of Utrecht, in the centre of the Netherlands, is the oldest Dutch herbarium (Erkens & Baas 2008). The Leiden herbarium, second in row, officially started as the 'Rijksherbarium' (= National Herbarium) and was founded on March 31, 1829 by the Dutch King Willem I, probably on the instigation of its first director, Carl Ludwig Blume (Smit 1979), to study his vast Indonesian collections. In those days the Netherlands also included Belgium and - because Leiden already contained a Natural History Museum - the National Herbarium started in Brussels in order to keep a political (and perhaps scientific) balance between the southern and the northern Netherlands (Smit 1979). The Wageningen herbarium was founded later, officially in 1896, though substantial collections were already present before that year (Aleva *et al.* 1996).

Two other university herbaria, those of Amster-

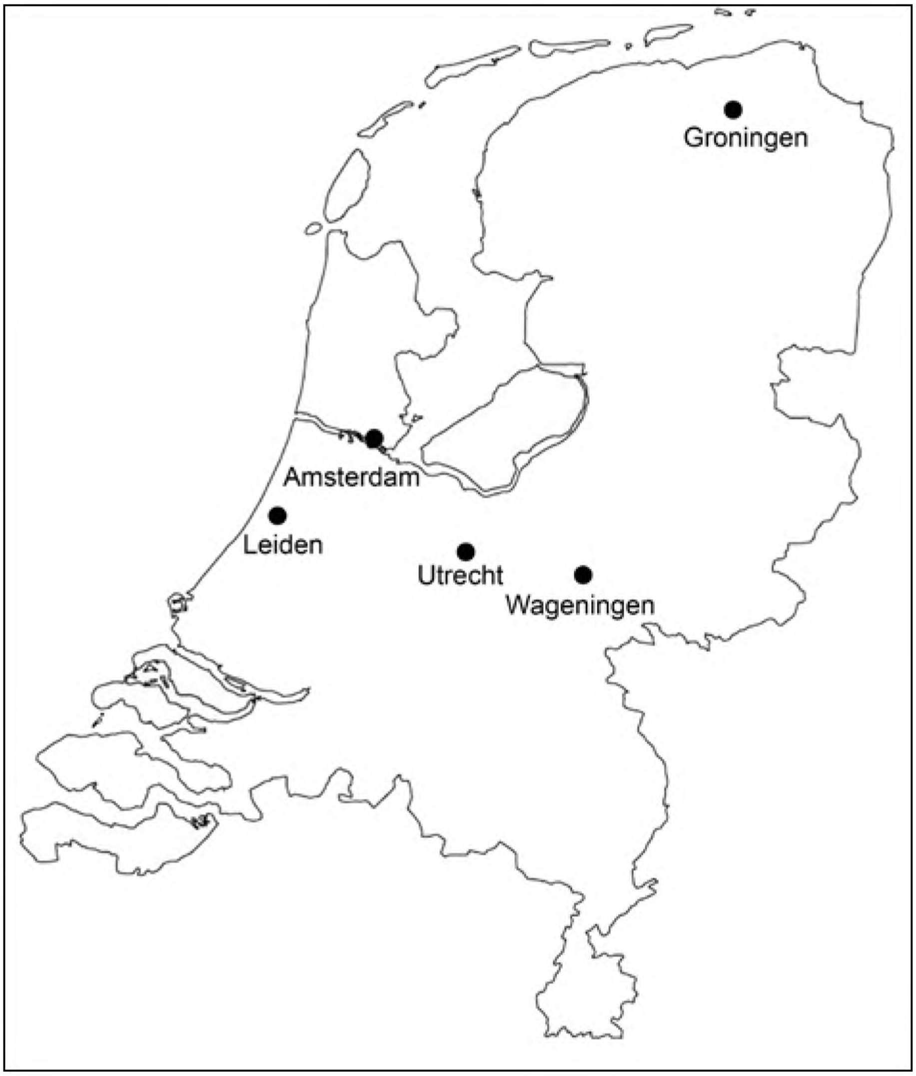



Fig. 1. Localities of (former) Dutch herbaria, presently all merged and in Leiden.

**Table 1.** Codes, founding years and estimated sizes of the five largest herbaria in the Netherlands.

| Herbarium | Code | Founding year | Size of collections |
|---|---|---|---|
| Utrecht | U | 1816 | 800,000 |
| Leiden | L | 1829 | 4,200,000 |
| Amsterdam | AMD | ? | 200,000 |
| Groningen | GRO | 1890 | 50,000 |
| Wageningen | WAG | 1896 | 1,000,000 |

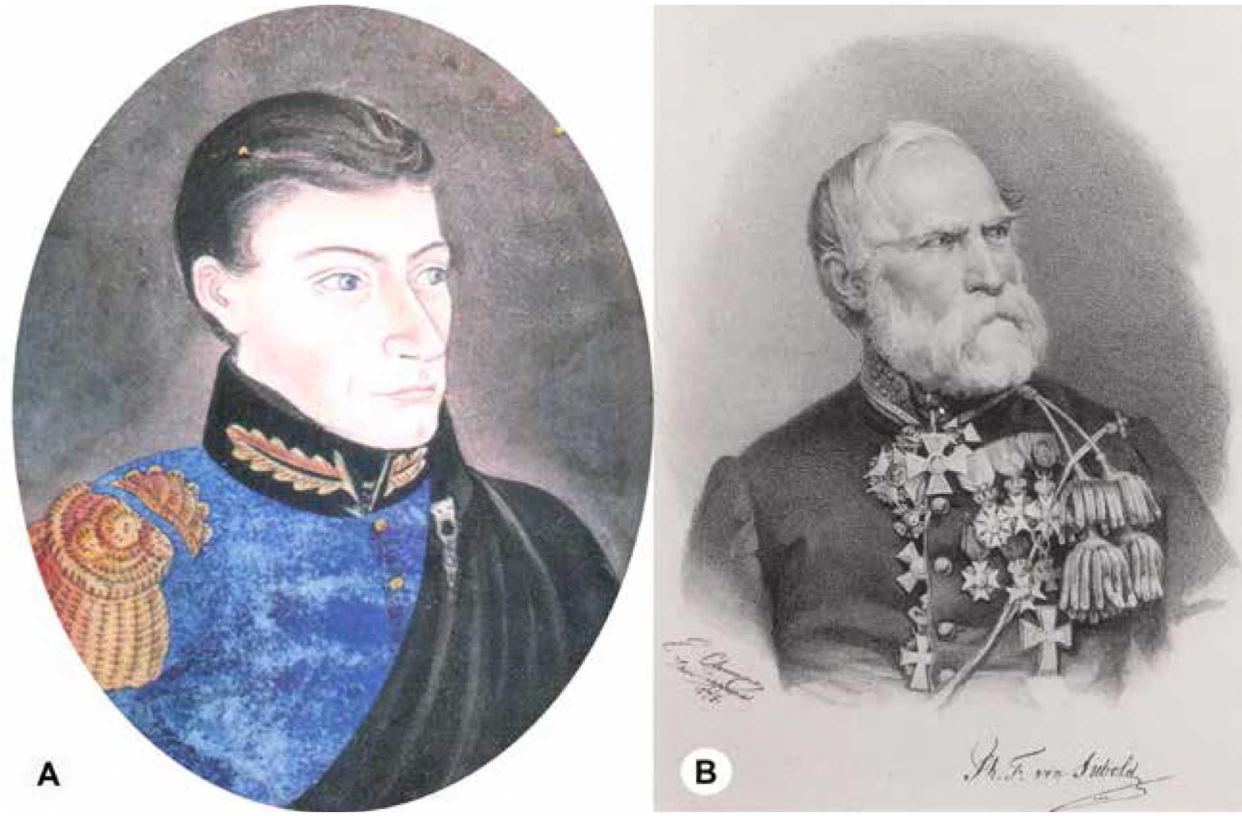



Fig. 2. Portraits of Philipp Franz von Siebold (1796–1866). (A) A watercolour-coloured pencil drawing of von Siebold by Kawahara Keiga (1786–1860?), a late Edo period Japanese painter who produced paintings of natural history for von Siebold. The portrait was painted in the 1820s and is now in the Saga Prefectural Museum of Art near Nagasaki, Japan. (B) Von Siebold in a colonel's uniform of the Dutch East-Indian Army. Portrait made in 1859, reproduced as a lithograph by E. Chiossone in 1875, now in Rijksmuseum voor Volkenkunde, Leiden. Both images are in the public domain and reproduced from Wikimedia Commons.

dam (University of Amsterdam) and Groningen, were much smaller. Both were abolished before the large merger of herbaria started. Amsterdam was incorporated with the herbarium in Leiden (though still kept separate), and the collections of the Groningen herbarium were divided between Wageningen (the African vascular plants) and Leiden (the remainder, merged with the Leiden collections).

As mentioned above, the National Herbarium of the Netherlands started in Brussels. To understand why it moved to Leiden, we first have to look to the other side of the globe. In the early $19^{th}$ century the Netherlands was the only country allowed to trade with Japan. The Dutch had to live on Deshima, a small fan-shaped artificial island, which had been constructed in the bay of Nagasaki in 1634. Among the Dutch on Deshima was a German physician, Philipp Franz von Siebold (Fig. 2). Von Siebold, with the aid of Japanese patients, friends, and students, gathered a vast collection of preserved and living plants, animals and ethnographical objects. After his return to the Netherlands he settled in the vicinity of Leiden, where he had most of his Japanese collections housed at various institutions (the Ethnological Museum, the Natural History Museum – now Naturalis Biodiversity Center, and the Hortus botanicus). In 1830, he went to Brussels to donate his collections of dried plant specimens to the National Herbarium. In those very days in 1830, the Belgian uproar started, resulting in the independence of Belgium. The director of the National Herbarium, Blume, was absent, and von Siebold, who realised the gravity of the situation, consulted with Blume's assistant and the government in The Hague (at that time, Brussels and Amsterdam alternated as capital of the Netherlands every second year, while the government remained in The Hague). With official approval, von Siebold had the collections in Brussels packed and moved to Leiden. Word has it, that when the collections were transferred to a barge in Ghent (Belgium), they were almost destroyed by a mob, but von Siebold could convince the mobsters of his neutrality based on his German identity and was allowed to ship off the plants. In Leiden the collections were gradually incorporated and united with collections already present at the Leiden University, though this was not an easy process. Blume had, to honour him, a personal title of professor, but he had no teaching obligations. Teaching was done by the professor of botany, in those days Caspar Georg Carl Reinwardt, who hardly had access to the specimens. The complete inclusion of the herbarium in Leiden University succeeded under the third director, Willem Frederik Reinier Suringar, who also occupied the chair of botany at the university (Smit 1979; Kalkman 1979).

The three major herbaria in the Netherlands (L, U, WAG) divided their labour and specialised in different areas, thus facilitating independent workflows. The staff at L worked on the Dutch and other European floras, on the south-eastern Asian (Malesian) flora, and had established a strong cryptogamic botany group. The staff at herbarium L gradually incorporated the *Flora Malesiana* botanists, when they returned to the Netherlands, which happened after Indonesia became independent in December 1949. Cornelis Gijsbert Gerrit Jan van Steenis, later one of the directors of herbarium L, was the founder of the *Flora Malesiana* project, covering an area ranging from the Malay Peninsula to New Guinea. As a result herbarium L focussed a large part of its research on the *Flora Malesiana* project. Herbarium U focussed on southern and central America, especially on the former Dutch colony Suriname and the Dutch Antilles, and coordinated the *Flora of the Guianas,* which covered Guyana, Suriname and French Guiana. Finally, WAG concentrated on Africa, particularly parts of central and western Africa, with flora projects like the *Flora of Benin*, *Flore du Gabon*, *Flora of Togo*, etc. Besides these taxonomic and geographical foci, there were wood anatomical, palynological and cytological research teams, either within or closely associated with the three main herbaria.

The herbaria house some of the oldest book herbaria in the world, like the En Tibi herbarium, perhaps the oldest surviving book herbarium worldwide, presumably dating from 1542 and made in Italy; part of the Clifford Herbarium (http://www.george-clifford.nl/); the Petrus Cadé Herbarium (dating from 1566; http://www.nationaalherbarium.nl/Cade/index.htm); but also the herbaria of of Leonhart Rauwolff (1535-1596), part of the Paul Hermann herbarium (1646-1695; http://www.hermann-herbarium.nl/), the herbarium of Paolo Boccone (1633-1704), etc. The Van Royen herbarium and some other old herbaria have their specimens mounted on loose sheets, not in books, with cut-out paper vases and banners (Fig. 3a) to hide the cut branch ends. The wood collection contains some historical treasures such as Junghuhn's collection of woods from Java, shaped as books (Fig. 3b), and the world-famous collections of woods from Hokkaido, with paintings of the leaves and branches by Mogami Tokunai, a Japanese samurai, scholar, geographer and explorer, who donated this collection to von Siebold, who in turn sent them to the Rijksherbarium (for an excellent overview of the history of the Leiden collections, see Steenis-Kruseman 1979).

The worldwide economic recession in the early 1980s resulted in heavy budget cuts. The herbaria of U and WAG were seriously affected by this, with a serious loss of staff. U even reduced its research mainly to the New World Annonaceae. The herbarium L lost some staff, but could prevent catastrophic damage by re-organising itself together with the Leiden Botanical Garden into a research institute, a new form of academic organisation introduced by the Ministry of Education, Culture and Science for excellent university departments, which had a greater than usual research task relative to their teaching duties. The


Fig. 3. Some notable old specimens in the botanical collections at Leiden. (A) Sheet with crocuses from the Adriaan van Royen herbarium, a friend of Linnaeus, note the printed vase (bottom) and the printed banner (top) glued over the specimens; from https://science.naturalis.nl/media/cache/a1/3d/a13d868341732481b2481b6c03917beb.jpg. (B) Junghuhn's wood specimens disguised as books; from https://science.naturalis.nl/media/cache/d8/4d/d84de71fe53c7b4c10ec7b-c785e5df9a.jpg. Both images available from the home page of Naturalis.

new research institute, officially combined the Rijksherbarium and the botanical garden (Hortus botanicus) into one organisation: RHHB (RijksHerbarium/Hortus botanicus) – a masterstroke by its then director Prof. Cees Kalkman.

Unfortunately, in 1993 the Leiden Science Faculty decided that maintaining large collections did not belong to its core business. It proposed such draconian budget cuts that the future of the herbarium L was in imminent danger – an ironic fate, one year following the global Convention on Biological Diversity (CBD) agreed at the Rio summit, with the Netherlands as an enthusiastic signatory. Not only the herbarium L was under threat, also in the course of time many of the Dutch botanical gardens attached to universities encountered financial problems. A committee of the Royal Netherlands Academy of Arts and Sciences (KNAW) analysed the problem, and in 1995 the Acad-

**Table 2.** Chronological order of events after the National Herbarium of the Netherlands (NHN) was established.

| | |
|---|---|
| 1999 | National Herbarium of the Netherlands (Leiden, Utrecht Wageningen) established |
| 2004 | University of Utrecht withdraws from NHN |
| 2005 | Negotiations to start Naturalis Biodiversity Center |
| 2008 | Utrecht leaves negotiations |
| 2010 | Merger of NHN and Natural History Museums of Leiden and Amsterdam to form Naturalis |
| 2016 | Start of new exhibition wing and restructuring old exhibition space for collection |
| 2020 | Expected union of all groups under one roof |

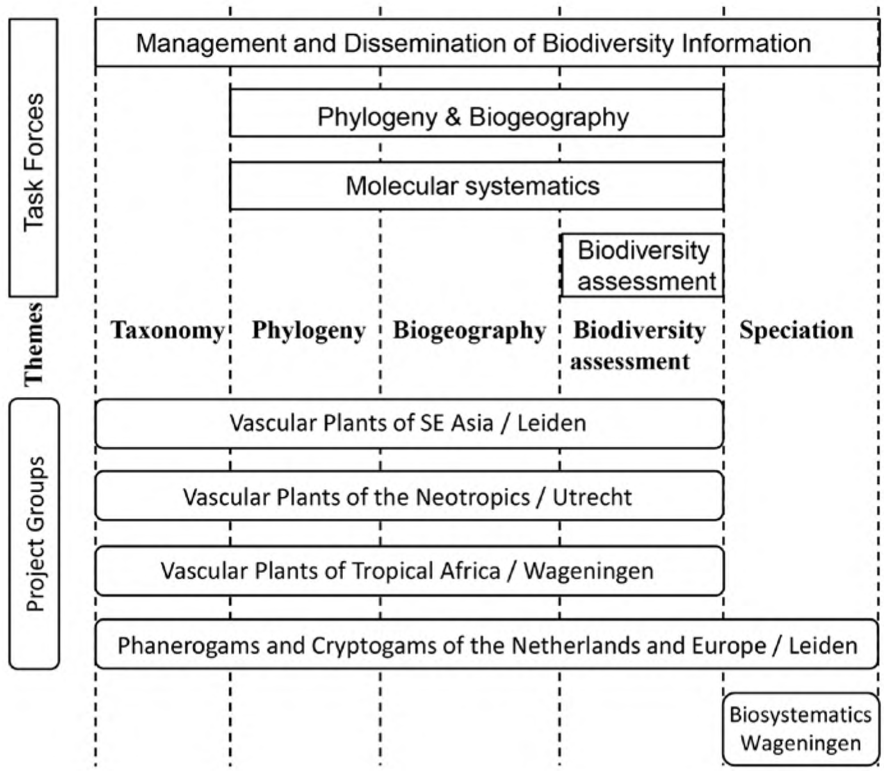
emy advised that the herbaria should be united into one decentralised institute (meaning central management, but with the work done at the different universities). In 1996, after much pressure, the responsible minister agreed to provide funds for this plan and asked the Academy to organise the decentralised herbarium. He announced it during the official opening of the new Van Steenis building in Leiden (by Her Majesty Queen Beatrix), controversially adding that all research should concentrate on south-eastern Asia. This gave a somewhat false start of the National Herbarium of the Netherlands (NHN); Africa and Neotropic taxonomists from herbarium WAG and U were understandably not amused – neither was the Leiden Director Prof. Pieter Baas (Baas 2000). The merger was officially completed on the first of January 1999 (see Table 2 for a chronological order of events to follow).

## National Herbarium of the Netherlands

The Dutch Government supported the NHN with, in addition to what came through the university budgets, a directly granted annual sum of 2 million guilders (c. € 0.9 million). This was granted in order to largely compensate for the budget cuts received by the universities. Prof. Pieter Baas, director of L, became the director of the NHN and had the task to create synergies between the three institutes, which used to be independent institutions with different curational methods, which prevented a physical integration. For instance, the three institutes used different sizes of herbarium sheets and different classification systems for their collection management. The herbarium L followed the oldest system (mainly the Dalla Torre's evolutionary classification) and the herbarium U followed the most modern system (then APG II). Families were arranged either alphabetically (U, WAG) or evolutionarily (L), geographically first (U) or taxonomically first (L, WAG). Each institute had one or several research groups, each with their own topics and geographic area of interest. In order to create a synergistic link between the three institutes, the planning of research was intensively discussed by a complete group consisting of permanent and adjunct scientific staff and PhD students. This bottom-up approach resulted in long-term support for the restructuring of research groups and the establishment of thematic cross-linking task forces (Fig. 4).

It was felt a nice idea to concentrate on fewer *plant families* for taxonomic research. Normally, a single researcher would work on one family for one of the flora projects. This had to change to teamwork for species-rich plant families, whereby an integrative approach was envisaged, and alpha taxonomy should be combined with molecular, phylogenetic and histori-

Fig. 4. Distribution of themes over Project Groups (active per herbarium) and Task Forces (inter-herbarial) (Adjusted from the Progress Report 1999 of the Nationaal Herbarium Nederland).




cal biogeographic approaches. Examples were studies of the Orchidaceae and the Annonaceae (Fig. 5). The latter was selected as a model taxon for phanerogam systematics, and was the only family for which a pantropical coverage was possible as all three institutes had staff working on this family. Unfortunately, this approach was later eroded due to understaffing. Synergy between the three former herbaria was also created by regular meetings, like those of the task forces, which rotated among the institutes.

One of the in-house published journals, *Blumea*, had to change its policy; before the merger it was (mainly) devoted to south-east Asian taxonomy, after the union of the herbaria it changed to a worldwide coverage.

During the establishment of the NHN, the Netherlands Science Foundation (NWO) helped by providing funds for digitisation of the type collections and their presentation on the internet. A specially appointed database manager, Luc Willemse, selected the Botanical Research and Herbarium Management System (BRAHMS) for this purpose (http://herbaria.plants.ox.ac.uk/bol/brahms/). BRAHMS was and is still being developed by Denis Filer at the University of Oxford, and the NHN became the largest and most complex user and tester of the software, which, over time, quickly expanded and changed to become one of the most versatile and most used packages for herbarium collections worldwide. The type project resulted in the digitisation of ca. 50,000 type specimens. High definition scans were made of the specimens and the label information was entered in BRAHMS. The Expert centre for Taxonomic Identification (ETI, then part of the University of Amsterdam, now incorporated in Naturalis Biodiversity Center in Leiden) created the software to search and view the specimens on the internet. The result was second to none in the world.

Maintaining quality and managing a decentralised herbarium was not easy. All botanical and zoological systematics at Dutch universities had been judged as poor by a broad peer review of the whole of Dutch

Fig. 5. The National Herbarium of the Netherlands has focussed on the pantropical Annonaceae, for example *Gueatteria pudica* N. Zamora & Maas. Photo by P.J.M. Maas; front page of *Blumea* 60 (2015), reproduced with permission.

Biology in 1993 by a non-systematist committee, but subsequent reviews were much more positive with – as a peek – the unanimous qualification of excellent for the herbarium L on all scores in 1999. The peers had very high expectations of the NHN-*in statu nascendi*.

## Further Threats and a Leap Forward

In 2004 the Faculty of Biology at the University of Utrecht had to realise severe budget cuts and decided to withdraw from the NHN and to discontinue their financial support for the Utrecht branch (Erkens & Baas 2008). This could result in the end of the NHN as a recipient of earmarked money from the ministry, as the NHN was intended to keep all three institutes (L, U, WAG) united. Long before, heavy clouds had also gathered above the Zoological Museum of Amsterdam University (ZMA; founded 1838), and a merger of ZMA and Naturalis (the natural history museum in Leiden) *sensu stricto* was on its way. The NHN Board therefore embraced the plan to safeguard all important biological collections by uniting NHN, ZMA and Naturalis. The former director of Naturalis, Ronald van Hengstum, had a strong interest in such a merger in order to safeguard the research capacity of his Museum and create an 'Academic Work Place' (an exception among Dutch museums, where normally only a few curators would be employed). The merged Naturalis should be co-funded by the Science and Education department of the Ministry, rather than only by the less research-friendly Culture department of the same ministry, responsible for the Dutch museums. On behalf of NHN, the negotiations were mainly conducted by its new director, Prof. Erik Smets.

Naturalis, founded in August 1820, was for a long time a museum without exhibition space. It had just moved to a new location in Leiden, close to the herbarium L, where a large exhibition space became available. Naturalis was already combined with the former National Museum for Geology and Mineralogy and was, by far, the biggest institute of all merging parties involved. The ideas of unification were received with enthusiasm by the Ministry of Education, Culture and Science and also by the University of Utrecht. However, the negotiations took longer than expected, also because the director of Naturalis, van Hengstum, suddenly died (he was succeeded by Bert Geerken in 2008, and in turn in 2011 succeeded by Edwin van Huis). Finally, the University of Utrecht decided to withdraw from the negotiations. It closed down the herbarium, and even considered to sell the collections to Brazil. The ministry prevented the latter, because they decided that the collections were Dutch cultural heritage and thus became owner of the collections. After this move, Naturalis was asked to manage the collections, and they were then transferred to Leiden.

Naturalis Biodiversity Center (starting under the name Netherlands Biodiversity Center Naturalis) was officially founded on 28 January 2010. It was a joined project by Naturalis, and the universities of Amsterdam (ZMA zoological collections), Leiden (herbarium L) and Wageningen (herbarium WAG), which are all represented on the Board of Trustees. The combined collections mounted to an estimated total of 37 million objects, and with this number of specimens the Naturalis Biodiversity Center is among the ten largest natural history collections in the world. The combined wood collections in Naturalis represent the largest collections of wood samples in the world.

It was also decided that there would be a unified location for the collections, no more decentralised 'institutes'. In fact, all collections were moved to Leiden, but at present they are still spread all over town until the construction of a new exhibition building (the old one being already too small), and the renovation of the old exhibition space into collection space is completed. Then, probably in 2020, Naturalis Biodiversity Center will be renewed with all personnel and all collections finally together. During the move of the botanical collections the opportunity will be seized to move all collections to the APG IV classification, which in itself will be a major operation.

Naturalis Biodiversity Center is not only a popular museum for family-visits (top 10 in the Netherlands), but it is also a research institute with more than a 100 researchers, housing one of the largest biodiversity collections in the world. The government helped the initiative by providing 30 million €, which were partly for a new building, but also for equipment, for digitising large parts of the collection and for DNA barcoding (the latter in cooperation with the KNAW Fungal Biodiversity Centre in Utrecht). Already, Naturalis offers excellent opportunities for state-of-the-art research: modern microscopy, scanning (SEM, TEM, Micro-CT), mineral and gem laboratories, plant-anatomical labs, next generation sequencing, DNA barcoding facilities, a large division for information and communication technology, ample computer facilities, and vast digitised collections. The general director is presently Edwin van Huis, and Erik Smets (education) and Koos Biesmeijer (research) are the two scientific directors.

## Digitisation

Before Naturalis Biodiversity Center started with large scale collection digitisation, the NHN and the combination now forming Naturalis had several times received funds by the Dutch Research Foundation (NWO) to digitise collections. In the NHN the 'special collections', kept separate, including the wood collection, the collection of material in spirit and the carpological collections (collections of dried seeds and fruits), were then to be digitised. However, once Naturalis started digitisation, all dried plants mounted on herbarium sheets were selected as one of the flagship projects. All plants had to be photographed

Fig. 6. One of the three assembly lines for photographing specimens. Shown is the beginning of the belt, were specimens and their folders are placed in two rows, halfway the QR codes are added (man with the black pistol-grip) and at the end, in the black box, the camera, which will only photograph the specimen row. The specimens are surrounded by buttons for colour calibration. Photo by the firm Picturae, reproduced with permission.

and a minimum number of label data had to be recorded. As the only exception within Naturalis, this job was to be done by an external company, Picturae (https://picturae.com/uk/). Following the example of herbarium P in Paris and with the aid of Luc Willemse and other staff at Naturalis, three almost fully automated assembly lines were created to photograph the specimens (Figs. 6, 7). At the start of every assembly line, boxes had the free mercury removed (the free mercury was condensed from evaporating sublimate, formerly in general use to safeguard the specimens against insect attacks), and staff then placed the sheets on the belt (Fig. 6). In this process, the specimens were provided with a QR barcode, and, while passing along the assembly band, photographed and assembled again in the same sequence as in which they started and were finally returned to their proper box (Fig. 7). Each photograph was automatically checked for various variables like presence of the QR code, focus, etc. (Fig. 7). If a photograph was found to be incorrect, then the belt would move back automatically and re-photograph the faulty specimen. Collections that occupied more than one sheet were marked with colour tabs at the side, so they could later be linked together in the database. At the peak of the work, more than 30,000 specimens were photographed and moved to and from the herbarium! – a total of ca. 600 boxes per day.

The files with the digital images of the specimens, with the QR codes functioning as identifiers, were sent online to Suriname, where a team of 50 trained data typists recorded the names of the collectors, collector numbers and dates, identifications, and collecting localities (and, if present, coordinates of the place of collecting). The names on the major folders were also photographed and formed a test of the identification of the specimens stored in the folder (Fig. 7). The digitised data were returned to Leiden, where another team of ca. 10 (mainly part-time) persons checked the data files before they were added to the Brahms database.

Fig. 7. End of the belt where the specimens are gathered again, put in their folders and the folders in their box. To the right the large greyish-black box with the camera, from where the photographed specimens come out on the band. In the front (near the panic-button) a specimen box and a major folder for specimens. The major folder is photographed before the specimens in order to record the scientific name of the following specimens (this is used in Suriname data input), then follows photographs of the plant specimens themselves. In parallel with the specimens follow the opened specimen folders. In the middle a computer screen showing the photographed specimens (folder, first specimen, etc.). On this screen the checking process is displayed automatically, correct items light up in green above the photos. Photo by the firm Picturae, reproduced with permission.

All herbarium sheets, 3.5 million, are digitised now and their label data is available via the internet version of BRAHMS, BRAHMS Online (BOL; http://vstbol.leidenuniv.nl/). The digital images are also available, but unfortunately still only in low resolution (100 DPI). High resolution images (300 DPI) are available on demand.

The completed Naturalis database has tested the limits of what BRAHMS 7 can handle. Problems have to do with the FoxPro software, the database management software, which does not allow for much more data. Another problem is that the FoxPro software is no longer maintained by Microsoft. Presently, BRAHMS 8 is being developed based on Microsoft NET Framework. As default, V8 will use SQLite software [SQL = Structure Query Language], completely portable and requiring no special installation, but larger institutions may opt for systems like Microsoft SQL Server (MSSQL) or PostgreSQL. For a description of BRAHMS 8, see http://herbaria.plants.ox.ac.uk/bol/brahms/Software/v8. This new version of BRAHMS has the possibility to link the database to other data via Application Programming Interfaces (API's). For example, if one visits e-Flora Malesiana (http://portal.cybertaxonomy.org/flora-malesiana/), it becomes possible to create distribution maps on the fly by loading the coordinates of collecting localities from BRAHMS via an API. The major weak spot of BRAHMS remains the dependency on its few designers, mainly Denis Filer at Oxford. Naturalis Biodiversity Center is trying to create a consortium, which can provide support during development of BRAHMS and safeguard the continuation of BRAHMS once the present staff retires. Interested parties are welcome to join consortium.

Naturalis Biodiversity Center is more than just a museum with vast collections. It offers excellent opportunities for researchers not only to consult the specimens, but also to do this with the most modern equipment. Botanical visitors are very welcome and can announce their intended stay via botaniecollectie@naturalis.nl.

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# North-South Collaboration: Flora projects and training

Review of presentations and discussion by the chairperson of this session, Ghillean Tolmie Prance, Royal Botanic Gardens, Kew, Richmond, Surrey, UK.

This session of the symposium showed that North-South synergy has improved greatly since colonial days and is now generally very collaborative rather than just one-way North-South. This, in part, is because over the last forty years many researchers have contributed to education rather than just removing specimens from tropical countries to the North. View from the speakers from both regions showed good examples of collaboration today. Herbarium specimens no longer end up exclusively in herbaria of developed countries and examples were shown of good functional herbaria in Ecuador, Cameroon, Ethiopia, and Brazil and also of collaborative research and the resultant publications. Local taxonomists are now able to carry out much more work on the specimens in local herbaria, but continued effort is needed to repatriate data from the large herbaria of the developed world, especially images and data on type specimens.

Capacity building featured strongly in this session both in the presentations and the discussion that followed. The example of Norway presented by Nordal showed the many ways in which education is being taken to the less developed world by the researchers and government of that dedicated country. There is a place for training both in-country and by sending students overseas. In the subsequent discussion there was a consensus that short-term "sandwich" periods were most useful and that greater effort needs to be made to train students in their own countries. An example of this is the post-graduate courses in Manaus, Brazil, run by the Instituto Nacional de Pesquisas da Amazonia and the Universidade de Amazonas described in Prance (2017). The Consortium of European Taxonomic Facilities (CETAF) was mentioned several times and it was suggested that greater effort should be made in collaboration with countries of the South.

In the discussions the importance of starting education younger persons than students was repeatedly raised. There is a need for greater efforts with school education if there is to be a future generation of taxonomists and conservationists in an increasingly urban world.

The digitization of data has helped the synergy between the North and the South. The usefulness of GBIF, Tropicos, IPNI and other databases was mentioned several times by speakers from the developing world. There are now many data available, but the consensus was that still more needs to be done to make herbarium data readily available to researchers in developing areas.

The need to connect with politicians was discussed. The attention of scientists both in the North and the South is necessary for this, and each scientist must take his or her turn in their own country. To achieve conservation goals there needs to be more political action and the consensus at the symposium was that we as scientists have not been effective enough. We need to encourage North-South synergy for conservation amongst the politicians at both ends if there is to be a future for the species that we study.

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# North-South Collaboration in Writing Tropical Floras: The Flora of Thailand at a crossroads

*Mark Newman, Kongkanda Chayamarit and Henrik Balslev*

## Abstract

The Flora of Thailand project has revised about half the species in Thailand in 50 years, a relatively fast rate for a diverse, tropical flora. The reasons why this project has progressed faster than similar flora projects in other tropical areas include a strong component of international cooperation from the start of the project. Recent changes in the structure of the editorial board aim to speed up the revision of the remaining species. The speed at which a flora can be revised is closely linked to the number of expert botanists available. While modern technology has streamlined parts of the process of revision, nothing can substitute for detailed examination of thousands of herbarium specimens by trained botanists.

**Key Words:** conditions, international, rate, revision, risks

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The Flora of Thailand project aims to publish descriptions of all vascular plants native in Thailand, along with keys to their identification. Each plant family is revised by one or more specialists, who examine all relevant herbarium material, decide on the delimitation of taxa and ascertain the correct name for each one. Only when the *Flora of Thailand* is complete will the full baseline information exist that permits conservation of Thai plants for future generations. By now, half the flora has been revised and the end of the project is within sight but we can not simply continue to work as we have for this last half century. The world is changing rapidly and those who work on the *Flora of Thailand* must react accordingly. Which way will be best for the future of Thailand's biodiversity and its people?

## History of Botanical Exploration in Thailand

By the $19^{\text{th}}$ century, when most of the tropics had been colonised by European powers such as France, Great Britain, the Netherlands, Portugal, and Spain, the herbaria of these countries held huge collections of tropical plants. Thailand was never colonised so it has taken a different path towards the scientific discovery and description of its native flora.

The earliest botanical collections made in Thailand were those of J.G. Koenig (1728-1785) who was born in Courland, now part of Latvia, and belonged to the Baltic-German ruling class. After some time as a pupil of Linnaeus in Sweden, he lived in Denmark before joining the Danish trade mission in Tharangambadi (in Danish Tranquebar), Tamil Nadu. From here, he was sent to explore southeast Asia and made collections in Thailand in the 1770s, particularly at Junk Ceylon, which is an old name for Phuket. Many of Koenig's collections have been lost but some are still to be found in the herbarium of the Natural History Museum of Denmark, Copenhagen (C), the herbarium of the Linnean Society of London (LINN), the Natural History Museum of London (BM), the Botanische Staatssammlung München (M), the World Museum Liverpool (LIV), and the herbarium of the Botanical Museum, Lund University (LD) (Seidenfaden 1995).

Few herbarium collections were made in Thailand in the 19$^{th}$ century. Most of those that we have were collected late in the century around the borders of Thailand by Clovis Thorel (1833-1911) and François Jules Harmand (1845-1921) near the River Mekong and by Charles Curtis (1853-1928) on the west coast of the Thai peninsula, from Phangnga southwards.

The second significant Danish initiative in Thai botany was the Flora of Koh Chang compiled by J. Schmidt (1901-1916). Koh Chang is an island administered as part of Trat Province in the Gulf of Thailand near the Cambodian border. Its area is small and its flora is not representative of the country as a whole, but the types of a number of taxa came out of this work and are also at C.

One of the most prolific collectors of Thai plants was A.F.G. Kerr (1877-1942), a medical doctor who arrived in Thailand in 1902 and stayed for 30 years until his retirement (Jacobs 1962; Parnell *et al.* 2015). His collection number series runs to 24,409 with some gaps, and there are also some unnumbered collections making nearly 26,000 collections in all, the great majority of them from Thailand (Parnell *et al.* 2015). Kerr's own set of specimens is in the herbarium of the Natural History Museum, London (BM) while the Thai set is at the Bangkok Herbarium (BK). Other sets of duplicates, in order of size and importance, are at the Royal Botanic Gardens, Kew (K), the University of Aberdeen (ABD), Trinity College Dublin (TCD), Aarhus University (AAU), the Royal Botanic Garden Edinburgh (E), and the Naturalis Biodiversity Centre (L).

Another Dane was the next European to be inspired by the plants of Thailand. Gunnar Seidenfaden was Danish ambassador in Thailand from 1955 to 1959 and a keen and highly competent amateur orchid specialist with a prolific scientific output on southeast Asian orchids. With his help, the first Thai-Danish expedition was organised from 1958 to 1959: the Danish participants were Thorvald Sørensen, Kai Larsen and Bertel Hansen. Sørensen did not work further on Thai plants but, from this date onwards, Bertel Hansen and Kai Larsen devoted much of their careers to the Thai flora. Kai Larsen is probably the most prolific collector of Thai plants. The exact number has not yet been counted, but his number series runs to more than 42,000.

In 1965, a meeting of botanists was called at Kew to discuss the formal founding of the *Flora of Thailand*. Representatives of Thailand (Forest Herbarium, Bangkok), Japan (Kyoto University) and six European herbaria (Aarhus University, Botanical Museum, Copenhagen, Muséum national d'Histoire naturelle, Paris, Royal Botanic Garden Edinburgh, Royal Botanic Gardens, Kew, and the Rijksherbarium, Leiden) were present. This marks the beginning of the *Flora of Thailand* project which, from its very inception, has been a North-South collaboration.

Two Thai botanists present at the foundation of the *Flora of Thailand* project were Tem Smitinand (1920-1995) and Chamlong Phengklai (1934-). Within a few years they were joined by Thawatchai Santisuk (1944-). All three spent their careers working on this project, making many collections themselves and with others, and supporting younger Thai botanists through their training and early years of work. Botanists from many

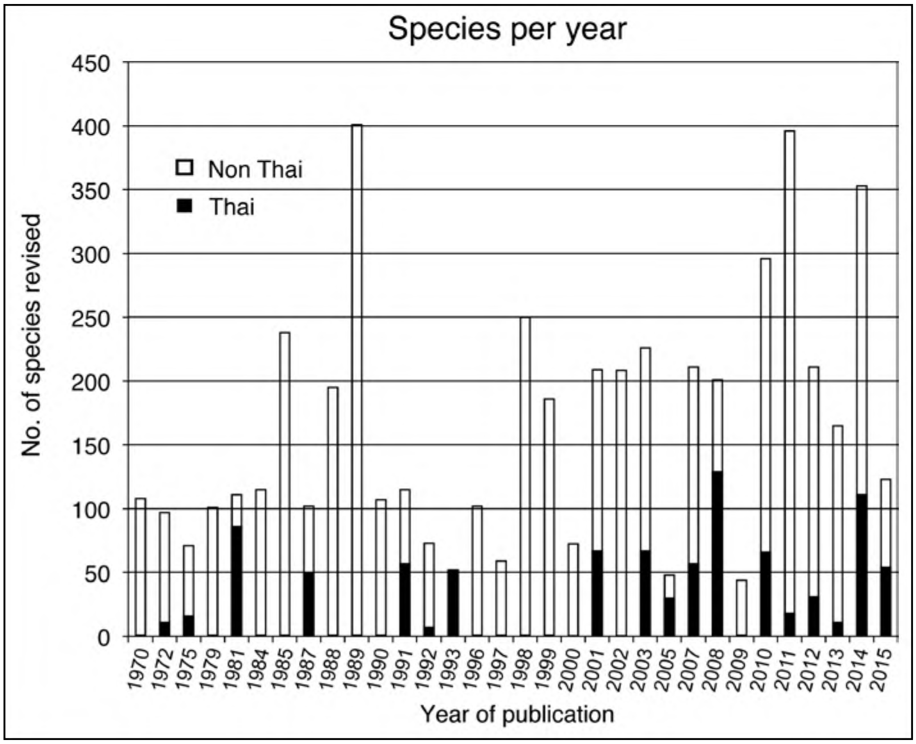



Fig. 1. The number of species accounts published each year in *Flora of Thailand*, showing the proportions revised by Thai and foreign experts.

countries have collected in Thailand so that the number of institutions actively working on the Flora has expanded since the early days and collection numbers have increased greatly. This level of international cooperation continues to this day.

## How does the Flora of Thailand work?

The number of species of vascular plants which occur naturally in Thailand is estimated at 10250–12500 (Middleton 2003). Roughly half have been revised in the *Flora of Thailand* or 104 species per year on average (Table 1, Fig. 1). While this may seem a slow rate of progress, it is faster than that of many other tropical floras.

The main goal of the *Flora of Thailand* is to describe the vascular plants of the country and give keys to their identification. The descriptions are brief, usually no more than 300 words to describe a species, and citation of synonyms is limited to those which are rele-

**Table 1.** Numbers of species revised and published in *Flora of Thailand*, compared to the total number expected. The row marked 'Finished Manuscrips' show the number of species revised but not yet published.

| | Families no. | Family % | Species no. | Species % |
|---|---|---|---|---|
| Published | 227 | 72 | 5536 | 51 |
| Finished manuscripts | 18 | 6 | 512 | 5 |
| Under revision | 69 | 22 | 4883 | 44 |
| Total | 314 | 100 | 10931 | 100 |

vant to Thailand. Obscure synonyms which may never be seen by Thai botanists are not given, especially in groups which have been revised in a more detailed format, such as *Flora Malesiana*. Specimen citation is kept to a minimum. Type specimens are only cited if they originate in Thailand and non-types are only mentioned in particular circumstances, for example, if a specimen is out of the usual range of morphology or distribution. The distribution in Thailand is given by floristic region and province, along with the global distribution by country. In addition, the ecological information relating to each species is critically compiled. Lastly, any uses and vernacular names in the languages of Thailand are recorded.

By working to a concise format like this, the *Flora of Thailand* has been able to proceed relatively quickly but it is also less exact in some ways. By contrast, the *Flore du Cambodge, du Laos et du Vietnam* cites types of all names and cites all the specimens studied. This forces the author of a revision to be more precise and to be sure about the application of names. It also allows curators in herbaria to curate their collections more easily.

One of the most important aims of the *Flora of Thailand* project is to increase the ability of Thai botanists to work at international standards so that Thailand can manage its own flora. This aim will be reached by Thai and foreign botanists working together so that, gradually, all attain the same standard. The revisions completed in the 1970s were almost entirely written by foreign botanists but the balance has tipped slowly towards Thai botanists (Fig. 1). In the last ten years, there has been only one year without a Thai contribution and the two most substantial Thai contributions have been made in this period. For the remaining part of the flora 46 families and 2591 species have been assigned to Thai authors and 47 families and 2914 species have been assigned to non-Thai authors. As a consequence the *Flora of Thailand* project has functioned as an exemplary North-South collaboration where the initial dominance by researchers from the north through extensive capacity building has slowly been substituted by a situation of almost parity in the contributions.

North-South collaboration works at two levels in the *Flora of Thailand* project. First, there are collaborating institutes which commit themselves to giving staff time to the project for long periods. While one or two institutes which collaborated at the beginning have had to withdraw, several more have joined in recent years.

## Institutions Collaborating in the Flora of Thailand

Sixteen institutions formally collaborate on the *Flora of Thailand* project (Table 2). Individual scientists undertake to revise families of plants for the *Flora of Thailand* but, in many cases, these individuals work in the collaborating institutes.

The funding of the *Flora of Thailand* also demonstrates North-South collaboration. Both in Thailand and the foreign collaborating institutes, governments maintain large herbaria and their staff. Since 1997, the Thai government has funded a great deal of training of taxonomists through the Biodiversity Research Thailand fund, something which has allowed a new generation of Thai botanists to be trained, many of them by spending periods abroad in the herbaria of the collaborating institutes. Likewise, the foreign institutes have accepted Thai and other nationals as students who have revised Thai plants as part of their training.

To summarise, the characteristics of the *Flora of Thailand* project are the following:

- it has been a North-South collaboration from the outset
- it is driven by practical goals
- it is supported by a number of institutes in terms of staff time
- financial support comes both from Thailand and from overseas, especially Denmark
- revisions of large families are frequently led by a co-ordinator

**Table 2.** Instiutions cooperating on the Flora of Thailand project. The participants in the founding meeting in 1965 are marked with asterisks.

| Institution | Herbarium code |
|---|---|
| Aarhus University, Denmark * | AAU |
| Bangkok Herbarium, Thailand | BK |
| Natural History Museum of Denmark, University of Copenhagen, Denmark* (withdrawn 2017) | C |
| Botanische Staatssammlung München, Germany | M |
| Chulalongkorn University, Thailand | BCU |
| Forest Herbarium Bangkok, Thailand* | BKF |
| Khon Kaen University, Thailand | KKU |
| Kyoto University, Japan* | KYO |
| Muséum national d'Histoire naturelle, Paris, France | P |
| Naturalis Biodiversity Centre (formerly Rijksherbarium), Leiden, the Netherlands* | L |
| Queen Sirikit Botanic Garden, Thailand | QBG |
| Royal Botanic Garden Edinburgh, UK* | E |
| Royal Botanic Gardens, Kew, UK* | K |
| Singapore Botanic Gardens, Singapore | SING |
| Botany Department, Trinity College Dublin, Republic of Ireland | TCD |
| National Museum of Nature and Science, Tsukuba, Japan | TNS |

## The Administrative Structure of the Project Until 2014

Two editors preside over the *Flora of Thailand* project, one Thai and one Danish (Table 3). Working for the editors are an assistant editor and a production editor. The assistant editor worked mainly on the scientific content of revisions and corrected the English, while the production editor oversaw typesetting, illustration, publication and distribution. The first *Flora of Thailand* meeting in 1965 has been mentioned above. Since then, the editorial board has met frequently, usually every three years, to discuss progress (Table 4). At first, the meetings were for board members only, but they soon evolved into open meetings where all aspects of Thai taxonomy were presented. The board would meet privately and report to a plenary session at the end of the meeting. *Flora of Thailand* meetings normally alternate between Thailand and Europe, and frequently attract more than 200 delegates. They are a valuable proving ground for young researchers wishing to present their work to an international audience.

At a *Flora of Thailand* board meeting, the status of

**Table 3.** Editors of the *Flora of Thailand*.

| | | |
|---|---|---|
| Editors [Editors-in-Chief] | Thai editors | Tem Smitinand (1965-1995) |
| | | Thawatchai Santisuk (1996-present) |
| | Danish editors | Kai Larsen (1965-2012) |
| | | Henrik Balslev (2014-present) |
| Assistant editors [Editors] | | Bertel Hansen (1970-1985) |
| | | Ivan Nielsen (1987-2007) |
| | | Mark Newman (2008-present) |
| | | Anders Barfod (2014-present) |
| | | Hans Joachim Esser (2015-present) |
| | | David Simpson (2016-present) |
| Production editors | | M.R. Sukshom Kashemsanta (1970-1972) |
| | | Tem Smitinand (1973-1993) |
| | | Thawatchai Santisuk (1993-1996) |
| | | Kongkanda Chayamarit (1997-present) |

each family revision is discussed and progress is noted. Many large families are revised by a team of botanists working with a coordinator. The coordinator is critical to rapid progress, catalysing the work and setting deadlines for completion of tasks. The use of coordinators is certainly among the reasons for efficient and timely production of published revisions in the *Flora of Thailand*.

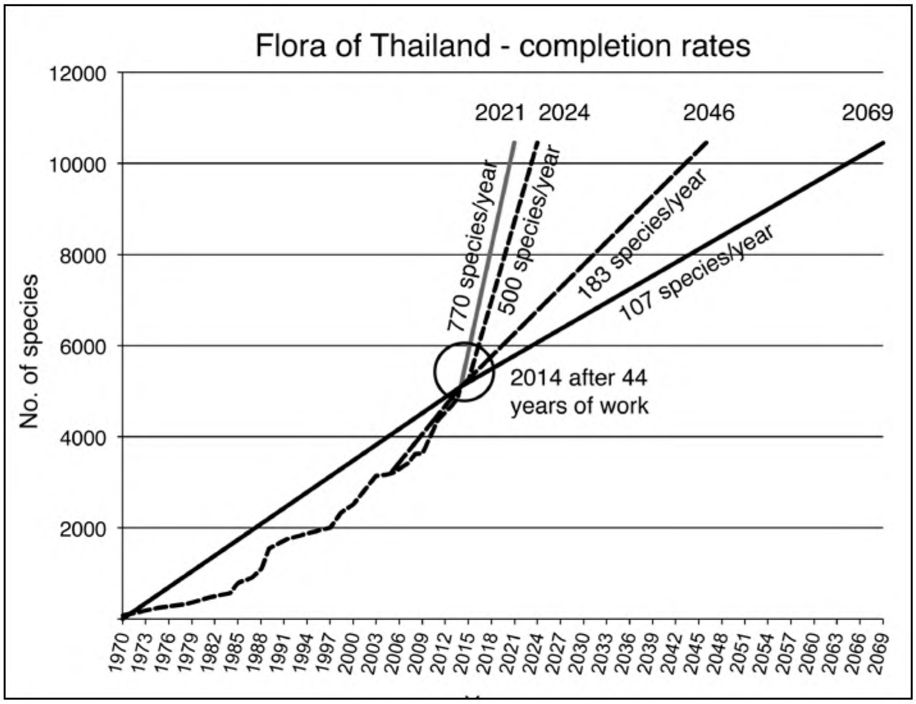
## The Flora of Thailand at a Crossroads

The editorial board of the *Flora of Thailand* met during the 16th *Flora of Thailand* meeting at the Royal Botanic Gardens, Kew in 2014 and discussed the speed of completion of the project. While progress has been relatively fast, it has not been fast enough to attract additional funding to allow the project to be completed. The choice facing the board, therefore, was to carry on as before or to accelerate the rate of revision of species. Since most funding bodies work in cycles of 3-5 years, it was felt that a target of seven years to completion might help to bring in additional funds. A number of completion dates were calculated according to various rates of progress (Fig. 2).

It was accepted by the editorial board that funding bodies would not consider supporting projects of very long duration so the two slower options were rejected. Every effort will be made to publish by 2024, though it is already clear that certain large, complex groups such as the Orchidaceae cannot be completed by then.

The structure of the editorial board was enhanced so that the two editors are now called editors-in-chief and the assistant editor is called editor. Three more editors were appointed in order to cope with the increased amount of editing, and added technical assistance is now based at Aarhus University. It was decided to meet annually, rather than every three years and the first of these annual meetings took place in Chiang Mai in August 2015.

Fig. 2. Recorded and projected rates of progress and estimated dates of completion of the *Flora of Thailand*, with different estimates of productivity.




## New Activities Following the 2014 Flora of Thailand Meeting in Kew

Following the 16th *Flora of Thailand* meeting at Kew in 2014 a relatively substantial grant of 15 million DKK (approx. 2 million €) was obtained from The Carlsberg Foundation to support the completion of the flora.

The budget allows for visits of Thai researchers to Danish or other relevant European herbaria for periods of 1-3 months duration. The granting of these visits is administered with a focus on those researchers who already have advanced manuscripts, and who need some 'quality time' to be able to finish their manuscripts. The Thai flora writers often find themselves engulfed in administrative and teaching obligations at their home institutions, and spending time away is usually advantageous in the situation where a concentrated effort is needed to complete a treatment. This scheme has been very successful and 21 Thai taxonomists have visited Aarhus University herbarium and some other European herbaria since the programme started. More visits are already planned, and this budget line will remain open for the next several years so more Thai botanists can take advantage of it.

The grant has also made it possible to fund several training courses in Thailand. The first series of courses has focused on the use of electronic media in the production of taxonomic work. Specifically courses in the use of the ScratchPad software have been held in Bangkok, Chiang Mai, Khon Kaen, and Ubon Ratchathani. Between 20 and 30 young taxonomists have participated in each of these courses and they have all created their own taxon specific pages, where they can present the results of their taxonomic work as it is under way to become final products in the *Flora of Thailand*.

The actual production of the printed volumes of *Flora of Thailand* is done at the Forest Herbarium in Bangkok, and has been funded by institutional support to the salaries of staff involved in the process, and also for the actual printing costs. With the ambition of publishing more species every year the annual cost increases, and that activity is therefore also supported by the grant, both for the printing and for some staff expenses.

**Table 4.** The year and location of each *Flora of Thailand* meeting.

| | Year | Location |
|---|---|---|
| 1st | 1965 | Kew |
| 2nd | 1967 | Leiden |
| 3rd | 1972 | Paris |
| 4th | 1975 | Aarhus |
| 5th | 1978 | Kyoto |
| 6th | 1984 | Edinburgh |
| 7th | 1988 | Chiang Mai |
| 8th | 1991 | Kew |
| 9th | 1994 | Aarhus |
| 10th | 1996 | Phuket |
| 11th | 1999 | Leiden |
| 12th | 2002 | Bangkok |
| 13th | 2005 | Dublin |
| 14th | 2008 | Copenhagen |
| 15th | 2011 | Chiang Mai |
| 16th | 2014 | Kew |
| 17th | 2017 | Krabi |

The coordination of the project is also supported by the grant for technical and other support staff at Aarhus. The budget includes a postdoctoral salary which was initially for work at Aarhus, but as things have progressed these funds are now being diverted to employ postdocs at the three large Thai herbaria (BKF, QBG, CMU) with the intention of making the large collections there more readily available to authors who work on the treatments of various families for the flora.

Finally the budget also allows for relevant fieldwork and travel related to the coordination of the project and participation in scientific meetings that are relevant to the *Flora of Thailand* project.

## Can the Flora of Thailand Serve as a Model for Other Flora Projects?

The fact that the *Flora of Thailand* is guided by an international editorial board and supported by herbaria in a number of countries has led to a relatively rapid speed of progress. Other revisions of tropical floras may be able to work faster by emulating the structure of the *Flora of Thailand*. One feature of the *Flora of Thailand* must be noted here, as it gives this work a significant advantage over some others. This is that the *Flora of Thailand* treats the plants of a single state. Attempts to revise the flora of multinational areas, such as the *Flore du Cambodge, du Laos et du Vietnam* and *Flora Malesiana* do not attract as high a level of support from the countries involved, perhaps because they do not clearly present the information needed by the participating nations.

Any country wishing to follow the example of the *Flora of Thailand* must make a number of commitments. The speed at which a flora can be revised is closely linked to the number of expert botanists available. While modern technology has streamlined parts of the process of revision, nothing can substitute for detailed examination of thousands of herbarium specimens by trained botanists.

On the part of the home country, there have to be students to be trained in taxonomy and revision of plants. This implies that there should be jobs to go to because students will not train in a subject which leaves them without the possibility of employment. There must also be strong government support to the institutes in which this work is carried out.

On the part of the foreign contributors, there must be a clear recognition that this is an important contribution to world science, and an adequate allocation of research time.

On both parts, there have to be taxonomists in employment who can undertake to complete revisions. Another factor which must be recognised is that revising plants for the *Flora of Thailand* does not result in publications that are measured using research metrics such as an impact factor. It is critical, therefore, that institutions which carry out taxonomic work measure the output of taxonomists fairly, taking into account their productivity even when it does not attract an impact factor.

## Thai Contribution to the Flora of Thailand

Throughout the *Flora of Thailand* project, the Thai government has given financial support to the Bangkok Forest Herbarium (BKF) which is the institute that publishes the flora. Originally part of the Royal Forest Department, it is now part of the Department of National Parks, Wildlife and Plant Conservation. The Thai government paid for the building in which BKF is now housed and has maintained staffing levels over a long period. In addition, the government's Biodiversity and Training Programme funded a number of studentships at MSc level aimed at producing the next generation of Thai botanists. These studentships were held at universities with strong interests in taxonomy, such as Chulalongkorn, Kasetsart, Khon Kaen, and Mahidol.

The Plant Genetic Conservation Project under the Royal Initiation of Her Royal Highness Princess Maha Chakri Sirindhorn (RSPG) also supports biodiversity research in Thailand, particularly at Queen Sirikit Botanic Garden and through the research carried out under the auspices of the Royal Society of Thailand, Academy of Science.

## Risks

The greatest risks to the successful completion of the *Flora of Thailand* are the same as those faced by every large floristic project. It is very widely accepted that it is necessary to have inventories of the biota of each country in the world (Plants2020 2015 – http://www.plants2020.net/ – accessed 9 November 2015). The Global Strategy for Plant Conservation has as its very first 2020 target, 'An online Flora of all known plants' but the means of achieving this target have not been put in place. The Taxonomic Impediment is the term for the world-wide shortage of important taxonomic information, gaps in our taxonomic knowledge, and shortage of trained taxonomists and curators (CBD Secretariat 2015 – https://www.cbd.int/gti/problem.shtml – accessed 16 Nov. 2015). Efforts have been made to address these problems but the results are mixed. In particular, there is much debate as to whether the science of taxonomy is productive enough to meet the world's needs or not. While authors such as Bebber *et al.* (2014) think taxonomy is stagnant at a time of great need, others such as Costello *et al.* (2012, 2013a,b) believe that taxonomic output is increasing. In Thailand, there are certainly more people studying taxonomy than there were at the beginning of the *Flora of Thailand* project but there are still not enough of them to write a complete floristic account in a reasonable time, relative to the disappearance of natural vegetation. Furthermore, Thailand still relies heavily on input from European taxonomists and it is precisely in Europe that the number of active taxonomists is falling very fast. The Natural Environment Research Council of the United Kingdom investigated the numbers of taxonomists in employment and found, among other things, that taxonomy has declined very steeply in the university sector and that succession-planning is a significant cause for concern (Boxshall & Self 2011 – http://www.nerc.ac.uk/research/funded/programmes/taxonomy/uk-review/).

## Consequences

One may well ask whether there is much to be lost by not finishing the *Flora of Thailand* soon. The underlying question is whether Thailand has the professional capacity to manage its flora in ways which have been laid down in international agreements. Thailand ratified the Convention on Biological Diversity in 2003 and became a party in early 2004, committing itself to the conservation of its flora for future generations. If the plants are to be conserved, they must first be known and this is where the *Flora of Thailand* comes in. The complete Flora will be Thailand's most comprehensive list of vascular plants, their names, descriptions, distributions and overall habitat requirements. Without such a vital baseline, many species may be lost unwittingly.

This is recognised in Thailand's Fifth Report on the National Biodiversity Strategy and Action Plan (https://www.cbd.int/doc/world/th/th-nr-05-en.pdf) which includes a target to increase the number of taxonomists employed by agencies involved in biodiversity work and the establishment of a national taxonomic institution to complete the *Flora of Thailand* project. The other half of the equation, the contribution made by foreign botanists, is less certain. The various programmes of the Convention on Biological Diversity give little weight to the idea that certain rich countries with relatively poor biodiversity may need to help poorer countries with very rich biodiversity. European countries focus very much on their own problems which include the spread of alien species, the introduction of new diseases, and food security, and give scant attention to the needs of tropical countries where the greatest number of extinctions is likely to occur in the coming decades and centuries.

## Conclusion

The *Flora of Thailand* is an excellent example of North-South collaboration which has resulted in relatively rapid revision of half the vascular plant flora of a diverse, tropical country. Its composition, with an international editorial board from the outset and a high degree of commitment from Thai and foreign participants, is a model that other tropical countries may follow. The editorial board has recently made strenuous efforts to increase the speed of work with the aim of completing the Flora by 2024.

## Acknowledgement

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# Training in the North of Researchers from the South: Experiences from Nordic-African collaboration

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## Abstract

Norwegian universities have trained students and other scholars from the South within fields related to African plant diversity through the last decades. The activities were funded by NUFU, the Norwegian Council of Universities Committee for Development Research and Education, and 30 students successfully obtained PhD degrees in taxonomy and other biodiversity related fields, and all but a few have entered into scientific position at universities or other relevant research institutes in Africa. Most collaboration involved Zimbabwe, Malawi, Ethiopia, and Kenya, and though successful, they all faced the challenges of multi-institutional and multi-cultural teaching and research collaboration. Basic research within botanical diversity is better taken care of when the university councils own and administer the projects, compared to the alternative ownership by aid agencies.

**Key Words:** botanical diversity, university education, sandwich model

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In this paper we present experiences from mainly Norwegian collaboration with African universities through the last 30 years, within the field of African plant diversity (including ecology, ethnobotany, medicinal plants, mycology, phylogeny, plant geography, and taxonomy). In the programme for this symposium (Organising committee 2015), the 5$^{th}$ Session, "The North-South synergy", was presented with these words:

> 'In recent time the relationship between North and South with respect to maintaining tropical plant collections has changed. Initially institutions from the North were dominating, but influence from the South has been continuously increasing – changing roles fostered by mutual interests and complementary possibilities with regard to access to technology and resources. This session explores options for developing further North-South synergies centered on the use of tropical plant collections'.

We will show that this synergy is particularly strong when it comes to education and joint supervision, teachers from the North and the South co-supervising MSc and PhD students, mainly from South, but also from North. Students from an early phase, often have become collaborators/co-supervisors later on.

## Olov Hedberg: A Nordic pioneer in training researchers from the South

In Scandinavia, the training of African botanists largely began with the late professor Olov Hedberg, who was an enthusiast, a driving force and a great source of inspiration when it came to training in the North of researchers from the South (Fig. 1A). He was in particular a stimulating supervisor, always involving his students with optimistic encouragement. When he started a postgraduate course at Uppsala University in 1960, focusing on one of the most fascinating plants of the East African mountains, *Canarina* L., it was an innovation in the teaching of taxonomy. His program was 'learning by doing'. He supplied the students with plant material from all relevant herbaria, sometimes also providing living material, and taught them how to make observations, to look for literature, use the modern taxonomic methods of that time and draw conclusions. Through teamwork, he trained the future taxonomists in relevant methods in taxonomy, morphometry, cytology, palynology, plant geography, etc. In 1966 he, together with his wife Inga Hedberg, organized the 6th plenary meeting of AETFAT (Association pour l'Étude Taxonomique de la Flore d'Afrique Tropicale) in Uppsala entitled *Conservation of vegetation in Africa South of the Sahara*. The proceedings of this conference were published under the same titel (Hedberg & Hedberg 1968). In 1969 he invited students to participate in an intensive year-long PhD course, specializing in tropical African taxonomy or ecology. In the taxonomy group there were three students: Ib Friis from the University of Copenhagen, Inger Nordal from the University of Oslo, and Mats Thulin from University of Uppsala, all three obtaining their PhD degrees in Uppsala during the 1970ies on African Urticaceae, Amaryllidaceae and Campanulaceae, respectively. Later, the three obtained professorships at their respective home universities, and have since themselves been active in supervising African students. Hedberg and his three early Nordic taxonomy students have through the years altogether supervised 38 students (of which 24 African) to PhD degree in projects related to African biodiversity (Nordal 2011).

One of the Hedbergs' most successful initiatives was the Ethiopian Flora Project. Inga Hedberg, who herself has played an important role in this project, wrote (Hedberg, I. 2011)

Fig. 1. Examples of training in North of researchers from South. **A.** Olov Hedberg with his plant press outside his tent in Ethiopia in November 1982. He was then leading an expedition aiming to collect as many specimens as possible for the benefit of the future *Flora of Ethiopia* (which was finished in 2011). **B.** Ezekeil Kwembeya and Brita Stedje outside his new institution, the National Botanical Research Institution, Namibia, in 2006. Kwembeya, originally from Zimbabwe defended his PhD on 'The genus *Crinum* (Amaryllidaceae) – its taxonomy, phylogeny and conservation in Southern Tropical Africa' at the University of Oslo in 2006. **C.** Elizabeth Mwafongo from Malawi, studying Hyacinthaceae in the herbarium at the Royal Botanic Gardens, Kew, in 2007. She defended her PhD on 'Studies of *Albuca* and *Ledebouria* (Hyacinthaceae) in the *Flora Zambesiaca* area; aspects of systematics, ecophysiology and ethnobotany' at the University of Oslo in 2009. **D.** Pressing plants by the camp fire in Zambia in 2002. From left Ezekeil Kwembeya, Jamestone Kamwendo, Brita Stedje and Gladys Msekandiana. Jamestone and Gladys were Malawian MSc students. **E.** Mary Namaganda and Charlotte Sletten Bjorå working in the Makerere herbarium, Kampala, in 2012, in connection with a visit to discuss a NORHED application. Namaganda defended her PhD on 'A taxonomic review of the genus *Festuca* in Uganda: AFLP fingerprinting, chromosome numbers, morphology and anatomy' at the Norwegian University of Lifescences in 2007. **F.** Students from The University of Zimbabwe attending a course in 'Modern Methods in Plant Taxonomy' given by Inger Nordal in January 1988. Of the students, Shakkie Kativu (to the right) and Clemence Zimudzi (standing as number four from the right) were selected from UZ as candidates for NUFU stipends. In 1994, they defended PhD theses on taxonomic and evolutionary studies on Anthericaceae and Hypoxidaceae, respectively.


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> 'After many years of fund hunting, the Ethiopian Flora Project was launched July 1st 1980, financially supported by SAREC (Swedish Agency for Research Cooperation with Developing countries ) later SIDA (Swedish International Development Cooperation Agency) and the Ethiopian Science and Technology Agency. Though, per se, a Flora covering Ethiopia and Eritrea, was badly needed, the training of Ethiopian botanists for the project and for the future would also be an urgent task ...'.

Sponsored, promoted or associated with the Flora project were 10 Ethiopian PhD candidates, who all have obtained permanent positions at Universities, at the moment eight of them in African universities (Sebsebe Demissew 2011). For the completion of the Ethiopian Flora Project, the following of Olov Hedberg's students have been particularly important and contributed considerably: Mesfin Tadesse (PhD on Asteraceae 1984), Sebsebe Demissew (PhD on Celastraceae 1985) and Ensermu Kelbessa (PhD on Acanthaceae 1990). They, again, have supervised students at all levels on topics related to biodiversity in Africa, a further example of scientific proliferation (Fig. 1). The proliferation of the Ethiopian Flora project has been described by Sebsebe Demissew *et al.* (2011).

## Student Initiative in Norway to Strengthen North-South Links in the 1970s

After the '1968 student uproar', and possibly as a by-product of this event, an increasing awareness of North-South University relations arose and gained momentum during the following years. At the University of Oslo (UiO) this lead to the establishment of the Council of International Developmental Studies (Rådet for internasjonale utviklingsstudier), which initiated the first attempts to organize teaching and supervising within the frame of North-South activities. The ideas behind the establishment of this council came from an interdisciplinary group of students, who asked for a more intentional and dedicated engagement from the Univerity of Oslo on North-South relations. After years of disputes the Council was established by the University Board in Oslo in 1977. It soon became a tool for North-South university cooperation. Obviously, a geographical focus in the South was needed, and from the start there were four main candidates for collaboration: The universities of Botswana, Mali, Sri Lanka, and Zimbabwe. The collaboration between the University of Oslo and the University of Zimbabwe (UZ) was the first to be established. After the initial 'bottom up' initiative, the discussions on collaboration were soon conducted on the top level between the two universities. However, this collaboration was not supported on all levels. At the Faculty of Mathematics and Natural Sciences at the University of Oslo several faculty members did not approve of the initiative, claiming this was not science, but ideology – and that it should therefore not be a part of the strategic program of the university.

## The Collaboration between University of Zimbabwe and University of Oslo

As a consequence of the student initiative in the 1970s, there were reciprocal visits between the University of Zimbabwe and University of Oslo on the level of Vice-Chancellor or Rector. This took place during the first half of the 1980s and was followed by visits both ways by scientists to find research areas of mutual interest. The establishment of a program of formal collaboration became a time-consuming, but instructive and stimulating process, where research groups from both sides gradually established closer contact. The two universities agreed on specific projects of collaboration, and jointly applied for funding from the Norwegian Ministry of Foreign Aid (Departementet for Utviklingshjelp, DUH). The process of getting funding was complicated and took more time than expected. The Ministry of Foreign Aid wished that Zimbabwe should prioritize research collaboration within the bilateral aid program (Country Program) with Zimbabwe, which would have meant competition with e.g. projects in poverty aleviation and health promotion. From the Zimbabwean side this was not regarded as desirable. The process ended up with funds from the Ministry being earmarked for research collaboration, and in 1985 the first pilot projects were established. Two years later, a three year agreement of collaboration (1987-1989) between the two universities and the Norwegian Ministry of Foreign Aid was signed. The emphasis was on: Staff development (allowing Zimbabwean staff members to acquire MSc- and PhD-degrees), joint research projects, support for participation in meetings and teacher-exchange. Projects launched in the first period were within the fields of economics, sociology, law (particularly law relating to women), education (particularly distant teaching), nutrition, pharmacy - and botany and biodiversity (Mohamedbhai *et al.* 1998). The botanical projects approved were 'Plant taxonomy - Integrated Project' by J.M. Gopo and Inger Nordal and 'Macrofungi of Zimbabwe - Integrated Project' by J.M. Gopo and Leif Ryvarden. Professor Gopo, a geneticist, facilitated the collaboration, although his field of expertise was different, because there were simply no trained plant taxonomist at the University of Zimbabwe (UZ) at that time. Nordal and Ryvarden spent January 1988 at the University of Zimbabwe and gave intensive courses within modern methods in taxonomy of plants and fungi, respectively (Fig. 1F). When these courses were finished, the University of Zimbabwe elected two candidates from each field (botany/mycology) for further training.

## The NUFU Period in North-South Collaboration

NUFU is the Norwegian acronym for 'Norwegian Council of Universities Committee for Development Research and Education'. It was established by the Norwegian Council of Universities in 1986, who established SIU (Norwegian acronym for the Norwegian Centre for International Cooperation in Education) to handle programs and general policy. This happened almost simultaneously with the establishment of the collaboration between the Univesrity of Zimbabwe and the University of Oslo described above. Five years after the establishment of SIU, in 1991, the Royal Norwegian Ministry of Foreign Affairs and the Council signed the NUFU agreement. The main objective was to fund long term cooperation between universities in developing countries and universities in Norway for the purpose of capacity and competence building at university institutions in the South. For the period 1991-1995, the NUFU program had a total budget of about 27 million US$, for the period 1996-2000 this had grown to about 30 million US$, increasing in the last period (2007-2012) to about 57 million US$. Most of the NUFU projects were in collaboration with African universities in Ethiopia, Mali, Sudan, Tanzania, Uganda, Zimbabwe, Botswana, Namibia, Cameroon, and Ghana.

NUFU has been regarded as Norway's flagship program for development in research and higher education. What is possibly unique about the NUFU-concept in an international context is that the activities were based on mutual interest between researchers in the North and researchers in the South, allowing them to carry out research activities within the frame of institutional cooperation. The basic principles have been equality and transparency in partnership, and equal ownership shared between the North and the South partners. The final report of NUFU states: 'The NUFU Program has a recognized brand and is well known for its accomplishments in PhD education and research collaboration' (SIU 2013). With regard to NUFU-projects within plant diversity in the wide sense, 30 successful PhD candidates have obtained their degree, and with very few exceptions the candidates now fill relevant positions at African universities or research institutions. Most candidates are from Ethiopia, Uganda and Mali (Fig. 2).

The last president of NUFU, Thorkild Tylleskär summarized the NUFU Program in the following way (SIU 2013):

> 'The focus has been on international research and training collaboration with low and middle-income countries, and for many universities in Africa and Asia the program has been nothing less than a door-opener to the world of international collaboration both in research and in higher education. Many of these universities are now equipped with a basic understanding of both how to initiate and to conduct international research collaborations and of how to apply for grants. What we see now is that these early adopters of the

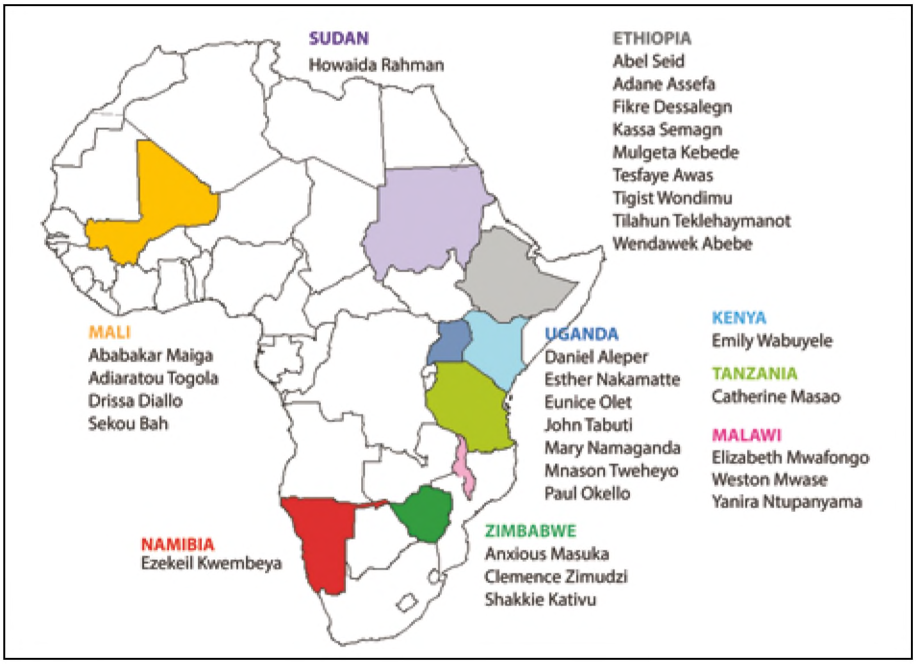


Fig. 2. A map showing the distribution of successful PhD candidates with project related to biodiversity of African plants. All, but a very few, have relevant positions within their home university or other African universities today.

> NUFU Program are becoming leading institutions in their home countries, guiding other, younger universities into the international community of universities and other institutions of higher education'.

Born in Denmark and a Swedish citizen, Tylleskär came to the University of Bergen in 2000 and could look at NUFU from the outside. He reported that over the years he had heard so many academicians from the South testify to what their NUFU collaboration has meant for them: it had been a series of positive surprises! The first surprise for the researchers from the South was to sit down and sincerely discuss how to go about a project and plan all the details, including the budget in the North. This was distinctly different from receiving 'orders' from the North about how to run the project. This type of local ownership has been a real game-changer for the institutions involved, not least those in the South. The second surprise was the NUFU Program's strong emphasis on capacity development. So many research projects in low and middle-income countries have focused on research, leaving the local partners behind when the foreigners moved on to obtain PhD degrees in the North, based on the research they had carried out together with scientists in the South. This inclusiveness was greatly appreciated, and it has also meant that the institutions in the South, in a sustainable way, were able to perform at a higher level than before. The third surprise came when researchers from the South visited the Norwegian institutions and witnessed the un-hierarchical interaction between professors and their students, in stark contrast to what many had experienced at their home universities. The forth surprise was the NUFU Program's strong emphasis on gender equity. After 20 years, it is easy to see the results: the proportion of female candidates at all levels has been considerably higher than in other comparable programs. This aspect has become increasingly appreciated and has contributed to a similar development in general in the countries concerned. The proportion of female graduates within the NUFU collaboration is 46 per cent at PhD level and 37 per cent at MSc level.

The benefit for Norway and Norwegian institutions has certainly also been substantial. Norwegian institutions of higher education now have first-hand contact with a range of institutions in the South. This is important for the understanding of global issues at

Norwegian universities, for setting goals and targets, and also for communicating the issues to the Norwegian society at large.

### *Case study 1: Zimbabwe and Malawi*

Shakkie Kativu and Clemence Zimudzi were among the first NUFU students in the period 1991-1995. They were selected by the University of Zimbabwe (UZ) after the above mentioned course in plant taxonomy given at UZ in 1988 (Fig. 1F). At that time, they had just passed their bachelor's degree (with honors). In a Scandinavian setting, it would have been natural to go via a master degree before entering a PhD program. The first lesson for their Norwegian supervisors was that the MSc level, so obvious for the Scandinavian students, might be a blind alley for an African student aiming for a PhD, and consequently suitable PhD projects were organised for both. The so-called 'sandwich model', with alternating periods in Zimbabwe and in Oslo, was used. In 1994 they both defended their theses at the University of Zimbabwe, and by this they started a new era of systematic botany in Zimbabwe, being the first 'non-colonial' botanists with permanent positions at the university. This first step later built the foundation for further collaboration and further training of African students by co-supervision. Both Kativu and Zimudzi are contributors to the *Flora Zambesiaca* (Amaryllidaceae, Anthericaceae, Hyacinthaceae, Hypoxidaceae). The *Flora Zambesiaca* covers the countries Malawi, Zambia, Zimbabwe, the Kaprivi strip of Namibia, Mozambique, and Botswana. Very few African botanists were then and in the following year found among the authors.

In 1994 there were 29 scientists on the staff of the Department of Biosciences at the University of Zimbabwe, during the following years of political unrest, the staff was for a period reduced to two, of which Kativu was one. Zimudzi went abroad for a period, but is now back. Despite a difficult political situation, we managed to run two successive NUFU projects during the years 1996-2000 and 2002-2007, including research collaboration and supervision of master and PhD students. The first project was entitled '*Flora Zambesiaca*: Systematic studies within petaloid monocotyledons and grasses' and the second 'Biodiversity of Southern Africa (Monocotyledonous plants) - Taxonomy, conservation and use'. In the last period the National Herbarium and Botanical Gardens, Zomba, Malawi were included as partners. Coordinators for the two mentioned periods were Brita Stedje from the University of Oslo and Shakkie Kativu from the University of Zimbabwe. Also Malawi lacked trained local botanists, and through the extended collaboration between the University of Zimbabwe and the University of Oslo Malawian students were included (Fig. 1C, D). This South-South collaboration between universities in Harare and Zomba, which was included in the NUFU projects, has raised the competence in botanical taxonomy in the region. One of the Zimbabwean candidates, Ezekeil Kwembeya, obtained the position as curator of the National Herbarium of Namibia (Fig. 1B), after he had defended his thesis at the University of Oslo, thus providing another example of scientific proliferation in the region.

### *Case study 2: Ethiopia and Kenya*

In contrast to the situation in Zimbabwe and Malawi, the botanical institutions in Addis Ababa and Nairobi had a long history of research by African botanists and were more established than their sister institutions in Harare and Zomba. Both in Ethiopia and in Kenya there were already local botanists with a PhD degree in research positions at the universities and herbaria. However, the main aims for the NUFU project proposals were the same: to strengthen the institutions in the South through research collaboration and training of students. The formal collaboration started in 1996 with the project 'Biosystematic and Genetics in the Ethiopian Petaloid Monocots (Lilies) and the genus *Eragrostis*', a project which ended in 2001. The project of the second period (2003-2007) was 'Biodiversity of Eastern Africa (Lilies, Orchids and Sedges) - Taxonomy, Conservation and Use'. In both periods the coordinators were Sebsebe Demissew, University of Addis Ababa, and Inger Nordal, University of Oslo. In the second period, the project included Kenya with Muthama Muasya as a coordinator, representing the National Museums of Kenya.

The general objectives of the NUFU project, formulated for the second period in this case study, might be considered representative for the NUFU concept when it comes to research and collaboration on biodiversity: (1) to contribute to the understanding of biodiversity in eastern Africa, a necessary prerequisite for the fulfilling of Ethiopia's and Kenya's obligations under the Convention on Biological Diversity (CBD, RIO 1992); (2) to sort out the taxonomy of complicated plant groups in order to define species delimitation, to define useful entities necessary to the understanding of biodiversity; (3) to identify evolutionary hot spots in eastern Africa, that will assist in decision making on issues related to conservation and management of the biodiversity; (4) to support the 17$^{th}$ meeting of the 'Association pour l'Étude Taxonomique de la Flore d'Afrique Tropicale' (AETFAT) to be held at the Addis Ababa University in September 2003; (5) to maintain and strengthen the the herbaria in Addis Ababa (ETH) and in Nairobi (EA) that house plant resources of eastern Africa (6) to upgrade the laboratories and computing facilities at the involved universities in the South.

## Multi-institutional and Multi-cultural Challenges

Collaboration on research projects of mutual interest can in a wonderful way wipe out differences in cultural backgrounds, age, status, and gender. Our main challenges have rarely been related to issues between persons, but have often been related to rigid systems and bureaucracy. One problem was because of differences in the support given from institutions in the South. Other problems that came out in our institutions in the North was that they have not always been as supportive as one could wish, and supervisors in the North have had problems getting a fair credit for the work done, particularly when the students have undertaken their final examinations or defended their theses in the South. The principle followed by NUFU has been that whenever feasible, the Ph.D. candidate should defend their theses at their home university. In the transition between the colonial and post-colonial periods we have encountered extra challenges with resistance from the established faculty in the South, themselves with lower formal education, against approving degrees of young, successful local candidates with degrees from the North.

Differences in traditions and codes of conduct may sometimes complicate collaboration and may cause unintended reactions. Openness about such issues may simplify the communication, or may at least help unraveling misunderstanding. Students from the South do not only meet scientific challenges when coming to the North. Extra time to settle down and time to adapt to the new society should be allowed. Leaving family, particularly children, behind may cause homesickness and severe worries about the family's well-being. For some students this may become such an issue that their ability to concentrate on the scientific work is reduced. In special cases the only way to solve this should be to grant an extra trip home. When receiving students from the South, supervisors will have both the challenge and the privilege to act as a caregiver when the situation requires, and this to a larger extent than what is needed for local students.

The long, dark winters, and generally the climate in the North, may also be a challenge for a student from the South. This particular problem might be reduced if the 'sandwich model' is applied. With the sandwich model, where students divide their time more or less equally between North and South, the problems of long stays abroad become less straining. It is not only a good way for students to keep in closer contact with their families, but it does also make it easier for them to keep connected with their home institutions and local supervisors. For our botany students from the South it has been particularly convenient to mainly be in Norway during the summer months of the North, doing laboratory work, coursework and getting supervision, combined with going home during the dark, Norwegian winter months, which often coincide with the fieldwork season in the South. Even if some of our students from South have experienced homesickness and problems adapting to dark and cold winter months, most regards the stay in Norway as an exotic experience. Many students have also expressed great pleasure in experiencing our society in general. The tax-system, health care and education in Norway is quite differently organized than in most of the countries where the students comes from. This part of the education is mostly neglected when one is counting numbers of degrees achieved, etc., but may represent quite an important part of the general education.

## Other Financial Norwegian Sources for Students in the South

Under the Norwegian Quota Scholarship Scheme the Norwegian government provides students from developing countries with financial support to study for an MSc or PhD degree in Norway. The main objective of the Quota scheme is to contribute to capacity building through education that will benefit the home country of the students, when they return. The scheme is also intended to strengthen relations between Norway and the selected countries and thus contribute to internationalization of Norwegian institutions of higher education (although – in contrast to NUFU – there is no formal agreements at the university level North-South). Most universities and university colleges in Norway participate in the Quota scheme. The institutions involved are allocated a certain number of students under the program each year. The Norwegian State Educational Loan Fund is responsible for managing the financial support provided for the Quota students. The students from the South receive, as any Norwegian student, 75% loan and 25% stipend, the loan being transferred to stipend when they finish and return to their home country. This program is currently under evaluation and its continuation is uncertain.

The NOMA program (NORAD's program for Master Studies) started in 2006, building on a previous Fellowship Program (1962–2005) by NORAD, the Norwegian Agency for Development Cooperation. Students from Africa, Asia and Latin America were offered opportunities for higher education relevant for their home countries. The program has provided diploma courses as well as two years MSc degree programs at Norwegian higher education institutions. Since 1962 nearly 6000 NORAD fellows have graduated with a diploma or an MSc degree from Norway.

## The End of NUFU and NOMA, the Start of NORHED

The NUFU Program was subjected to an external evaluation in 2009. The evaluation report, which was presented in February 2010 (SIU 2013), concluded that the contribution by the NUFU and the NOMA programs to capacity building in research and higher education had been significant, and that this was both widely recognized and highly valued. At the same time, the report presented a number of recommendations for improvements in program design, management and administration. Partly based on the evaluation report, the Norwegian Ministry of Foreign Affairs and NORAD developed the Norwegian Program for Capacity Development in Higher Education and Research for development (NORHED), which was implemented from 2013 and replaced the NUFU and NOMA program.

Thorkild Tylleskär, chair of the Program board for NUFU and NOMA summarized (SIU 2013):

> 'The NUFU Program is now coming to an end, but the positive impact of the NUFU Program projects into the future. In the near future this means the completion of more PhDs, more publications, etc. In the longer term it means stronger universities better equipped to serve their nations and populations in their future development. We say thank you to NUFU and welcome to its successor NORHED!'

In brief, NORHED aims to increase academic capacities in Low and Middle Income Countries (LMIC). All the NUFU ideals were in principle transferred to NORHED: A long term perspective, based on mutual South-North partnerships and institutional commitment and involvement, and programs should be

South demand-driven, with thematic and/or geographic focus. However, the program is no longer administrated by the Norwegian University Council (via SIU), but by NORAD. The experience, so far, when applying for funds under NORHED, has been that the focus are more on institutional collaboration and less on a researcher to researcher relationship. Institutional commitment is certainly imperative, but the value of personal involvement and close, good relationships between research partners should not be underestimated. When unforeseen problems suddenly arise the success or failure of a project will depend on the quality of such relations. In the NORHED framework, there is a limit on the number of project, and the budget of each project should amount to about 2 million US$. The financial frame of any NORHED project is in general considerably larger than the frames for projects under its predecessor, NUFU. We realize that big projects may be powerful, but we also have the experience that smaller projects can work very well, be very cost efficient and build strong foundations for bigger projects later on. Big projects may also require much administration, which may totally or in part rest on the shoulders of the researchers involved and may thus steal valuable time from potential research. We would advise that at least a fraction of funds should be allocated to smaller projects. Under NORHED, the basic research components of the projects seem to us to be given less importance, and the demand for 'applied research' is particularly emphasized, logical enough for a program owned and administered by an aid agency.

We have experienced that the application procedure introduced with NORHED is more restricting than under NUFU. It has been widely felt that it might be more important to fit a previously fixed application format than to develop and formulate interesting research questions. In the NORHED application form, the available space for describing the scientific project is very restricted, implying that science was not the most important aspect, as it could scarcely be properly evaluated based on the limited description allowed. In an actual case (an application related to botanical biodiversity) one of the shortcomings mentioned in the evaluation was that that the project was weak when it came to the possible application in society of practical results in practice. This was a surprise, as a main part of the project was to strengthen and modernize the local herbaria. The quality of the research seemed to be of less importance to the evaluators than the consequence for the local society in the low and middle-income countries (LMIC).

About 50 projects were approved in the first cycle of NORHED, which began in 2012. Of these, 12 were allocated to the theme 'Natural resource management, climate change and environment'. All of them were applied and related to agriculture, aquaculture, natural resource economics, sustainable livelihood, and plant diseases. No project had reference to basic research of biodiversity.

## Conclusions

(1) It is mainly when the universities in the North and the South, directly or indirectly, are the 'owners' of programs or projects, that the importance of basic research is fully appreciated.
(2) When aid agencies (as e.g. NORAD) come into ownership and leadership, the focus changes, and the importance of basic research on biodiversity is reduced compared to what is seen as the 'needs of the society'.
(3) It is important for the future success of 'Training in North of researchers in South' that they are based on formal agreements at the top levels of the involved universities. But it is just as important that the projects should be rooted in the community of dedicated researchers from both sides.
(4) The 'sandwich model' seems to be the best model, meaning that the scholars and students from the South are allocated their time for study and research equally shared between residence in the North and the South.
(5) Project allocation should not always be reserved the big project (sometimes even inflated to fit the donor organization). It is also important to include smaller pioneer projects, sometimes 'small is beautiful'.

(6) What started out as 'Training in the North of researchers in the South' in the 1970ies, gradually changed to collaboration between equal partners with knowledge transitions floating both ways.

(7) When researchers from the North and the South are collaborating, it will almost necessarily create a synergy effect, to the benefit of the researchers – and to the knowledge of biodiversity in the world!

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# Danish-Ecuadorian Collaboration in Botany as an example of North-South mutualism

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## Abstract

The Danish-Ecuadorian collaboration in botany started as a coincidence when two undergraduate students from Aarhus University travelled to Ecuador on an adventure trip in 1968. Subsequently these two students became staff at Aarhus University and the collaboration changed into a formal inter-institutional collaboration with the private Pontifica Universidad Católica del Ecuador (PUCE) in Quito. It culminated with a twelve year (1990-2002) Danida-supported program for enhancement of research capacity at PUCE during which the initially 1000-specimen herbarium grew to a 200,000-specimen herbarium, and the completion of 45 Ecuadorian first-degree theses at PUCE and eight Ecuadorian PhDs and five MSc trained at Aarhus University. Following the Danida funded period, collaboration between PUCE and Aarhus University has continued through several research projects with funding raised by Ecuadorian as well as Danish partners.

**Key Words:** building herbaria, first degree training, MSc training, PhD training, research capacity building

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Ecuador is a megadiverse country with 19,000 species of vascular plants in a great variety of vegetation types, from semi-desert to rainforest, and distributed from sea level to more than 5000 m elevation. This richness has been an inspiration for the botanists from Aarhus University for nearly 50 years. Sharing this interest with Ecuadorian colleagues and students has inspired extensive collaboration to equal benefit of Aarhus University, the botanists of the Pontificia Universidad Católica del Ecuador (PUCE) and of The National University of Loja.

The Danish initiative was also inspired by the Swedish project *Flora of Ecuador* which was initiated 1968 by Gunnar Harling (University of Göteborg) and Benkt Sparre (Naturhistoriska Riksmuseet, Stockholm). The botanists from Aarhus became involved in the Editorial Board, by Lauritz B. Holm-Nielsen, and they contributed treatments of several families to the Flora. Simon Lægaard became co-ordinator for Gramineae, and Benjamin Øllgaard for Pteridophyta.

## Danish Expeditions to Ecuador 1968–1976

In 1968 two third-year biology students, Lauritz B. Holm-Nielsen and Stig Jeppesen spent seven weeks in the field in Ecuador, and made more than 1600 general collections at 12 localities ranging from the Pacific coastal plain across the Andes to the Amazonian lowland. During this stay they caught special interest in the Passifloraceae and Helobiales, and the Lobeliaceae. These became the subject of their master theses, and later were published in *Flora of Ecuador* (Holm-Nielsen *et al.* 1988; Jeppesen 1981). At the time botany was new at Aarhus University, having been established five years earlier in 1963 by professor Kai Larsen, who had also established the Aarhus University Herbarium (AAU). He was keen on expanding the herbarium so he supported the expedition of the adventurous students with funding for shipment of specimens. This first expedition was also supported economically by the Danish amateur botanist Troels Myndel Pedersen who owned cattle farms in Argentina, and who wanted the two students to collect specimens of Amaranthaceae for his revisions of that family.

The collections of the 1968 expedition brought excitement to the botany group at AAU and inspired the planning of the next trip in 1973 after the participants' graduation. In addition to Lauritz B. Holm-Nielsen and Stig Jeppesen, Benjamin Øllgaard, who had special interest in ferns and lycopods (Øllgaard 1988; Øllgaard *et al.* 2001, Stolze *et al.* 1994) and Bernt Løjtnant with special interest in Orchids joined the activity. During three and a half months in the field in Ecuador about 5300 general and special collections were made at some 100 localities, including the Pacific coastal plain, and nearly a complete north-south transect of the Ecuadorian Andes. Again professor Kai Larsen and Troels Myndel Pedersen supported the activity, and the small Danish community in Ecuador was a great help. The expedition contacted PUCE and discussed the possibility to collaborate in a botany program, including teaching and development of the herbarium. They received a very positive response.

A third expedition in 1976 was funded by the Danish Natural Science Research Council with the aim to focus on the diversity and ecology of Ecuadorian Lycopodiaceae. Benjamin Øllgaard had Henrik Balslev as field assistant, and he initiated a study of the Ecuadorian Juncaceae (Balslev 1979) that later was expanded to a monograph for *Flora Neotropica* (Balslev 1996). The field work was carried out during three and a half months, mainly in montane forest and páramo. Four hundred special and 1900 general collections were made, followed by 400 additional ones by Henrik Balslev after finishing the Lycopodiaceae project (Øllgaard & Balslev 1979). Again the small Danish community in Ecuador was a great help.

## Permanent Danish Staff in Ecuador 1979–1989

A formal and obliging collaboration with the biology department at PUCE began in 1979 when Lauritz Holm-Nielsen, funded by a Danida grant, moved to Quito to stay for two years in order to build up botanical teaching and to improve the herbarium for the purpose of education and reference. Zoological and ecological disciplines had good levels, but botany was only now included in the biology program. Holm-Nielsen contributed botanical courses and engaged Ecuadorian students in extensive field work in order to expand the existing 1000-specimen herbarium to a more representative status. During his two years he added more than 14,000 specimens, representing most of the Ecuadorian vegetation types, especially together with Jaime Jaramillo and Flavio Coello. During the same period visiting Danish and local Ecuadorian students and other collaborators added another ca. 6000 specimens. Jaime Jaramillo and Flavio Coello subsequently stayed one and a half year in Denmark, undertaking taxonomic revisions of Ecuadorian plants at herbarium AAU.

When Holm-Nielsen left Quito, Henrik Balslev, with a PhD degree from The City University of New York took over, this time on a local contract with the university in Quito, to carry on the teaching of first-degree students and to organize the newly accumulated plant collections for practical and scientific use. He increased its floristic coverage with more than 4000 new collections.

He added practical activities to the formerly mainly theoretical teaching attitude, and engaged first-degree students in field courses on flora and vegetation, páramo vegetation, Amazonian rain forest of Cuyabeno, and supervised several first-degree theses in taxonomy and ethnobotany.

During this period several people from Aarhus served the functions and activities established during the previous period, and at the same time pursued personal research interest. Funding was from a variety of sources and young Danish botanists were employed in Quito mainly on local conditions, whereas Aarhus University staff spent their sabbatical leave, or some even worked in Ecuador based on small grants and personal economic investment.

At the end of this phase Herbarium QCA had reached close to 100,000 specimens, and 40–50 students had acquired local first-degrees, 'licenciado' in biology with specialization in botany. Simon Lægaard stayed at herbarium QCA 1984–1985 during a sabbatical from the University of Aarhus, and made extensive field studies of native grass species (Lægaard 1997; Lægaard & Peterson 2001; Lægaard & Balslev 2014). Bo Boysen Larsen continued studies of the Valerianaceae 1985–1986 while teaching and curating the Quito herbarium (Boysen Larsen 1986). Peter Møller Jørgensen established studies of forest diversity and ecology in sample plots in Volcán Pasochoa and in the montane forest on the western Andean slopes during 1986–1989, parallel with teaching botany in the laboratory and in the field to many Ecuadorian students (Møller Jørgensen & Ulloa Ulloa 1994; Møller Jørgensen & León Yánez 1999). Henrik Borgtoft Pedersen and Birgitte Bergmann took over the post and taught botany and curated the herbarium during 1989–1990 while they also studied the ethnobotany and economic botany of palms, especially the vegetable ivory palm (Brokamp *et al.* 2014). At the end of this period, Jens Elgaard Madsen collaborated for two years with the Herbarium of the National University of Loja, and the forestry department about a reforestation project with native species from the Podocarpus National Park (Aguirre *et al.* 2002); he also carried out studies of the Cactaceae (Madsen 1989).

## The Enreca Program

The Universities in Quito (Ecuador), Loja (Ecuador), and Aarhus (Denmark) entered a formal collaboration during 1990–2002 in a Danida funded Enreca project entitled 'Natural Resources for Development – a research collaboration between Denmark and Ecuador.' Danida's Enreca programme was established in 1990 to **En**hance **Re**search **Ca**pacity in developing countries. Enreca functioned through *twinning arrangements* between a developing country and Danish research institutes and they included research and training in order to promote capacity building through long term collaborations, up to several phases each of three years duration. A basic idea of this program was that sustained development is based on the capacity to find and apply existing knowledge, to create new knowledge, and to remain updated by connection to relevant international specialist networks. The first grant for the Danish-Ecuadorian Enreca program was given in 1990 and subsequently extended for three additional three-year periods until 2002. During the program, permanent Aarhus staff was seconded to Ecuador under the project management of Henrik Balslev with the aims (Balslev & Paz y Miño 1991):

- to consolidate herbarium QCA to about 150,000 specimens.
- to provide adequate technology and methods (computers, microscopes, databases, etc.)
- to train students to local first-degrees 'licenciado en biología' with specialization in botany
- to train Ecuadorian PhDs and MSc at Aarhus University.
- to strengthen taxonomic research in Ecuador
- to expand research into vegetation ecology, ethnoecology, systematics and biodiversity studies, and relating to ecosystems services.

Under the Danish-Ecuadorian Enreca program residence in Quito was attended by Benjamin Øllgaard (1990–1992), Finn Borchsenius (1992–1994) and Henrik Balslev (1994–1999). After the third project period Danida judged the achievements at PUCE to warrant a more independent continuation of the project on the part of PUCE, with a reduced funding, and subsequent collaboration on equal terms with Aarhus. During the second three-year period Aarhus became involved in a research enhancement project in the regional university in Loja in southern Ecuador, where Aarhus had collaborated about five years earlier (Aguirre *et al.* 2002). Residence in Loja was attended by Henrik Borgtoft Pedersen (1993-1996, with spouse Birgitte Bergmann teaching seven months in 1994), Bente Bang Klitgaard (1996-1998, with spouse Gwilym P. Lewis), Simon Lægaard (1998-2000), and Jens E. Madsen (2000-2001). In Loja the most urgent need was to improve the infrastructure, and to organize the existing collections and incorporate them in the general herbarium.

During the period several PhD students were inscribed from the start of the project at PUCE: Guillermo Paz y Miño (lowland Amazonian forest diversity and ecology, Cuyabeno, after two years appointed Undersecretary of Environmental Affairs to the Minister of Energy and Mines); Renato Valencia (forest diversity and ecology; Valencia *et al.* 2000, 2004, 2013); Carmen Ulloa Ulloa (high Andean arborescent flora and diversity; Ulloa Ulloa & Møller Jørgensen 1993; Møller Jørgensen & Ulloa Ulloa 1994); Katya Romoleroux (Ecuadorian Rosaceae and related families; Romoleroux 1996; Freire-Fiero & Romoleroux 2004); Carmen Josse (coastal lowland cloud forests, diversity and ecology; Josse & Balslev 1994); Lucia de la Torre (Catalogue of Useful plants of Ecuador; de la Torre *et al.* 2008, 2009, 2012). Two students were inscribed in local PhD programs at PUCE: Hugo Navarrete (fern taxonomy and diversity) and Esteban Terneus (limnology). Four students were inscribed in the Aarhus MSc program: Priscilla Muriel and Tatiana Jaramillo (taxonomy of the genus *Virola*, Myristicaceae, in Ecuador; Jaramillo *et al.* 2000, 2004); Selene Baez (palm ecology, continued to the PhD programme at Gainsville, Florida; Baez & Balslev 2007); Rommel Montúfar (Palm community ecology, continued to the PhD programme at Montpellier, France; Brokamp *et al.* 2014; Montúfar *et al.* 2011). The programme for each of the participants was designed as a sandwich with up to nine months yearly dedicated to field work in Ecuador and work with collections in the herbarium, and at least three months in Aarhus with access to library, herbarium and laboratory facilities, specialized supervision, and participation in international conferences in order to connect with specialist networks.

The Danish DIVA projects collaborated 1994-1998 with Herbarium QCA as a counterpart and other institutions in Peru and Bolivia in order to investigate the cultural and biological diversity of Andean rainforests. At Aarhus University, Flemming Skov and Benjamin Øllgaard were involved, while Renato Valencia and Hugo Navarrete participated as Ecuadorian counterparts to the program for QCA. This activity provided a great number of herbarium collections to both QCA and AAU.

In conclusion the Danish-Ecuadorian Enreca project achieved the enhancement of research capacity in Ecuador, not least through the training of 45 first-degree graduates in botany and of eight Ecuadorians for the PhD and five for the MSc degrees in Denmark. In sheer numbers the collections in the herbarium QCA of the university in Quito increased from 100,000 to 150,000 (Fig. 1) which makes it one of the most important collections of Ecuadorian plants. The Enreca project also provided field and laboratory equipment for studies in plant taxonomy and ecology.

## Subsequent Careers of Ecuadorians in the Enreca Project

Training of human resources is obviously important to any capacity building project. But it is equally important that those who are trained end up in meaningful positions afterwards, and this has actually happened with the Enreca trained Ecuadorians, though many of them have moved on to other institutions than the one they were trained in. Carmen Ulloa Ulloa has moved on to become a curator at the Missouri Botanical Garden, where she continues her research in Ecuadorian plants and actually carries out important capacity building in Ecuador as part of that. Carmen Josse worked for more than a decade as Senior Regional Ecologist at the NatureServe, Wash-


Fig. 1. The herbarium QCA at Pontificia Universidad Catolica del Ecuador (PUCE), in Quito. A, B, C. Compactors for storing and sorting tables. D. Specimen of *Myrcia magnoliifolia* DC. (Myrtaceae). E. Specimen of *Magnolia* sp. (Magnoliaceae).

ington, where she handled many Latin American programs for conservation on a regional scale; now she works for Ecociencia, and Ecuadorian NGO dedicated to research for conservation of nature. Renato Valencia, became the first Ecuadorian director of the herbarium QCA at PUCE in Quito 1994-2001, and he has since functioned as professor of botany at the same place, and has been involved in higher level administration at the university as vice dean of the Faculty of Natural Science; he also was the Scientific Director of the Ecuadorian Research Council (FUNDACYT, later SENECYT) for over two years, 2002-2004. Katya Romoleroux returned to teach botany at PUCE and was named director of the herbarium in 2012. Priscilla Muriel has returned to the university as herbarium database manager and specialist and became professor of botany in 2011. Lucia de la Torre functions as an independent consultant in Quito and has many projects together with the university. After her MSc at Aarhus University Selene Baez went on to do a PhD at Gainsville University in Florida and is now back as a professor of botany in the National Polytechnic University in Quito. Hugo Navarrete became professor of botany at PUCE and also director of the herbarium (2001-2011), and was for a long period dean of the Faculty of Natural Sciences, before returning back to teaching botany and doing research at the Biology department. In general all those

Fig. 2. The reference collection with 18,000 specimens kept at the Yasuni Scientific Research Station in Amazonian Ecuador, where it is used in the identification of the more than 1000 tree species registered in a 50 ha plot which is part of the international network of large forest plots. Front left: A. Perez, back row right (dark green shirt): Renato Valencia.

trained have subsequently served in positions where their training was important.

In the south Ecuadorian town of Loja the urgent needs of improvement of the infrastructure for proper storage, preparation, organization, and documentation of herbarium specimens, establishment of library function, and databasing of collections have been filled. In addition, ordinary mail, and electronic communication was established. The collections have increased substantially, from an estimated 6500 specimens to now perhaps 20,000 partly by means of local collectors, in part by means of deposition of duplicate material from Ecuadorian and Danish collectors. Limited knowledge of English both of staff and students was a impeding the use of international sources of information, so staff and students were offered language courses, in order to overcome this problem. Several courses of basic botany were given by the Danish botanists, in addition to local forestry courses. In addition, the students were offered to participate in relevant courses given at PUCE in Quito

## Flying Alone since 2002

During the last several years of the Enreca project in Ecuador the leadership of the botanical teaching and research at PUCE was taken over by Ecuadorians trained in the project. Danish senior staff was present as advisors and also helped with the teaching and the large research projects related to the botanical collections in the herbarium. They also help in the curation of the collections and in making them useful to research by Ecuadorians and a growing number of international scientists who consulted and used the collections.

The same period saw increasing independent research and fund raising for scientific projects that were entirely free of support from the Enreca-project. Maybe the most important of those projects was the large-scale forest dynamics plot at the Yasuni field station in the Amazon part of Ecuador. That project was carried out in collaboration with the Smithsonian Tropical Research Institute at Balboa, Panama. It has produced a number of high-level publications in scientific journals (Valencia *et al.* 2004, *etc.*) as well as high quality publications with scientific content in an easily accessible format (Perez *et al.* 2014). The Yasuni forest dynamics project has all the time been closely related to the herbarium and has used the herbarium for identification of the megadiverse tree flora and also for the deposit of voucher specimens. It also maintains a reference collection at the Yasuni Scientific Station that consists in about 18,000 specimens (Fig. 2). This collection documents the morphological variation of each of the 1150 species found in the large 50-ha forest plot and the seeds and fruits collected during the last 22 years of continuous research.

Another project carried out independently at PUCE/QCA is the inventory and ecology of dry inter-Andean forests. The project was funded by the Ecuadorian Government and it included a PhD scholarship to Catalina Quintana to study at Aarhus University. This PhD study 2012–2015 (Quintana *et al.* 2017) hence is an example of Danish-Ecuadorian research collaboration funded by Ecuador.

## Conclusions

- The collaborating partner has achieved considerable scientific independence and now functions as an equal research partner
- It **is** possible to build capacity through scientific collaboration
- It takes time
- It takes mutual interest and engagement to achieve the goals
- The scientists' drive to achieve research results must be considered as an important driver of the process
- Cross disciplinary research including natural and social aspects provide important knowledge concerning ecosystem services

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# Some Experiences of North-South Synergy from the New World Tropics

*Ghillean Tolmie Prance*

## Abstract

As an example of North South synergy, the setting up of a graduate course in botany at the Instituto Nacional de Pesquisas da Amazônia in Manus, Brazil is described. Founded in 1975, the course continues to the present and is now extended to many other disciplines than botany. The details behind the production of the Flora of the Reserva Ducke near Manaus, another North-South project, are also given.

**Key Words:** Amazon flora, Flora da Reserva Ducke, graduate education, Manaus, Instituto Nacional de Pesquisas da Amazônia (INPA)

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I am very glad that the topic of North-South synergy has been included in this symposium and book of proceedings. It is a topic that has been central to my work as a field botanist over the past fifty years, and as can be seen in the other papers of this section in the book, great changes and progress have been made over that time. We have progressed from a colonial relationship to true collaboration. I will present a rather autobiographic approach to the subject here. The first time I began to collaborate with the Instituto Nacional de Pesquisas da Amazônia (INPA) in Manaus in 1965, I was almost refused permission because a recent previous expedition of The New York Botanical Garden had not left any specimens in the Manaus herbarium, poor as it was at that time. I persuaded the Director of INPA to phone the herbarium in Brasília, my base for my 1964 expedition, to confirm that I had left specimens there with duplicates for three Brazilian herbaria. Having been assured of this, I received the fullest possible collaboration from INPA that led to much collaboration over many years, some of which is described below.

## Learning from the South

The first important aspect I want to cover is that we in the developed world do not know all. When I first went to the tropics as a novice, I would not have got very far without the help of two well-trained Brazilian botanists; in 1974 João Murça Pires in Brasília and in 1975 William Rodrigues in Manaus (Fig. 1). My collaboration with both of these botanists continued over many years, but the most important time was at the start when I was a novice, learning from two good teachers with an intimate knowledge and experience of the Amazon flora. I have seen too many young botanists from the North arriving in the South thinking that they know it all and ignoring the wise counsel of the local botanists with more experience. Anyone going from the North to the South must be prepared to learn from our counterparts. This is even more so now than in 1964, when I first went to Brazil, because there are now so many more well-trained scientists in the tropical countries of the world.

Fig. 1. The author (right), speaking with João Murça Pires (left) and William Rodrigues (centre), outside the herbarium building of INPA in Manaus. Photograph from the 1970s.

## Students from the South

My third visit to Brazil was for a symposium held in Belém on the Amazon biota in 1966, which resulted in one of my early papers on the Chrysobalanaceae (Prance 1967). At this meeting I was precipitated into training students from the south by meeting Professor Alavaro Fernández from the Universidad Nacional in Bogotá, Colombia. He approached me and informed me that the best student he had ever trained had just graduated from the university and that I must take him on as a graduate student in New York. He explained that Enrique Forero did not speak much English, but if he joined my next expedition he would then easily learn enough to pass the TOEFL test, a requirement for study in the City University of New York. I agreed to this, and soon Enrique was in the field with me on my 1967 expedition to Amazonian Brazil. He was a good field assistant and was soon speaking adequate English. So I gained my first graduate student from the South. It was not long before I had another Colombian student and so the training of students became an important aspect of my life.

## The 'Curso de Botânica' at INPA

Graduate student training increased considerably in my life in 1975 after an evening drinking whiskey with the then director of INPA, Dr. Paulo Almeida Machado, who later became Brazil's minister of health. Dr. Paulo complained to me that he had just had some bad news. Two of the scientists he had sent abroad for training in the USA had reneged on their promise to return and work at INPA for three years after receiving their doctorates. One planned to remain in the USA and the other to work in São Paulo where the laboratories had the elaborate equipment he needed to continue his research. The director complained that now three people he had financed for training had not returned to INPA. I pondered this over my second glass of a good single malt and then spoke up. I said that what was needed was to train students in Manaus in the Amazon forest. If they trained here and used the forest as their laboratory rather than sophisticated apparatus in the laboratories of the USA, they would fall in love with the forest and not want to leave INPA. Dr. Paulo considered this for a short while and then said to me "Design me such a course.

Fig. 2. The author (back center) mainly with students of the Manaus courses of INPA in November 2013. Extreme right front Michael Hopkins, coordinator of the *Flora da Reserva Ducke*, next to the author in blue shirt, José Ferreira Ramos, mateiro and my long time field assistant.

I will need it tomorrow morning when the head of the National Research Council (CNPq) is coming through Manaus on his way back from Miami". I left the director's house and spent the whole night designing a full two year Master's course in botany with my wife at my side typing it out on paper torn from our daughter's school exercise book as I wrote. In the morning, I handed in a course curriculum and went to our hammock to sleep. By mid-afternoon the director's messenger came to the house and said that Dr. Paulo wanted to see me. When I entered his office he told me "Your course is approved by the CNPq." I replied that it was his course, not mine. He informed me that I would be the director of the course. When I replied that I worked for The New York Botanical Garden and that it would not be possible, Dr. Paulo informed me that he would be in New York in five weeks' time and he would visit Howard Irwin, the President of NYBG.

He did just that and requested a two-year leave of absence for me from New York. This was granted, and as a result, six months later my family and I moved to Manaus for two years to establish a master's course in tropical botany for the twelve initial students. I was given a generous budget for visiting professors, as there were only two of us with a Ph.D. at INPA in Manaus. Those students were taught by a remarkable faculty of visitors, for example, Theodosius Dobzhansky taught them genetics, Friedrich Ehrendorfer taught cytology and Rolla Tryon pteridology. One of my Colombian graduate students in New York, Eduardo Lleras, taught plant anatomy and microscopy and eventually took over the coordination of the botany course at INPA after I moved back to New York. A collaboration was arranged between INPA and the Universidade de Amazonas for the awarding of degrees. More details of the course are given in Prance (1975).

The result of this first course was that eleven students completed their master's degree in botany, and afterwards most continued on to train for and submit Ph.Ds. More significantly, all of these students remained in the Amazon region to continue their careers in botanical institutions and universities, rather than leave the region, so the initial objective of the course was achieved. During my last few months in Manaus, we were able to add courses in ichthyology, entomology and ecology to the curriculum. These courses and others continue to the present time and have about 120 students inscribed. At a recent conference in Manaus, I was able to meet some of the students of my students, and even some great grand students (Fig. 2).

## Flora of the Reserva Ducke

From my first encounter with William Rodrigues in Manaus, he expressed his desire to compile a flora of the Reserva Florestal Adolpho Ducke that belonged to INPA and is located 25 km east of Manaus. Over the years I made frequent visits to the reserve to collect plants with the flora in mind. It was not until 1990 that I was able to obtain funding from the British Government to support the preparation of a flora of the reserve. Michael Hopkins from the UK was contracted as the coordinator of the project, and all the rest of flora project team was Brazilian. The Field guide, *Flora da Reserva Ducke* (Ribeiro *et al.* 1999), was published in 1999, and the authors of each family treatment were a fine mixture of contributors from the North and the South. What is the most impressive is the number of Brazilian authors involved, indicating how Brazilian plant taxonomy has progressed since the 1970s. Some of these authors were students at one of the Manaus courses at some time.

## Conclusions

The course described above was a reaction to the circumstances of the time. Education has always been an important part of North-South relations, but what is so significant is the number of well-trained botanists in Latin America today, and that many of them have been trained in the region. Short-term sandwich courses abroad give experience and are better than long term studies away from the home country. Today we need to concentrate more on the repatriation of the data that we house in our herbaria. I became fully aware of this need through helping the students who chose taxonomy as the subject of their thesis in the first and subsequent courses in Manaus. Teaching has been a rewarding experience for me whether through the course described above or in the many other places in Latin America where I have taught courses or trained students.

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# Tropical Plant Collections and 'Big Data'

Review of presentations and discussion by the chairperson of this session, Stephen P. Hubbell, University of California, Los Angeles, USA.

The world is now engulfed by the perfect biodiversity storm: the concatenation of rapid global climate change, large-scale habitat loss, and accelerating extinction rates. Evidence from many sources indicates that we are in the midst of an anthropogenic mass extinction event, possibly the sixth great mass extinction in the history of life on earth. This perfect storm also comes at an inopportune time when a large fraction of the world's biodiversity still remains undiscovered and undescribed, much less its distribution and abundance known and its ecological function understood.

Plant collections have a vital role to play in confronting the global biodiversity crisis, not only as repositories of types and reference specimens, but also as sources of new knowledge and syntheses of patterns of plant biodiversity, evolution, ecology, and biogeography across the globe. In the last two decades, enormous strides have been made in digitizing collections and making data available through advancements in electronic data capture, storage, retrieval, presentation, analysis, synthesis and dissemination. But the sheer volume of the data and the rapidity at which new information is becoming available online has created a series of major computational and analytic challenges now widely referred to in diverse fields as 'big data'. In this section of the symposium volume, we presented papers from experts on both the challenges and opportunities that 'big data' present in plant biodiversity studies that to varying degrees are collection-based. Many exciting 'big data' opportunities are now unfolding not only to expand our understanding of the evolutionary origins and ecological maintenance of plant biodiversity across the globe, but also to generate better, more data-informed strategies for conserving and managing this biodiversity.

Kenneth Feeley discussed diligently how collections-based research and fieldwork together can reveal historical rates of migration of plant species in response to climate change. Simon Queenborough gave us a fascinating look at how functional traits and their distribution across taxa can be studied from collections. This was followed by an outstanding synthetic paper by Alexandre Antonelli, integrating big data from phylogenetics, geography, modern studies of functional traits, and fossils to understand regional and global patterns of plant biodiversity and their evolutionary origins. Jorge Soberón finally took up the question of how big data can inform biogeographic inference and help in conservation planning, but not without thoughtful use of the data building on biological theories.

While listening to the presentations by the speakers in the 'big data' session of the symposium, several questions came to mind that caused me to reflect on the prospects for using 'big data' to help with global conservation and ecosystem management efforts over the next several decades. I take the liberty of sharing these questions with the readers of these proceedings: (1) Who are the target audiences or 'consumers' of 'big data' on global plant biodiversity? (2) What are the most pressing specific questions about plant biodiversity that need answers for conservation or land management decision-making, and can these questions be answered by collections-based 'big data'? (3) In what ways can access to 'big data' increase the perceived value of the collections from which they are derived? (4) Conversely, what is the risk that the increasing availability of 'big data' will reduce the perceived value of the collections themselves? (5) Many sources of 'big data' used in the examples presented by Feeley, Queenborough and Antonelli are not collections-based, as, for example, remote-sensing data. As these additional sources are added, can we say that this strengthen the long-term value of collections-derived data?

A concluding comment: As a tropical plant community ecologist, I am largely an outsider to the plant collections scientific community who attended this meeting. Nevertheless, I was honoured to be invited because my research program and that of my colleagues across the world who study tropical (and now also temperate) forest dynamics in a global network of large, permanent forest inventory plots (a consortium known as the Center for Tropical Forest Science or the Smithsonian Global Earth Observatory) would be impossible without the herbaria, the collections they house all over the world, and the botanical expertise they maintain. Indeed, collections are the essential foundation for all of plant ecology and plant conservation, and must not only survive, but must be strengthened, to successfully confront today's perfect biodiversity storm.

# Using Herbarium Collections and Plot Data to Track the Effects of Climate Change on Tropical Forests

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## Abstract

One of the primary ways that tropical plant species are expected to respond to climate change is through shifts in their geographic distributions (i.e., 'species migrations') leading to altered patterns of diversity and community composition. Unfortunately, studies tracking these types of changes are sparse or nonexistent for most of the tropics. One reason for the paucity of tropical studies is a simple lack of data which limits our ability to map species' ranges and track, or predict, changes in the distributions of species through time. In this paper, I discuss the availability, or lack thereof, of inventory plot and herbarium collections data for tropical plant species. I then review a series of studies using collections data to track changes in the distributions of Amazonian plant species through time, and combinations of collections and plot data to track changes in tree species composition in Peru, Costa Rica and Colombia. These studies show that climate change may potentially be causing changes in species distributions driven mainly by range retractions. The studies also show that the composition of tropical montane forests are changing to include greater relative abundances of lowland thermophilic species and that these changes are likewise being driven primarily by retractions of species' ranges from hot, lowland areas. These results all suggest that tropical forests are at high risk of species extinctions and biodiversity loss. Finally, I discuss the need for additional high-quality collections and plot data so that we can increase our understanding of the different ways that tropical plant species are responding to climate change and the reasons for their differential responses.

**Key Words:** biotic attrition, extinction, Global Biodiversity Information Facility, global warming, natural history data, species migrations, thermophilization

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Tropical forests harbor the majority of known and unknown species (Raven 1988; Dirzo & Raven 2003; Joppa *et al.* 2011a) and provide vital ecosystem services such as food production, carbon sequestration, and climate regulation (Costanza *et al.* 1997; Cincotta *et al.* 2000; Fa *et al.* 2002; Milner-Gulland & Bennett 2003; Naidoo *et al.* 2008; Saatchi *et al.* 2011; Baccini *et al.* 2012). Despite their diversity and importance, tropical plants are systematically underrepresented in studies investigating or predicting the impacts of global climate change (Feeley *et al.* 2015; Feeley *et al.* 2017). For example, in their oft-cited study summarizing the predicted effects of climate change on species' extinction risks, Thomas *et al.* (2004) included studies of more than 1100 species worldwide but only 172 tropical plant species – 163 from the Brazilian Cerrado and nine from the Amazon (Thomas *et al.* 2004). More recently, Urban (2015) synthesized more than a hundred studies representing many tens of thousands of species to estimate the number of species in different parts of the world that are likely to be driven to extinction by climate change (Urban 2015). Included in the analyses of Urban were data for several thousand species of tropical plants (the exact number of tropical plant species is impossible to discern due to lack of specification of the species' identities or provenances in some of the original datasets). While this is clearly a marked improvement over past syntheses (including that of Thomas *et al.* 2004), it is still just a small fraction of actual tropical plant biodiversity (Joppa *et al.* 2011b), especially considering that the included plant species were meant to represent all possible tropical plant taxa, biogeographic realms, habitat types, and life forms (from Asian cloud-forest bryophytes to Amazon rainforest trees to African savannah grasses). Another important consideration is that none of the studies of tropical plant species included in either Thomas *et al.* (2004) or Urban (2015) looked at how tropical systems are actually responding to climate change but rather were just predictions based on projections of species' estimated ranges (i.e. species distribution models) into the future under different climate change scenarios.

A simple explanation for why tropical plant species are so poorly represented in studies that investigate or predict the impacts of climate change is an extreme paucity of data available for these species. We simply do not have enough data about most tropical plants to map their species distributions or make informed predictions about how they are faring, or will fare, in the face of climate change (Feeley *et al.* 2012; Feeley 2015b).

In this review, I briefly discuss the availability of distribution data for tropical plant species. I then synthesize a series of four recent studies that have used the available herbarium collections and plot data to track changes in the distributions of tropical plant species and the associated changes in forest community composition in response to modern anthropogenic climate change. These studies are still just a 'drop in the bucket' compared to the vast diversity of tropical plant species and ecosystems, but they provide examples of the type of analyses that can be conducted using the available data as well as a concrete framework for future research.

## The Availability of Collection and Plot Data from Tropical Forests

The most basic information needed to track and predict species' risks of extinction due to climate change are their ranges, which in turn require maps of where the species occur and, ideally, where the species do not occur. Currently, the available data are simply insufficient to make such maps for most tropical plant species (Feeley & Silman 2011a).

For temperate realms, one of the most common sources of data for mapping species ranges and tracking the effects of climate change are plot inventories. In the United States, for example, the national forest service (USFS) maintains a network of over 125,000 permanent forest inventory plots in its Forest Inventory and Analysis (FIA) program. These data are publicly available (http://www.fia.fs.fed.us/) and have been used in numerous ecology and biogeography studies (e.g. Iverson & Prasad 1998; Zhu *et al.* 2012; Woodall *et al.* 2013; Fei *et al.* 2017; Janowiak *et al.* 2017). Likewise, many European countries maintain large comprehensive networks of inventory plots that provide detailed data on where species are present and absent (http://forestportal.efi.int/). National census plot networks such as these do not exist as of yet in the tropics (although national inventories are planned for several countries).

For an example of how scarce plot data are for tropical plants, one can look to South America, which contains the largest tract of tropical forest (the Amazon), supports the greatest diversity of plant species (Slik *et al.* 2015), and is arguably the best-studied of all tropical realms. Collating data for five of the largest and most prominent tropical plot networks: RAINFOR (http://www.rainfor.org/), the Amazon Tree Diversity Network (ATDN; http://web.science.uu.nl/amazon/atdn/), Forestplots.net (https://www.forestplots.net/), the Smithsonian Institute's Center for Tropical Forest Science (CTFS; http://www.ctfs.si.edu/), and the Red de Bosques (http://www.condesan.org/redbosques/), there is a combined total of approximately 1500 census plots distributed throughout all of Tropical South America (i.e. just 1% the number of plots maintained by the USFS in the USA, Feeley 2015a). One recent study analyzed tree species occurrences in 1100 (73%) of these plots in the Amazon (ter Steege *et al.* 2013). The included plots contained a total of approximately 5000 distinct tree species. Of these species, more than 1500 were recorded in only one or two plots each; the median number of individuals per species was 18 and the median number of plots per species (i.e. distinct occurrence locations) was seven. Furthermore, there are estimated to be more than 11,000 additional Amazonian tree species that are not included in any of the plots (ter Steege *et al.* 2013). Clearly, it is not possible to map the geographic distributions or estimate the climatic niches for the majority of Amazonian tree species using these plot data alone.

An alternative source of data for mapping the geographic distributions of plant species is herbarium or natural history collections. But here again, data from the tropics are woefully sparse. For tropical South America, there are nearly two million georeferenced plant collection records available for download through the Global Biodiversity Information Facility (http://www.gbif.org, accessed on February 1st, 2014). These records include collection coordinates for more than 52,000 valid species names (validity of names determined through http://tnrs.iplantcollaborative.org/). Approximately 1/3 of these species are represented by just one or two collections each (Feeley 2015a) and the median number of collections per species is just six. There are likely to be several thousand more species that are not represented by any collections at all or that have yet to be properly identified (Bebber *et al.* 2010). Given that other parts of the tropics, such as Africa and Asia, have even lower collection densities (Feeley & Silman 2011a), the number of tropical plant species worldwide for which there exist little or no information is truly daunting.

Despite their paucity, the data that are currently available can still provide useful information on the ranges and realized climatic niches for at least a subset of the best-collected tropical plant species. As discussed below, this information can in turn be used alone, or in combination with plot census data, to track how species' ranges and community composition are changing through time in response to climate change or other anthropogenic disturbances.

## Tracking the Effects of Climate Change in Tropical Forests

There are only a few possible responses of any species, including tropical plants, to global climate change: (1) species can acclimate or adapt to changes in climate; (2) species can shift their distributions (i.e. 'migrate') to remain at equilibrium with climate; or (3) failing to do either of these two, species will eventually decrease in population size to the point that some will become committed to extinction (Feeley *et al.* 2012). For many tropical plant species there are good reasons to believe that 'migration' is a more viable response than acclimation or adaptation. For example, various constraints (e.g. long-lived individuals, long-generation times, low genetic variation, high levels of habitat/population fragmentation, and accelerating rates of climate change) suggest that most tropical tree species will be unable to adapt to anthropogenic climate change (Feeley *et al.* 2012). In addition, studies show that the composition of paleo-plant-communities in the tropics were tightly linked to temperature and that many plant species shifted their distributions upslope as temperatures increased after the late glacial maximum (Bush *et al.* 2004). As such, we can predict that tropical plant species should likewise be actively migrating upslope due to contemporary warming.

A large and growing number of studies have documented upward and poleward shifts in the distributions of various taxa. Most of these studies are from temperate systems and unfortunately, tropical species, and especially tropical plant species, remain

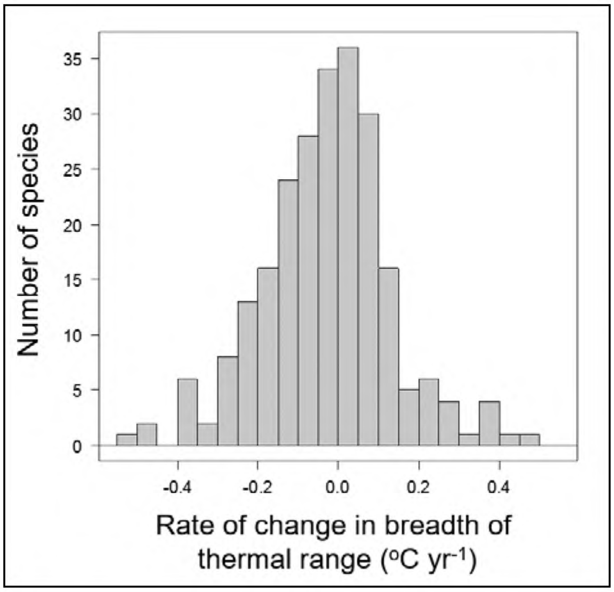


Fig. 1. The annual rate of change in the ranges of mean annual temperatures over which Amazonian plant species were collected between 1970 and 2009 as based on analyses of herbarium records available through GBIF and after correcting for collection biases (Feeley 2012). The average rate of change was -0.029 °C $yr^{-1}$ (95% CI = -0.047 – -0.009 °C $yr^{-1}$) indicating that species' realized thermal niches, and hence geographic distributions, are contracting through time.

grossly underrepresented in these studies (Rehm 2014; Feeley *et al.* 2017). For example, a meta-analysis published in 2011 (Chen *et al.* 2011) included over 50 studies representing more than 2000 different plant and animal species. At the time of meta-analysis, no studies were available for any tropical plant species.

Given sufficient data, it should be possible to determine if species are migrating by tracking changes in the locations from which they have been collected through time. Feeley (2012), analyzed thousands of herbarium collection records from tropical South America to test for changes in species distributions. For approximately 240 of the best-collected Amazonian plant species, the changes in the average, maximum and minimum elevations from which they had been collected over the past four decades (1970–2009) was quantified. After correcting for geo-referencing errors and spatiotemporal collection biases (confounding factors that need to be accounted for in all studies using natural history records; Schulman *et al.* 2007; Tobler *et al.* 2007; Boakes *et al.* 2010; Feeley & Silman 2010, 2011b), it was found that the majority of species (59%) did in fact show some evidence of distributional shifts towards higher areas that were previously 'too cold'. More specifically, the mean collection location shifted upward in 13% of species, the leading high-elevation range edge shifted upward in 28% of species, and the trailing low-elevation range edge shifted upward in 38% of species (Feeley 2012). The fact that more species shifted their lower trailing range edges upward than shifted their high leading range edges upward suggests that many species are 'migrating' through range retractions rather than range expansions or range 'marches' (Lenoir & Svenning 2015). In fact, a comparison of the leading and trailing edges of the species' ranges shows that the realized thermal niches of Amazonian plant species contracted by an average of 1.13 °C between 1970 and 2009 corresponding to an annual rate of change of -0.03 °C per year (95% CI = -0.05 – -0.01 °C $yr^{-1}$; Fig. 1). In terms of elevation, this means that the species' ranges shrunk by an average of more than 200 vertical meters over just the past four decades, or in other words, by an average of approximately five vertical meters every year. The fact that thermal ranges are shrinking so rapidly though time certainly does not bode well and suggests a high risk of decreasing population sizes and eventual extinctions.

Another approach that holds great potential for tracking the effects of climate change is to combine the data from herbarium collections with plot recensus data and test for directional changes in community composition. This type of analysis involves three general steps: (1) use the location of herbarium collections to estimate the preferred or optimum temperature (or other environmental condition of interest) for each species represented in the plots; (2) calculate the Community Temperature Score (CTS) of each study plot during an initial and subsequent census based on the relative abundance of species and their optimum temperatures, and (3) calculate the annualized differences of each plot's Community Temperature Score

**Table 1.** Community Temperature Scores (CTS; °C) and Thermal Migration Rates (TMR; °C century$^{-1}$) and their 95% confidence intervals (CI) calculated from recensuses of neotrppical forest inventory plots. Data for Peru from Feeley *et al.* (2011), for Costa Rica from Feeley *et al.* (2013) , and for Colombia from Duque *et al.* (2015)

| Country | CTS | (95% CI) | TMR | (95% CI) | % plots with positive TMR |
|---|---|---|---|---|---|
| Peru | -2.7 | (-3.1 – -2.2) | 1.12 | (0.29 – 2.1) | 0.79 |
| Costa Rica | -4.8 | (-5.6 – -4.0) | 0.6 | (-0.10 – 1.11) | 0.90 |
| Colombia | -4.3 | (-3.5 – -5.0) | 1.04 | (0.19 – 2.13) | 0.81 |
| Combined | -3.5 | (-3.9 – -3.1) | 0.95 | (0.48 – 1.53) | 0.83 |

to characterize the rate and direction of compositional change.

To date, this approach has been applied to analyze compositional changes in three different systems of forest inventory plots in the tropics, each containing many hundreds of tree species: the Kosñipata valley transect in Southern Peru (14 1-ha plots spanning 950–3400 m asl), the Volcan Barva transect in Costa Rica (10 1-ha plots spanning 70–2800 m asl), and a network of plots in Antioquia, Colombia (16 1-ha plots spanning 40–2950 m a.s.l.). While these three studies were conducted independently, there was enough overlap in methods and analyses that we can now combine the results to get a larger-scale picture of how species composition relates to temperature and how climate change is influencing the composition of species in these tropical forests (Feeley *et al.* 2011; Feeley *et al.* 2013; Duque *et al.* 2015).

According to the steps 1 and 2 listed above, in all three studies, the optimum temperature (or elevation which can then be translated to temperature on the basis of an adiabatic lapse rate) was calculated for each species represented in the plots. The optimum temperature was estimated as the average of the mean annual temperatures occurring at all locations from which the species had been collected according to available records in the Global Biodiversity Information Facility after correcting for collection biases. The CTS of each plot was subsequently estimated in the initial and all subsequent censuses as the mean of the

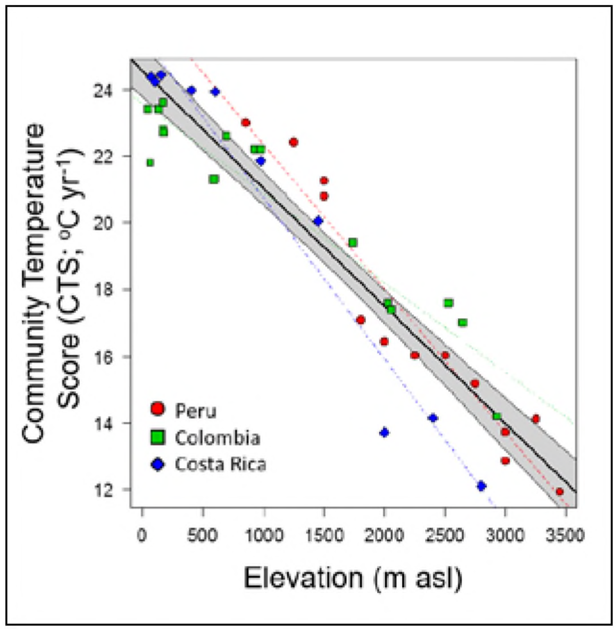


Fig. 2. The Community Temperature Scores (CTS = mean of the constituent species' optimum temperatures weighted by relative abundance) of plots in Peru, Colombia, and Costa Rica vs. plot elevation. CTS decreases significantly with elevation within each system and for all three systems combined. The gray shading indicates the overall relationship between CTS and elevation with 95% confidence interval (lapse rate = -3.5 °C km$^{-1}$ [95% CI = -3.9 – -3.1 °C km$^{-1}$], $R^2$ = 0.89. The individual relationships for Peru, Colombia and Costa Rica are shown in red, green, and blue lines, respectively (Peru: lapse rate = -2.7 °C km$^{-1}$ [-3.1 – -2.2 °C km$^{-1}$], $R^2$ = 0.91; Colombia: lapse rate = -4.3 °C km$^{-1}$ [-3.5 – -5.0 °C km$^{-1}$], $R^2$ = 0.92; Costa Rica: lapse rate = -4.8 °C km$^{-1}$ [-5.6 – -4.0 °C km$^{-1}$], $R^2$ = 0.95).

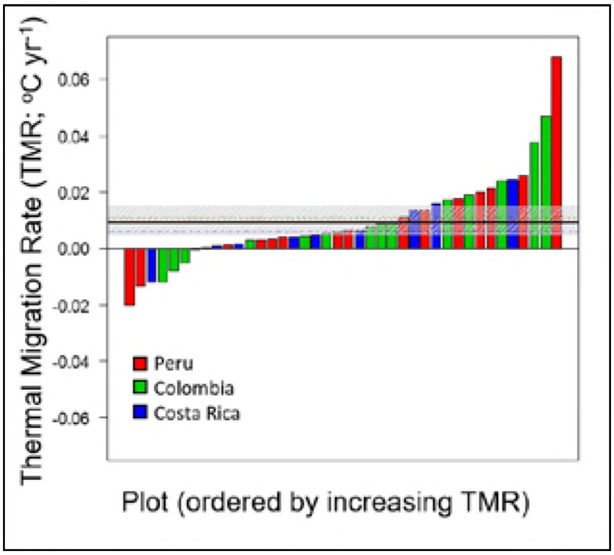


Fig. 3. The Thermal Migration Rates (TMR = annualized change in Community Temperature Scores) of plots in Peru, Colombia and Costa Rica. Combining systems, the overall thermal migration rate is 0.95 °C century$^{-1}$ 95% CI = 0.48–1.53 °C century$^{-1}$; black line and gray shading). The thermal migration rate does not vary significantly between the different plot networks (95% CIs = Peru: 0.29–2.1 °C century$^{-1}$; Colombia: 0.19–2.13 °C century$^{-1}$; Costa Rica: -0.10–1.11 °C century$^{-1}$). The mean TMR for Peru, Colombia, and Costa Rica are indicated with red, green, and blue lines, respectively.

optimum temperatures of all represented species with the species weighted based on their relative basal areas.

For each system independently and for all plots combined, CTS was very strongly correlated with plot elevation with slopes corresponding to lapse rates between -2.7 °C and -4.8 °C km$^{-1}$ (Table 1; Figure 2). As discussed in Feeley *et al.* (2013), the relationship of CTS vs. elevation tends to have a lapse rate that is shallower then the true adiabatic rate (~5.5 °C km$^{-1}$) due to niche truncation at high and low elevations (cold and hot temperatures, respectively).

The decrease in CTS with elevation indicates that cold, highland plots tend to have greater relative abundances of species that are most often collected from the highlands while hot, low-elevation plots tend to have greater relative abundances of the more-thermophilic species typically collected from the lowlands. While this result appears obvious, it is actually extremely informative and important. The strength of the relationship confirms that a species' optimum temperature as estimated from collection records is in fact a meaningful measure of the species' niches and that community composition is strongly determined by temperature vs. by other environmental factors (for example, in Colombia it was found that there is no significant relationship between the plots' Community Precipitation Scores [analogous to CTS but based on the total annual precipitation at collection locations rather than the mean annual temperatures] and actual rainfall; Duque *et al.* 2015). As such, we can predict that even fairly minor changes in temperature should lead to observable directional changes in composition. Specially, we can predict that increases in temperature should lead to a thermophilization of community composition which will be evidenced by increases in the CTS of plots.

To test for thermophilization, changes in CTS are tracked through time within each plot to provide an estimate of the constituent species' mean Thermal Migration Rate (TMR). Based on this analysis it was found that the vast majority of the plots (33 of 40 plots [83%], binomial probability <0.0005) did increase in CTS through time (i.e. had positive TMR; Fig. 3). The average TMR was 0.95 °C century$^{-1}$ (95% CI = 0.48–1.53 °C century$^{-1}$) and does not vary significantly between the different plot networks (Table 1).

It was previously argued that the thermal migrations rates in Peru and Costa Rica were slower than required to keep pace with concurrent warming (Feeley *et al.* 2011; Feeley *et al.* 2013). However, updated estimates of regional warming rates indicate that while TMRs are in fact slower than the rate of warming in Costa Rica, average TMRs are not significantly slower than the rates of warming in Peru (or Colombia; rates of warming since 1960s in the nearest major cities of Cusco, Peru; San Jose, Costa Rica; and Medellin, Colombia; have been 0.63±0.31, 1.60±0.47, 1.45±0.17 °C century$^{-1}$, respectively; http://berkeleyearth.org/). Across all systems, TMRs were sufficient to keep up with warming in 47.5% of the study plots (Peru: 71.4%; Costa Rica: 30.0%; Colombia: 37.5%). That said, in agreement with the herbarium-based study described above, it appears that most of the observed changes in species composition were due to range contractions (Feeley *et al.* 2013; Duque *et al.* 2015). In other words, the relative abundance of highland tree species is decreasing in the plots through time not due to the incursion or increased abundances of lowland thermophilic species but instead due to dieback of the highland species. As above, this suggests a high risk of extinction for many species as well as a high risk of biodiversity loss and biotic attrition (Colwell *et al.* 2008; Lenoir & Svenning 2015). Adding to this risk is the fact that rates of warming are accelerating. It is generally accepted that global temperatures will increase by at least 2 °C by the end of this century (IPCC 2013). This will require that species not only continue to migrate but that they more than double their current rate of migration. For many species, this simply may not be possible.

## Summary and Prospects

Taken together, the studies described above provide compelling evidence that many plant species from several sites throughout the neotropics are migrating upslope potentially in response to warming. These migrations are in turn causing changes in species composition towards increasing relative abundances of thermophilic species. Worrisome is the fact that the observed species migrations appear to be occurring primarily as a consequence of range retractions rather than range expansions or range shifts/marches. Indeed, the herbarium-based study (Feeley 2012) indicates that species' geographic and thermal ranges are shrinking rapidly through time. If this continues, range retractions will eventually lead to local and possibly global extinctions.

These analyses and their results, which are only possible because of the public availability of collections data and information online, provide us with a 'first run' understanding of how some tropical forests are responding to global warming and can be used to help guide future conservation efforts. However, many important questions remain to be addressed. For example, how are other species and other tropical systems responding? How are individual species migrating and what factors determine the sensitivity of plant species to environmental change and their ability to migrate? Are migration rates determined by dispersal, by phenology, by specialization on factors other than climate, or other life history traits yet to be considered?

To answer these and other questions, more and better data are required (Feeley 2015b). Ideally we would like to know where species occur and why they do not occur elsewhere so that we can better predict how individual species are responding to environmental change. This requires higher-resolution data than what is currently available. Specifically, we need enough plots or collections to characterize the ranges, and especially the range edges, of tens of thousands of species and how these range edges relate to various environmental factors. Alternatively, physiological studies and experiments can be used to determine the tolerances of select species for different factors (Feeley 2015b). Given the pending impacts of climate change on the megadiverse forests of the tropics (Perez *et al.* 2016), we must strive to rapidly increase the amount and quality of data. Towards this end, herbarium, natural history collections, and census plot networks all serve vital roles. Indeed, we must push for increased public access of existing data at the same time that we support ongoing inventories, collections, and research.

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# Collections-based Studies of Plant Functional Traits

*Simon Queenborough*

## Abstract

Herbaria may be collections of dead plants, but the information these collections provide is very much alive and growing, allowing a host of questions to be addressed, from a fuller description of the nature and distribution of diversity to a deeper understanding of plant evolution and adaptation. The use of herbarium specimens allows species-level functional trait data to be estimated for a much broader range of species that would otherwise be very time-consuming or difficult to collect from new specimens in the field. Fundamental traits such as leaf area and specific leaf area (SLA) can be easily collected from herbarium specimens. However, questions remain regarding the comparability between the trait data from live specimens versus herbarium samples, and there have been few attempts to quantify these differences. Other traits can also be collected from herbarium specimens, allowing new questions to be quickly answered. Basic traits might include leaf shape or margin type, while more detailed traits could indicate leaf venation patterns or the presence of extra-floral nectaries. Linking these trait data with plant distribution and biophysical data (climate, soils, etc.), as well as plot-level population dynamics data allows us to ask, for example, whether drip-tips are adaptations to high rainfall, what the abiotic drivers of leaf size are, or how fruit type is related to spatial pattern and life history. Thus, collecting functional trait information from plant herbarium specimens opens up a rich vein of new data with opportunities to verify old questions and expand into new areas of inquiry.

**Key Words:** Herbarium, specimen, databases

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The study of functional traits underpins investigations of plant resource use and life-history strategies because these two research areas characterize the fundamental trade-offs that determine the ecological roles of species (Grime 2006; Tilman 1988; Westoby & Wright 2006). By replacing species names with the quantitative values of physical traits, analysis of these traits from the individual level to the community-level allows us to step back from the specific identity of individuals and ask what factors drive their response to environmental variation, their influence on ecosystem processes and services, and the structure and function of ecological communities (Wright *et al.* 2004; Reich *et al.* 2007; Kleyer *et al.* 2008; Suding & Goldstein 2008; Suding *et al.* 2008; Swenson *et al.* 2012). As such, functional traits can provide the basis for an ecology and global change science that is more quantitative and predictive than has been possible in the past (Lavorel & Garnier 2002; Westoby & Wright 2006; McGill *et al.* 2006; Cavender-Bares *et al.* 2009; Webb *et al.* 2010).

Functional traits of plants include the morphological, anatomical, biochemical, physiological, and phenological features measurable at the individual level (Cornelissen *et al.* 2003). These traits reflect the outcome of evolutionary and community assembly processes in response to abiotic and biotic environmental constraints, and are evidence of trade-offs in structure, function, and resources within organisms. The trade-off between seed number and seed size illustrates this point (Leishman 2001; Coomes & Grubb 2003; Muller-Landau 2010). Plants devote finite resources to reproduction, resources which can be allocated among few large seeds or many small seeds (or some combination along this continuum). Large seeds give rise to large seedlings capable of surviving in sites of low resources and high competition; in contrast, small seeds require high resources and low competition to survive – their success lies in the higher chance of dispersal to such sites. Seed size is an easily-measured functional trait that informs our understanding of the relative quality of competition and dispersal of different species.

The development of standardized protocols for measuring individual functional traits (Cornelissen *et al.* 2003; Pérez-Harguindeguy *et al.* 2013) has driven efforts to compile these data into large functional trait databases, either with direct contributions from researchers or extracting data from existing literature (Chave *et al.* 2009). These varied databases are impressive. The TRY Plant Trait Database (https://www.try-db.org/; Kattge *et al.* 2011) contains more than 5 million trait records for 1100 traits of 2.2 million individual plants, representing 100,000 plant species. Half the data are geo-referenced, from over 12,000 measurement sites. The Global Wood Density database contains 16,500 data entries for 8412 species (http://www.datadryad.org/handle/10255/dryad.235; Zanne *et al.* 2009). Kew's Seed Information Database v.7.1 contains seed mass, dispersal, oil content, and other data on 33,346 taxa (http://data.kew.org/sid/).

Notwithstanding these impressive feats, trait databases have two main flaws. First, the values included in or extracted from such databases are often average values and generally not from the specific location(s) or even habitats of the study that uses them second-hand (Cordlandwehr *et al.* 2013). There are many well-documented causes of intraspecific variation in plants (Albert *et al.* 2012), but the question remains as to how this variation affects the value and utility of trait databases (Albert *et al.* 2012; Violle *et al.* 2015).

Second, trait databases remain for many individual traits, woefully incomplete, highly skewed toward common species, and with trait values for rare species often biased by low sampling effort (Violle *et al.* 2015; Sandel *et al.* 2015). Given this issue is more of a problem for rare species, the impact of this flaw will vary according to the study. For instance, missing or erroneous values for rare species might not affect estimates of mean trait values at the community level.

The only way to address these two problems is to collect new trait data for each study, to ensure that data are appropriate to the question in hand. However, an apparently overlooked method that could rapidly and cheaply address the issues of both intraspecific variation and undersampling of live plants is to extract functional trait data from preserved and curated herbarium material. Using herbarium material ensures that trait data are linked to individual plants and opens up a greater sample size from which to measure traits, as well as other advantages detailed below.

The use of herbaria to add value to other scientific fields has been explored for many years (Smith 1956; Funk 2003), from making additional collections to examine population-level variability (Anderson & Turrill 1935; Anderson 1941), to studies of biogeography (Holland 1975), invasions (Lavoie *et al.* 2007), migrations (Feeley 2012), and phenology (Calinger *et al.* 2013). Thus, there should be no a priori reason to discount their use for studies of functional traits as well.

## Sources of Trait Data

Functional trait data can be sourced from a variety of plant material. Trait data are best obtained from fresh material collected in situ (Cornelissen *et al.* 2003; Pérez-Harguindeguy *et al.* 2013). However, other options are available: In extremis, living collections could replace wild-collections; published species descriptions, floras and monographs contain data on life form, life history, size, and reproductive structures;

importantly, there is also a vast wealth of data in the dried plant collections in herbaria from which a number of significant traits could be determined, especially for species that are rare, or located in hard-to-reach or difficult collecting environments.

*Living wild plants in situ*

These plants will be acclimated to local climate and abiotic conditions and should therefore reflect the adaptive strategy that maximizes fitness. Because many plant species are plastic, traits should be measured on robust, healthy, mature plants, located in well-lit environments, unless specific goals suggest otherwise (Cornelissen *et al.* 2003). Collecting sun leaves is particularly important for some leaf traits that are known to be very plastic in response to light (Markesteijn *et al.* 2007; Rozendaal *et al.* 2006).

*Living collections*

Many botanical institutions have living collections in their greenhouses and gardens, often numbering tens of thousands of individuals (e.g. the Royal Botanic Gardens, Kew (K) has an estimated 19,000 species from 178,000 accessions; The Royal Botanic Garden Edinburgh (E) 15,000 species; The New York Botanical Garden (NY) has over 1 million accessions), many of which are available for research purposes (Dosmann 2007). Taking trait data from living collections is not ideal, in large part because of plants' high plasticity. In contrast to herbarium specimens, the whole plant is available for study, but many species will adapt in physiology and morphology to local growing conditions, which are often quite different from those experienced in their natural environment. As such, living collections are more akin to the 'common garden experiments' often run by evolutionary ecologists to determine the relative contribution of genes versus habitat on phenotype (Goldberg & Barton 1992). With little knowledge of the intra-specific variation in each trait of a particular species, the use of these data for large-scale comparative functional trait studies is not recommended.

*Literature and descriptions*

All descriptions of new species, as well as many floras and monographs, contain data that could contribute to trait databases (e.g. Croat 1978). These descriptions are written by taxonomists and systematists and based on observations of many fresh and dried specimens. As such, and depending on the author, the descriptions will generally reflect average values for quantitative traits such as seed, fruit and leaf size; qualitative traits such as life form, seed and fruit type, and dispersal mode, are likely to also be presented.

*Herbarium specimens*

After fresh, wild-collected specimens, herbarium specimens may be the next-best source of material for extracting functional trait data (for the parts that are collected, often limited to leaves, stems, flowers, and fruits). This is largely because these specimens are already collected, often from locations that would be difficult or expensive for trait ecologists to visit specifically to collect trait data (Mann 1997; Funk 2003). Further, as with fresh plant material, these data will be linked to individual specimens, and any errors or changes are much easier to correct than if using aggregated data from the literature.

## Collecting Trait Data from Herbarium Specimens

### *Advantages of herbarium specimens*

*Using collections increases species coverage* – By definition, herbarium specimens include all species ever described. As such, it is theoretically possible to sample all these specimens to build a complete picture of intra- and interspecific variation in trait data. Further, one can access a far greater range of species and range of variation in a herbarium than is possible at a single field site, depending on the quality and nature of the collections. Large botanical institutions, in particular, have millions of specimens and many thousands of

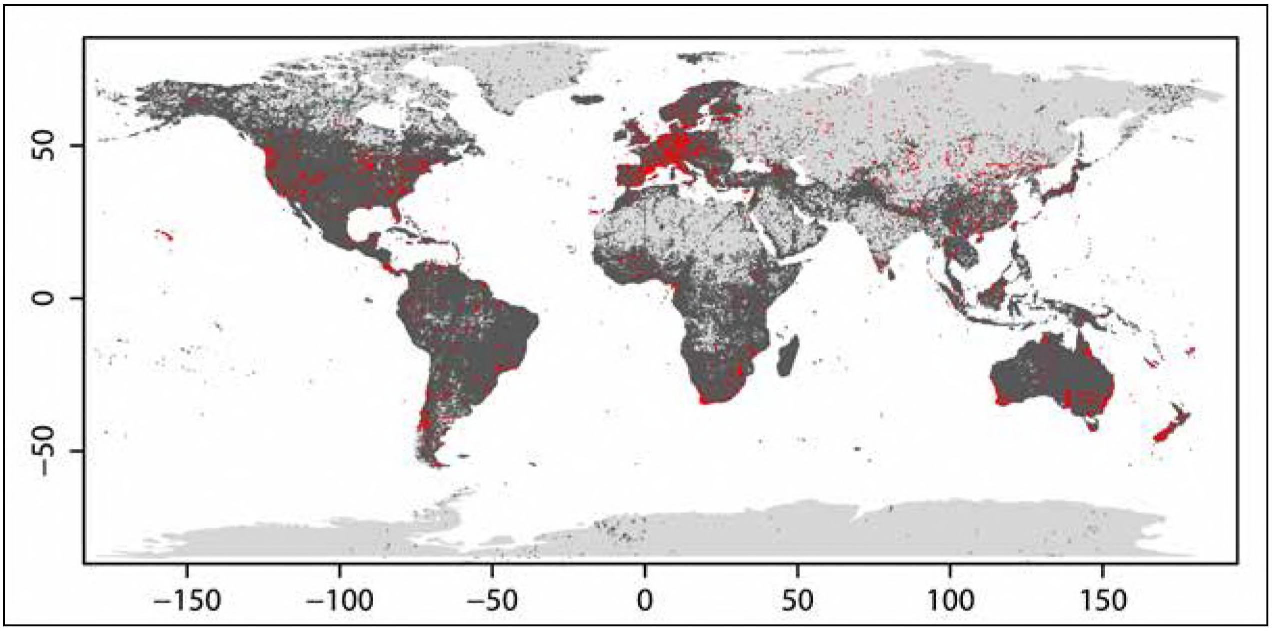


Fig. 1. A comparison of sites where plant trait data have been measured (red; geo-referenced measurement sites in the TRY database) with the location of all angiosperm herbarium specimens recorded in GBIF (grey; Global Biodiversity Information Facility, http://www.gbif.org).

specimens that could be accessed easily and cheaply for their existing trait data.

This advantage is highlighted when we compare the distribution of sites and ecosystems from which trait data has been sampled (e.g. Kattge *et al.* 2011). In general, functional data for traits such as specific leaf area and leaf nitrogen content remains a very small part of the total geographical and biome hyper-space that has been sampled as herbarium specimens (comparing the distribution of specimen data in GBIF with the trait data in TRY, Fig. 1). This situation is exacerbated in the tropics because most trait data comes from the temperate grasslands of Europe, North America, South Africa and Australia. The use of herbarium data would quickly and dramatically improve data coverage of areas and biomes that are under-represented in trait databases.

*Historical and geographic record of trait variation, within and between species* – Along with the variety of species present, many herbaria also have considerable historical collections going back over hundreds of years. These specimens can provide valuable data on how traits may have changed over time, especially with regards to phenology and leaf-level traits (see examples below). Such trait data are invaluable. Given that we cannot go back in time to collect fresh trait material, herbarium specimens are likely the sole manner from which we can obtain information on trait values in the past.

Likewise, because many different plant collectors contribute duplicate specimens to multiple herbaria, these repositories have accumulated specimens from a wide range of geographical locations (local, regional, and global), often much wider than a single researcher could visit over the duration of a project. Determining the temporal and spatial nature of trait variation is a key issue to understanding the ecology and evolution of plant communities.

*Trait data are linked to individual curated specimens* – A major advantage of obtaining trait data from a herbarium specimen is the fact that the data are then linked to a specific enumerated and curated sample (assuming adequate records by the plant collector, herbarium, and trait researcher). While this system may seem a constraint, it permits much flexibility in the future. First, it allows easy access to these specimens by taxonomic specialists to ensure that the determination of the specimen is correct; single trait-based specimens or samples for trait analysis stored in the researcher's laboratory are often inaccessible to taxonomists to complete this task – and ecologists are sometimes bad taxonomists! (Gotelli 2004; Bortolus 2008; Dexter *et al.* 2010; Gomes *et al.* 2013). Second, if the determination is incorrect, the system permits the name to be changed and for this name change to propagate through to any second-level datasets and analyses based on this specimen; if trait data are based on species names and those names change, there is no way to know if any particular datum from a researcher-collected specimen should also be reassigned a different taxonomic identity.

Following this advantage, it is recommended that voucher specimens be made from all field-collected data specimens (in line with all plot-based research), and duplicates deposited in international herbaria and sent to specialists for confirmation of their identity.

*Herbarium specimens are already collected* – A final advantage of using herbarium specimens is that they are already collected, avoiding the need for expensive and lengthy field excursions (Mann 1997). The researcher can get straight to work collecting and analyzing the trait data itself.

The combination of advantages listed above suggests that the use of herbarium specimens should open up a wide field of trait research that will rapidly produce results and insights. Unfortunately, there are a number of caveats to this exciting possibility.

## *Disadvantages of herbarium specimens*

*Herbarium specimens are collected already* – Despite the time and financial advantages that having ready-collected specimens can provide, this benefit also has a disadvantage. The trait researcher is generally unsure if the herbarium specimens were collected according to standard trait protocols (see Living Wild Plants, above), unless the specimen label provides this information. Ideally, trait data should be collected from mature, fully-expanded, healthy sun-lit plants (Cornelissen *et al.* 2003) – but many collected specimens were growing in no such state, especially the specimens that exist in historical collections. The question remains as to whether the benefits of using herbarium specimens outweigh the increased trait variance from using non-standard samples.

It should be noted, however, that many trait researchers who use wild living plants do not use 'ideal' samples because the nature of their studies renders prohibitive collecting such samples (Pérez-Harguindeguy *et al.* 2013). Tall rain forest trees are one such life form where climbing all of the 1000 species found in a large forest plot would almost certainly restrict trait-based research in such environments, and so data from saplings are frequently used instead (Kraft *et al.* 2008). As in all studies, the nature of the question should drive the data collected, and trait data from saplings for 1000 species may provide better answers than trait data sampled from the canopies of 10 species.

*Biased collecting and sampling of the natural world* – While ecologists may be less-than-perfect taxonomists, plant collectors are not immune to the bias of a particularly pretty flower or easily accessible tree. Ideally, we would sample the world at random. However, many studies have demonstrated the biased nature of taxonomic collecting, with more collections and higher species richness of focal taxa around taxonomic centers (Dennis & Thomas 2000; Dennis *et al.* 1999; Beck & Kitching 2007), and greater numbers of specimens collected from alongside roads and rivers (Funk *et al.* 1999; Kadmon *et al.* 2004).

As with the previous disadvantage, some data may be better than none, but the fact remains that rare and disturbed ecosystems such as rivers and roads are sampled with much higher intensity than continuous tracts of forest or grassland, especially in the tropics (Fig. 2). Traits may differ between these environments, and again, the variance in herbarium samples may be greater than that found between species, rendering the data less useful. At the same time, traditional trait researchers should also be warned that their field sampling schema may result in biased esti-

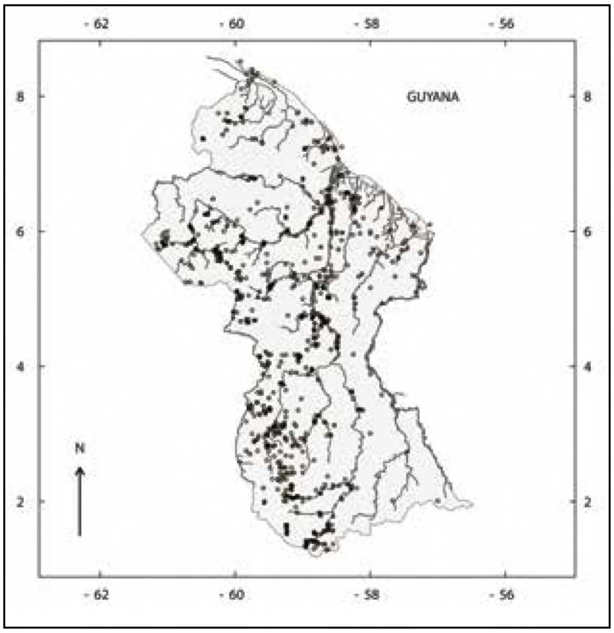


Fig. 2. Highlighting the biased nature of sampling from the natural world. Map of Guyana with main rivers, showing higher intensity of sampling near the rivers than elsewhere. Each dot represents at least one collection of Fabaceae registered in GBIF. Figure based on Funk *et al.* (1999) with additional data from GBIF.

mators of reality and to guard against this issue (Baraloto *et al.* 2010).

*Specimens may have incorrect labels* – Despite being the place where names are bestowed, herbaria often contain errors (Allen 1981; Bisang & Urmi 1994; Ahrends *et al.* 2011). In many cases, these errors reflect name changes that curators and specialists have yet to update. In other cases, the plant collector may have erred in the original label name. In taxonomically difficult groups, material essential for accurate determination, such as flowers or fruits, may not even be present within the specimen.

However, at least when a name is associated with a herbarium specimen it can be verified (too many field identifications in ecology, without a voucher, are not even available for verification). Many of these errors may be corrected in time, and as stated above, the advantage of linking data to specimens is that name changes can easily propagate throughout data sets if they are designed and managed correctly.

*Drying and pressing changes specimens* – The final, and most important, disadvantage is that the actual process of collecting and preserving may alter the specimen to a point where accurate trait data is impossible to obtain (Pérez-Harguindeguy *et al.* 2013). For many historical collecting trips, preservation in alcohol was the only way to ensure that specimens survived the climate of their origin and the journey back to the herbarium (Mori *et al.* 2011) – drying in situ was not an option. Even today, this technique may be the best choice in remote tropical locations. However, most taxonomists can now rely on returning to a semi-permanent field site where specimens can be dried and pressed quickly in drying ovens, packed, and transported rapidly to secure and dry herbaria for curation. This process does not leave the specimen unaltered, with several recent studies showing changes in leaf shape or proportion (Queenborough & Porras 2013), as well as documented changes in color that occur in several families (Gentry 1996; Pérez-Harguindeguy *et al.* 2013). From these observations, it appears that drying-induced changes in leaf (and other organ) morphology are primarily related to the structure of the organ. Tougher leaves hold their shape better, giving similar results for measures such as specific leaf area (area/dry mass) when calculations are performed on the same leaf when fresh or dry; fleshier leaves tend to shrink more and may undergo other internal changes (Queenborough & Porras 2013). Thus, care must be taken when taking trait data from dried samples. Ideally, before undertaking such a project, researchers should conduct some preliminary analyses, examining the mean and variance in trait data from samples they collect and prepare from both fresh and dried material for their trait/s of interest. They will then be in a position to decide whether or not to use herbarium material.

### *Linking trait data to other data types*

The power of functional trait data lies in linking it with other data in order to examine patterns and processes of ecology and evolution at various levels and scales (McGill *et al.* 2006; Westoby & Wright 2006). Currently, these linkages are made through the key of the species name (i.e. genus and specific epithet). Various resources are available to update and resolve nomenclatural issues, such as the Taxonomic Name Resolution Service (http://tnrs.iplantcollaborative.org/), the Plant List (http://www.theplantlist.org/) and others. None of these online services can ensure that the name matches the underlying sample or specimen in hand. This issue applies to all species-level data, trait or otherwise, and guidance is needed for what researchers should do if species names change, are split, or combined. Ideally, all trait data would be backed up with a valid voucher specimen that could be referred to in the event of such discrepancies, linked to in the trait database within which the data reside.

Collecting data from specimens sidesteps this issue, because it is the specimen itself that comes first. Thus, it is already collected and curated. Data taken from the specimen need to be linked back to it to allow any name changes to propagate through the databases and analyses. Any analysis based on these data might then calculate species-level means 'on demand' and then archive and reference the version of the database used. The wide availability of scripted programming and statistical software, version control software, and supplementary or archival websites make this issue trivial in terms of its technical nature, but likely would require a non-trivial change in the workflow of many researchers.

### *Tropical versus temperate collections*

Many of the above issues equally apply to the use of collections from the tropics and the temperate zones. However, given the two issues of how collecting in alcohol in the tropics might impact functional trait data and just how many more collections exist from the temperate zone, there may be benefits to trialing large-scale extraction of traits from temperate specimens. Contrary to this recommendation, however, is the fact that the most extensive collections of tropical plants often reside in the temperate zone. It may, therefore, make more sense to trial data collection from a group of related taxa that are found throughout the world.

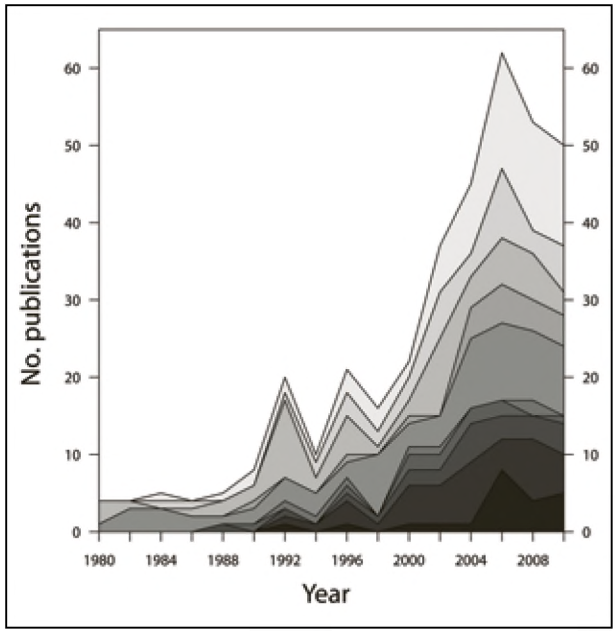


Fig. 3. Trends in publications using herbarium data, 1980–2010. The figure shows the number of publications every two years from 1980, in ten categories from bottom to top: biases associated with herbarium specimens, biogeographical patterns, plant diseases, historical floristic assessments, plant invasions, plant phenology, pollution (including carbon dioxide), rare or declining plant species, and multiple or other topics (including climate change and distribution range of plants and conservation priorities). Data from Lavoie (2013).

## Examples of herbarium-based trait analysis

Given the advantages and challenges of working with this data source, increasing numbers of ecological and evolutionary studies are making use of herbarium specimens (Fig. 3; Lavoie 2013). Most of this work is not trait-based, but instead focuses on species distribution modeling (Loiselle *et al.* 2008; Elith & Leathwick 2007; Phillips & Dudík 2008; Feeley & Silman 2011) and investigations of invasive species (Delisle *et al.* 2003; Peterson *et al.* 2003). These studies make extensive use of only the species identity and location data associated with collections, and many trait analyses make use of field-collected trait databases (e.g. Wright *et al.* 2004; Poorter & Bongers 2006; Edwards *et al.* 2007). However, researchers are increasingly using information from actual specimens to answer not only intriguing biological questions but scientific questions of global importance.

*Phenotypic change over time*

As discussed above, collections of the same species from similar locations provide a time series of data that can be used to ask whether these populations have changed, and also to investigate the drivers of that change, for example in terms of phenology (see below) as well as other aspects of plant phenotype. Plant size, particularly of annuals, is especially amenable to study. In contrast to animals, little is known about changes in plant body size over the last 100 years. Leger (2013) measured herbarium specimens of seven species of small annual plants from the Great Basin-Mojave Desert floristic province in the western USA collected between 1893 and 2011. Most species were found to decrease in height and leaf size, with no obvious climatic driver. A limitation of using herbarium specimens for this kind of study, however, is determining if these changes are plastic responses to climate variation or a product of evolution in response to climate or another factor.

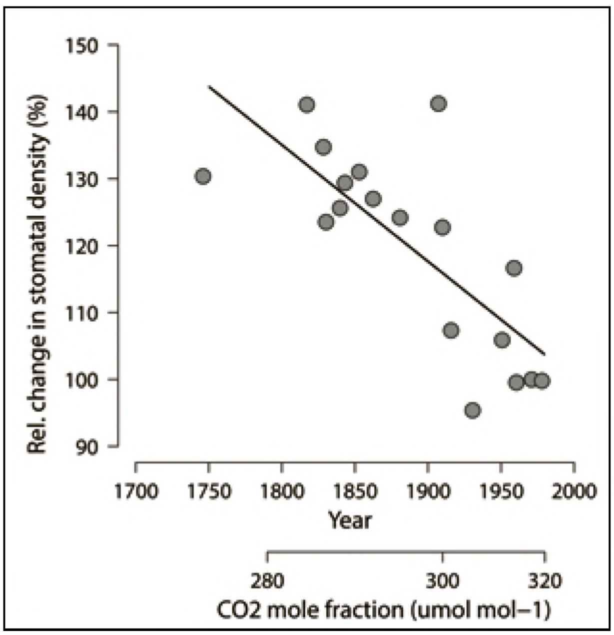


Fig. 4. Stomatal densities of herbarium stored leaves of eight species of temperate forest trees, and reconstructed atmospheric $CO_2$ based on ice cores. Data from Woodward (1987: Fig. 1).

*Historical $CO_2$ and stomatal density*

Herbarium specimens collected over historical time were put to innovative use by Woodward (1987). He examined specimens of eight temperate tree species from the University of Cambridge's Department of Botany herbarium that had been collected between 1750 and 1981, and calculated stomatal density of these samples. Some attempt was made to use ideal full-sunlight leaves by only using samples from reproductive shoots. He found a convincing strong negative correlation between stomatal density and estimated atmospheric $CO_2$ concentration (from ice-core data) (Fig. 4) – and confirmed this result experimentally, suggesting that climate change was already having an effect on vegetation before recent shifts in species distributions were observed. Further studies corroborated this investigation (Beerling *et al.* 1991, 1993; McElwain *et al.* 1995), many even using fossil collections to demonstrate the effect of $CO_2$ on leaf stomata (Royer 2001).

*Phenological change in response to climate*

The study of plant phenology (the timing of life events such as reproduction) has traditionally been undertaken solely in the field at single intensively monitored sites (Fitter & Fitter 2002; Miller-Rushing & Primack 2008), or via networks of volunteers or citizen scientists (Dickinson *et al.* 2010, 2012; Miller-Rushing *et al.* 2012). The use of herbarium specimens permits analyses over much wider geographic ranges and time-scales. For example, several recent studies have linked reproductive trait data from herbarium specimens with historical temperature or rainfall data to examine the impact of climate change on phenology. Using the collection dates of reproductive specimens as a proxy for flowering time and with sufficient numbers of specimens, patterns and changes in phenology can be accurately calculated. This approach has been used successfully for single locations

(Primack *et al.* 2004; Lavoie & Lachance 2006; Robbirt *et al.* 2011; Panchen *et al.* 2012) and over wide geographical areas (Zalamea *et al.* 2011; Calinger *et al.* 2013; Hart *et al.* 2014; Park & Schwartz 2015).

### *Harvesting and artificial selection*

Paleontological collections can obviously be used to examine the evolution of plants over deep time, as in the case of leaf stomata referred to above (Royer 2001). However, plants can also evolve rapidly and historical collections provide a snapshot or sample of populations that can be compared to more recent collections or fresh material. This approach can be especially useful when determining the effects on populations of harvesting by humans, because collecting based on certain traits may unintentionally select against that trait in the remaining population. For example, Law & Salick (2005) used historical herbarium samples and compared them to plants recently collected for the medicinal trade, showing that the medicinal snow lotus (*Saussurea laniceps*, Asteraceae) had reduced in size over the last 100 years, whereas its less-used sister taxon (*Saussurea medusa*) remained the same size. In passing, it should be noted that scientific collecting, at least from trees, generally has little impact on the individual or population (Phillips *et al.* 1998).

### *Adaptive variation of plant traits*

Exciting developments in understanding questions of evolutionary adaptation are being realized with the combination of herbarium data and traits with large-scale vegetation plot networks. The advantage of plots over specimen collections is that in addition to incidence (i.e. whether the species is present or not), plots also provide quantitative information on the abundance of each species – species may be uniformly common or rare, or vary in abundance throughout their range (ter Steege *et al.* 2013). Using species-average trait values allows researchers to compare how the mean and variance in plot-level trait values (in terms of both species or individuals) vary over wide geographic ranges, climates, and soils. For example, Malhado *et al.* (2009, 2012) used the RAINFOR network of over one hundred 1-ha tree plots to determine that larger leaves tend to be found in drier areas and leaves with drip-tips are more common in wetter areas, suggesting a strong role of water in driving the structure and function of leaves even in generally wet environments as tropical forest.

In addition to incidence and abundance, many vegetation plots are censused numerous times, allowing the inclusion of demographic data in the analysis. Muehleisen *et al.* (2016) used a mixture of field collections, herbarium specimens, scanned herbarium specimens and previously collected data to analyse the distribution and demographic correlates of extra-floral nectaries – nectar-producing glands on the leaves or stems of plants that attract ants, often hypothesized as a defensive strategy. Despite the wide distribution of extra-floral nectaries on the phylogeny, they found little evidence of an effect of extra-floral nectaries on the performance of mature trees, suggesting that examining seedlings and sapling might be where any fitness and/or performance benefit would be found.

## Future Directions

There is important potential for large datasets from herbaria to expand our knowledge of how ecological systems interact and change over global scales. The goals of a quantitative and predictive ecology and global change science might be characterized as follows (McGill *et al.* 2006; Lavorel & Garnier 2002): (i) To determine the adaptive nature and/or fitness of plant traits; (ii) To understand the determinants of past and present plant diversity, distribution and abundance; (iii) To predict how species and vegetation will respond to future climate change. Attaining these goals will require the dynamic linking of numerous sources of data, from vegetation plot and demographic data to field-collected trait data as well as herbarium specimen location and trait data, and molecular phylogenetic data.

Several traits could very easily and quickly be collected from herbarium specimens. These are largely restricted to leaf traits, such as leaf size, shape, and margin type, as well as specific leaf area and even nitrogen content. Flower and fruit traits could also be determined from herbarium sheets or carpological collections. For many such traits, access to a virtual herbarium is all that is required, because leaf area, shape and margin can all be measured visually (M. Sullivan & S. Queenborough, *unpublished data*). Indeed, it may even be possible to automate the collection of some of these traits, allowing entire (virtual) herbaria to be measured remotely (Belhumeur *et al.* 2008; Cope *et al.* 2012).

In conclusion, there are sound biological, theoretical, and financial reasons to explore the use of herbarium specimens in trait research. Initial studies comparing traits from herbarium to fresh specimens suggest that, with care, certain traits can certainly be used. Given the rapidly changing nature of the global climate, it behooves researchers to use creative methods to understand how plant community structure and function were driven by past climate and how they will likely respond to new and future climates.

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# Comparative biogeography, big data and common myths

*Alexandre Antonelli*


## Abstract

The scientific value of biological collections extends far beyond the naming, classification, and mapping of the world's biodiversity. Molecular phylogenies constructed from voucher specimens, in combination with fossil records, can be used to infer the biogeographical history of lineages, the relation between their diversification and past biotic and abiotic events, and the historical assembly of entire biotas. However, two major challenges remain. First, in order to identify common processes underlying biodiversity patterns, we need to perform analyses under standardised procedures – which I define here as 'comparative biogeography'. This includes data-driven identification and delimitation of biogeographical regions, and the spatial coding of species to estimate range shifts and diversification. Second, we have to learn how to deal with 'big data.' To this end we need to embrace innovative bioinformatic solutions for dealing with errors and biases in public databases, we should make software 'black boxes' more transparent, self-contained and reproducible, and we must increase the engagement of citizens for logging and identifying species. By addressing the common myths about big data and engaging the manifold resources available to us, biodiversity research can move past many standing shortcomings of the field to become a time of huge opportunity.



**Key Words:** crowd science, evolution, molecular phylogenetics, public databases, species occurrences



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> 'We are drowning in information, while starving for wisdom.' (Wilson 1999: 294).

There are two striking aspects of the data used in biodiversity research. First, you never know how the information that you gathered today will be used by someone else tomorrow. The type specimen of *Solanum elaeagnifolium* Cav. stored in Madrid is just labelled 'del viaje de los españoles alrededor del mundo' [= from the travels by the Spaniards around the world] (S. Knapp pers. comm.). While that information might have been enough for the purposes of the collector, it drastically reduces the chances of this specimen being useful for more than a handful of research questions. Second, publicly available biodiversity data have increased at a speed and volume similar to that experienced by several other scientific disciplines and society. So both in terms of quantity (breath and

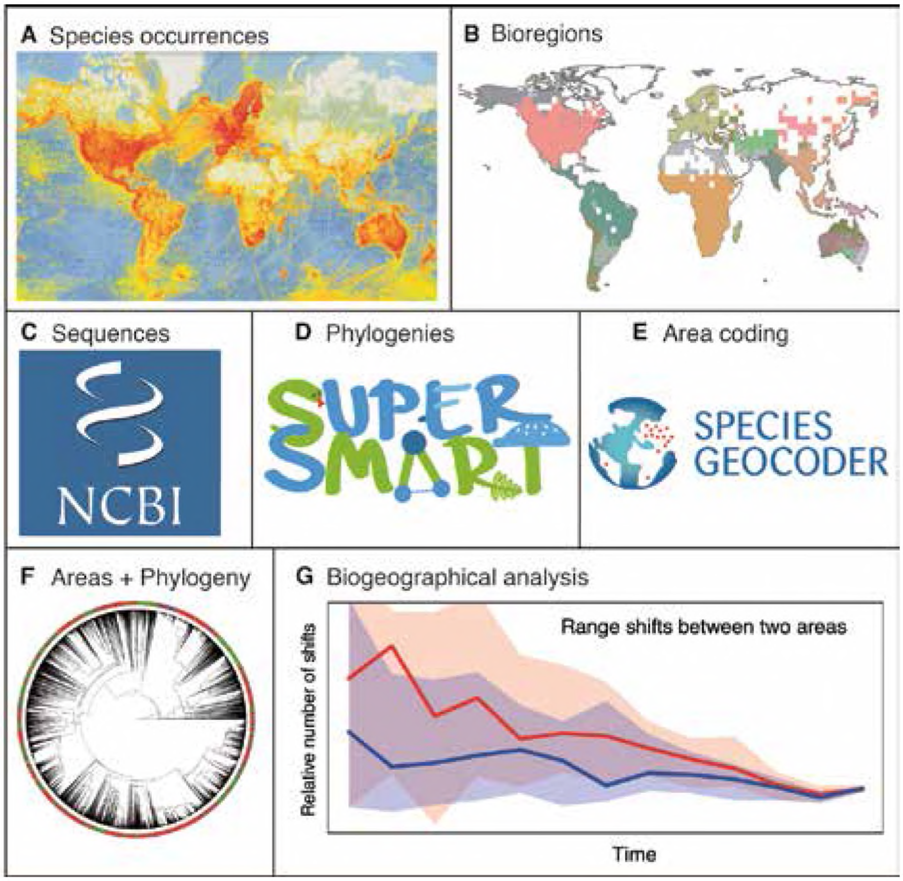


Fig. 1. Schematic workflow of the 'comparative biogeography' approach. First, species occurrence data that have been automatically and/or manually cleaned (A) are clustered into bioregions (B). Molecular sequence data (C) are downloaded, clustered and aligned to produce dated phylogenetic trees with the addition of fossil information (D). Species in the resulting phylogenies are then coded into each of the bioregions delimited (E). The coded phylogeny (F) can then be used by a large number of biogeographical applications, such as ancestral range reconstructions that infer the number of biotic range shifts between any set of areas (G). See the text for more details and references to the packages used.

density) and diversity (taxonomic, genetic, morphological, ecological, spatial, and temporal), biodiversity data are now widely recognised as 'big data' and there is no indication that the rate of data proliferation will cease its rapid outward expansion.

This review is meant to provide an admittedly personal and biased perspective on how to concretely advance some outstanding aspects of biodiversity research, with a focus on the use of species occurrence data and molecular sequences for biogeographical research.

## Using Biological Collections in Comparative Biogeography

Fine-scale biogeographical studies based on voucher specimens, such as those investigating the diversification history of a particular genus or clade (e.g., Meseguer *et al.* 2014; Zhang *et al.* 2015; Lagomarsino *et al.* 2016), are essential to our understanding of biogeographical processes. However, in order to identify the factors driving the major patterns of biodiversity observed today, we need to investigate the evolutionary history of many lineages in relation to biotic and abiotic events and the fossil record (e.g., Wesselingh *et al.* 2010; Antonelli & Sanmartín 2011; Favre *et al.* 2014; Linder 2014). Although the term comparative biogeography is not new (Parenti & Ebach 2009), I choose to define it here as "the approach of inferring the evolutionary history of multiple taxa under standardised methods in order to enable direct comparisons and the identification of common processes underlying biodiversity patterns". Unfortunately, the lack of consensus on how to conduct biogeographical studies (albeit beneficial to methodological development) has led to the accumulation of results that cannot be readily compared. As a practical illustration of how comparative biogeography may be conducted, a short and simple workflow for inferring the geographic history of lineages is provided (Fig. 1) and explained below.

### *Selecting areas for biogeographical analyses*

In most biogeographical methods currently available (e.g., Ree & Smith 2008; Matzke 2014), it is first necessary to decide on a set of discrete operational units (spatial polygons). These could be anything from clearly defined geographical units (such as continents and islands), to regions defined on the basis of their biota (such as biodiversity hotspots, biomes, and ecoregions), units based on geological history (such as the Indian subcontinent, which was long separated from Asia), or a combination of any of these. In many studies, the choice of operational units is not well explained or lacks consistent criteria, and authors do not investigate how arbitrary decisions may influence subsequent results.

One possible solution to standardise operational areas in biogeography is to apply data-driven detection approaches. The idea is not new, as several algorithms have already been proposed based, for instance, on the concept of areas of endemism (Morrone 1994; Linder 2001). However, new methods are able to use massive amounts of geo-referenced species occurrence records that are available, for example, through the Global Biodiversity Information Facility (GBIF; www.gbif.org; Fig. 1A) to identify how species group spatially into higher-level clusters, often called biogeographical regions or simply bioregions. The accuracy of these methods can then be statistically evaluated (Kreft & Jetz 2010). We recently described one such approach – Infomap Bioregions (Fig. 1B) – based on network clustering that appears to outperform similarity-based algorithms (Vilhena & Antonelli 2015; Edler *et al.* 2017).

### *Assigning species to areas*

Once the operational spatial units for biogeographical analysis are decided upon, it is time to assign each species to one or several areas where it occurs. Taking into consideration the rapidly increasing number of geo-referenced specimens now available (over 150 million plant records through GBIF), this task may be extremely time-consuming and error-prone. To facilitate this process, we have developed a software package called SpeciesGeoCoder (Töpel *et al.* 2017), which enables the fast categorisation of species (or population, individuals, etc. – depending on the taxonomic level surveyed) into operational areas (Fig. 1E). These areas may be purely spatial and defined by the borders of a GIS polygon, such as the bioregions delimited in the previous step. However, they can also be defined on the basis of an altitudinal range – such as 'this area under 500 m' – which would facilitate the coding of species occurring in topographically heterogeneous regions. In this way, it would be possible to code species that occur at low, middle, and high elevation zones. Biogeographic analyses would then allow researchers to estimate the origin of the species in each of those zones, for instance along a mountain slope in Borneo (Antonelli 2015; Merckx *et al.* 2015).

### *Inferring the evolutionary history of lineages and biotas*

We are still far from having well-resolved phylogenies for most taxa, as most species have not yet been sequenced. For example, only data for c. 9–11% of all tropical angiosperms with georeferenced species occurrences were available to be assembled into a phylogenetic tree (Zanne *et al.* 2014; Antonelli *et al.* 2015). In addition, most of the molecular sequences produced so far lack any spatial information associated with their records in the National Center for Biotechnology Information database (NCBI/GenBank). For example, only 6.2% of all sequenced species of tetrapods have associated spatial data in GenBank, despite being such a charismatic clade (Gratton *et al.* 2017).

Rapidly decreasing sequencing costs and new sequencing technologies should soon ameliorate this issue. In plants, sequencing coverage may be greatly increased in the coming years by massive sequencing of herbarium samples (Bakker *et al.* 2016; Bakker *et al.*

2017). Large initiatives targeting the sequencing of full genomes and/or transcriptomes of birds (Zhang *et al.* 2014), insects (Misof *et al.* 2014), and vertebrates (Haussler *et al.* 2009) will further increase taxonomic coverage across the tree of life. However, it is important to consider that even if research labs worldwide would together manage to sequence all species, without proper co-ordination of efforts and synthesis of results we would still be unable to address most questions in comparative biogeography. This is because researchers are now using widely disparate sets of sequence regions for phylogenetic inference, different methods for estimating divergence times, and fossils of very different quality and informativeness for calibrating molecular phylogenies. This is a fundamental issue that cannot be solved by synergistic initiatives such as the Open Tree of Life (Hinchliff *et al.* 2015), which essentially produces a mega-tree by grafting together smaller trees from various studies. We recently proposed a complementary approach (Antonelli *et al.* 2015), which allows the inference of phylogenies based on all suitable sequences publicly available. Our initiative, termed the Self-Updating Platform for Estimating Rates of Speciation and Migration, Ages and Relationships of Taxa (SUPERSMART) is designed as a user-friendly platform for producing dated phylogenies for any taxon (Fig. 1D). It differs from so-called 'supertree' and 'supermatrix' approaches (e.g., Haeseler 2012) by performing phylogenetic estimation in a stepwise way. First, SUPERSMART produces higher-level backbone trees based on a set of common sequence regions, which are typically slowly evolving and well represented taxonomically. Then, the package expands internal nodes to comprise all suitable species and sequences, calculating their relationship and divergence times under coalescent methods. Finally, it grafts all species-level phylogenies back to the backbone tree, thus resulting in very large species-level dated phylogenies for all sequenced taxa. Once the species in a phylogeny are area-coded (Fig. 1F), it becomes relatively straightforward to perform any phylogeny-based biogeographical analysis (e.g., Fig. 1G).

## Dealing with Big Data

The examples provided above for biogeographical research depict some of the drastic changes that are affecting the research landscape in biodiversity. These include a rapid increase in the volume of data (and the associated biases and errors), an urge to use biological collections to address a plethora of new questions as compared to earlier uses, and an increased complexity associated with understanding, choosing and applying new methods. In order to further advance biodiversity research, it is therefore crucial to re-evaluate some of the most prominent myths in our community regarding this recent onslaught of easily accessible data.

### *Myth 1: Public databases are useless for research*

There is general and widespread scepticism concerning the use of publicly available databases – such as GBIF and GenBank – for 'serious' research. Just as many researchers today refer to Wikipedia for a rapid check on a term or event, public databases are often seen as a place where researchers can do a quick check of what is available, but no more. One critical limitation of public data is that the resolution (e.g., spatial, taxonomic, genetic, temporal) might not be appropriate to the study question. But even when the available biodiversity and molecular data at first sight seem appropriate, they may contain numerous errors and biases (Valkiunas *et al.* 2008; Mendonça *et al.* 2011; Nilsson *et al.* 2012; Meyer *et al.* 2015; Meyer *et al.* 2016). Fortunately many of these can now be properly identified and quantified, and analytical tools are being developed to further increase their usefulness in research.

'Errors' can often be identified by algorithms. For instance, when dealing with species occurrence data, SpeciesGeoCoder can flag terrestrial species with occurrences in the sea, those with coordinates outside of the countries in which they were recorded, those located significantly farther away from the rest, and those with occurrences in country centroids, among other anomalies. The package biogeo (Robertson *et* *al.* 2016) goes a step further, providing suggestions to correct entries after approval by the user. When time or resources are scarce, researchers can thus focus their initial attention on such automatically identified potential errors. Similarly, when constructing molecular datasets for phylogenetic inference, SUPERSMART will not include those sequences that are significantly different to other sequences for the same taxon, thus reducing the inclusion of wrongly identified or spuriously sequenced specimens.

'Biases' are equally amenable to automated detection and quantification. For instance, taxonomic biases are straightforward to calculate by counting how many sequences and occurrence records are available in public databases in relation to the expected diversity in a clade. Collection biases can also be calculated by computing the distance between each geo-referenced record and the nearest road, river, city, national park, etc. (Fithian *et al.* 2015; see also https://github.com/azizka/sampbias).

Most biogeographical methods now allow for the incorporation of biases, such as incomplete species sampling, in diversification rate analyses (Cusimano *et al.* 2012; Rabosky 2014). Others allow the user to set absolute and relative thresholds to account for undetected errors. For instance, in SpeciesGeoCoder the user can set a minimum of 10 records (or a certain percentage) before a species is coded as present in an area. By testing multiple threshold levels, it becomes easy to assess the robustness of results in relation to varying degrees of error in the data used (Antonelli *et al.* 2015).

## *Myth 2: Humans outperform analytical 'black boxes'*

Many biologists do not trust computers. Some systematists prefer to spend days checking and adjusting molecular sequence alignments by hand, despising those who run a sequence alignment software for a few seconds. Some will fight tooth and nail for the use of parsimony over likelihood-based methods (Editors 2016), largely because parsimony is easier for most of us to grasp. Botanists will rarely trust computer programs for the identification of species, despite the fact that trained software has been shown under pilot tests to identify species based on leaves (Durgante *et al.* 2013; Wilf *et al.* 2016) and pollen grains (Punyasena *et al.* 2012; Riley *et al.* 2015) at similar or even higher success rates than humans. We must be open to novel bioinformatic and technical developments, in particular when dealing with the time-consuming analysis of increasingly large data volumes (García-Roselló *et al.* 2015; Maldonado *et al.* 2015).

Besides saving us time and often improving quality, software also has the ability to make biodiversity research more explicit and reproducible. Ideally, researchers should provide all input and output files for their analyses, as well as the settings they used, in supplementary material to articles, or in permanent open repositories. However, given the wide range of tools currently available, even when such data are provided it may still be nearly impossible to reproduce a published study, due to the continuous update of versions in the software and operational platforms used.

Biodiversity research is not an exception to the increasing concern for the reproducibility of studies, which is a growing problem for all sciences (e.g., Buck 2015; Open Science Collaboration 2015). Self-contained, integrative analytical platforms - sometimes unfavourably denoted 'black boxes' - have the potential to solve the general issue of reproducibility, when combined with long-term data storage, and proper reporting of analytical methods and settings. The common fear of using such platforms is that researchers loose control over what is done. To tackle this valid criticism, it is essential to make such 'boxes' less black and more transparent (Borregaard & Hart 2016), but still retaining their 'boxiness' – i.e., containing all software dependencies in one file that can be properly version-tracked and re-run. To this end, collaboration between biologists and bioinformaticians is key.

## *Myth 3: Citizen identifications cannot be trusted*

Systematists have long held a monopoly over taxonomic knowledge, and the word 'amateur' (s/he who loves) is too often used as someone inept. This atti-

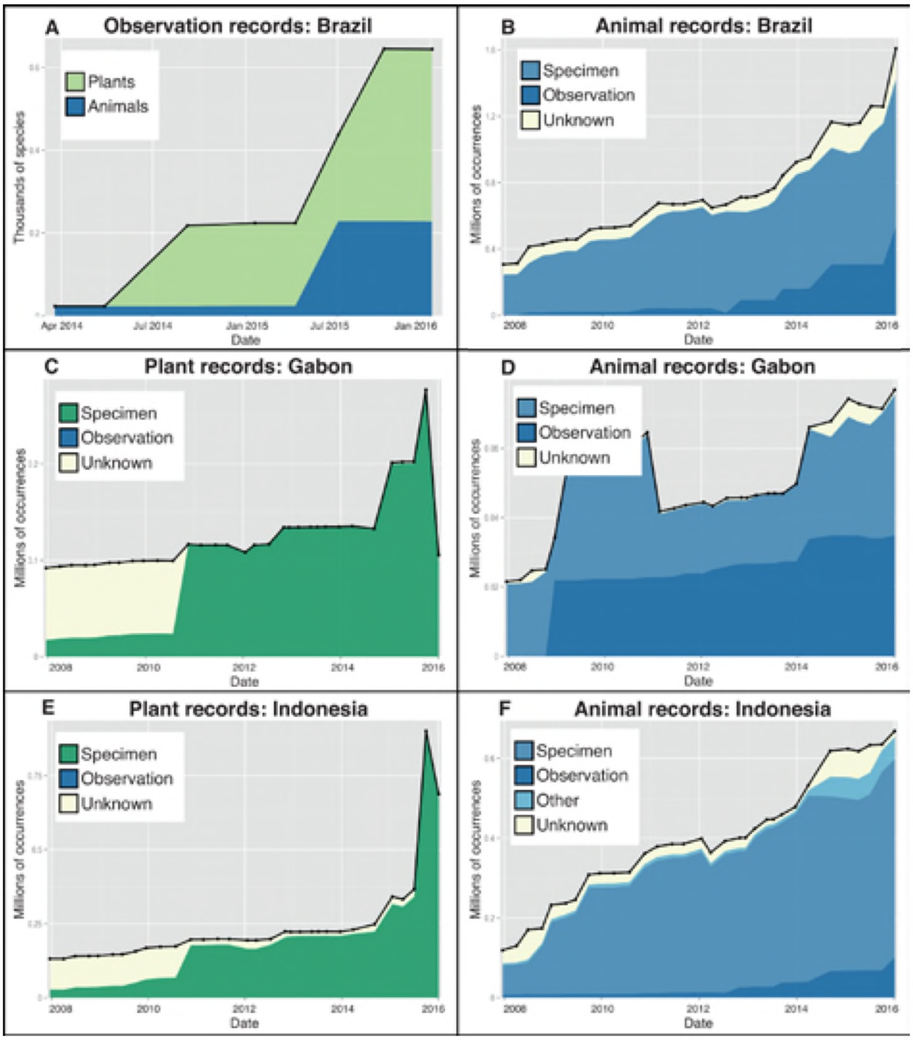


Fig. 2. The increase in observation records in GBIF. The graphs show temporal trends in the rate of new records being made accessible through the Global Biodiversity Information Facility (GBIF) for three tropical countries: Brazil (A–B), Gabon (C–D) and Indonesia (E–F). (A) exemplifies the differences between animal and plants records, while (B–F) highlight the differences between specimens and observation records. Observations are records that are not associated with a voucher specimen, such as geo-referenced photographs from citizens and records from ecological monitoring projects. (Downloaded and adapted from http://www.gbif.org/analytics on 29 March, 2016).

tude is seen not only among scientists, but also governmental agencies. In some countries, people lacking a PhD degree cannot apply for collection permits. While we complain about the lack of funding for biodiversity research, outside our ivory towers are potentially billions of people who could contribute valuable data for biodiversity research and conservation. It is now time to seize the opportunity given by the smartphone era and the increased appeal of outdoor activities in order to engage citizens in locating, identifying, and sharing information about species.

Several mobile applications already facilitate the logging and identification of species, such as iSpot, iNaturalist, Project Noah, Plant-o-Matic, and Map of Life. It is clear that certain species are not as amenable to identification through smartphone photos as others (e.g., when micro-morphological characters are required for reliable identifications). However, despite general scepticism that citizens cannot be trusted to identify specimens, this is likely not a major concern. In a recent assessment, citizens were able to correctly identify about 92% of all sightings recorded on iSpot, and more than half of these within an hour of submission (Silvertown *et al.* 2015).

Thanks to the recent engagement of citizens and scientists alike, the number of observation records – i.e., those sightings not associated with a museum specimen, but often containing georeferenced images and other locality data – is increasing rapidly in many databases, such as iNaturalist (over 2.3 million observations to date). However, there are still large differences among countries and between plants and animals, which can be seen by comparing the statistics in GBIF for three tropical countries (Fig. 2). In Brazil, there are currently about twice as many recorded observations for plants as for animals (Fig. 2A), although most records entering GBIF are still specimen-based (Fig. 2B). Both in Gabon (Fig. 2C–D) and Indonesia (Fig. 2E–F), only observations of animals are accessible through GBIF. Interestingly, the number of observation records for animals in Gabon is about the same as the number of digitized museum specimens (Fig. 2D). However, it should be noted that many of these observations were recorded during research projects and not by citizens, as just a few citizen science databases (such as eBird and iNaturalist) currently provide data to GBIF.

Species observations do not replace the fundamental role of voucher specimens for biodiversity research, a role that is correctly demonstrated throughout this volume and in the literature (e.g., Rocha *et al.* 2014). However, engaging citizens in recording novel sightings of species will greatly complement biological collections and increase our knowledge on the distribution of species - thus decreasing the 'Wallacean shortfall' (Hortal *et al.* 2015). This knowledge will in turn improve our studies on the biogeographical history of taxa, the future distribution of species based on ecological niche modelling, and the conservation status of species, among many other applications. In addition, this could also lead to a general increase in the societal understanding and appreciation for biodiversity at large.

## Conclusions and Outlook

Most people outside academia have no idea about how little we actually know about the natural world. For instance, few realize that we still have not described nearly about 86% of all terrestrial and about 91% of all marine species (Mora *et al.* 2011), and of the described ones only about 20% have been sequenced or barcoded (Hinchliff *et al.* 2015).

We have not even picked the low-hanging fruit. Until very recently, it was widely assumed that the clash between the North and South American continents through the Panama Isthmus took place 3.5 million years ago – an event with major significance for the biotic interchange between these continents, global ocean circulation, and climate. It therefore came as a surprise that the connection probably took place approximately 10 million years earlier, as was shown by biogeographical analyses based on biological collections (Bacon *et al.* 2015) and backed up by new geological evidence (Montes *et al.* 2015). Similarly, 150 years after the first classifications of the world's biogeographical regions (Sclater 1858; Wallace 1876), we are still at a point where the simple use of different methods on the same dataset of species distributions can produce large discrepancies in results and different delimitations of the world's biogeographical regions (Holt *et al.* 2013; Vilhena & Antonelli 2015). Clearly, many controversies remain to be settled and major discoveries to be made.

I hope to have convinced you that there is an exciting and prosperous future for many upcoming generations of biodiversity scientists. Public databases, open bioinformatic tools, and increased data sharing hold the potential to greatly advance biodiversity and biogeographical research (Wen *et al.* 2013; Borregaard & Hart 2016; Poisot *et al.* 2016). However, the promising prospects are accompanied by big challenges. These include our ability to thrive in an age where data are big, full of gaps and biases, and (still) poorly synthetized and integrated. In addition, we need to increase openness while safeguarding intellectual property – e.g., by providing data providers and software developers the adequate credit for their work. And we must, or course, still strongly encourage, support and reward fieldwork and the generation of novel biodiversity data. Bioinformatic solutions can do a great deal of the 'dirty work' for us, so that we can focus our limited time and resources on making sense out of noise, improving algorithms to do what we want them to, and engaging the scientific community and the general public to join forces in the understanding and protection of biodiversity.

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# Challenges for Biodiversity Science in the Era of Big Data

*Jorge Soberón*


## Abstract

The extremely fast growing amounts of 'big data' made available to modern scientists, have consequences for particularly taxonomists, phylogeneticists, biogeographers and ecologists. Therefore, new machine learning algorithms designed for pattern recognition are now common, leading to an ultimately 'black box' model of science. While it is necessary to go ahead with this development in order to detect patterns in the increasing amount of 'big data', conventional theoretical analyses of the problems will still be indispensable for interpretation and to establish the limits of reliable forecasting – in other words, to enhance understanding.


**Key Words:** CONABIO, species distribution modelling, theoretical understanding

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The term 'big data' has gained much popularity in recent years, as the extremely large and almost instantaneously updated bodies of data on banks, airlines, social networks, astronomy, elementary particles, and others are becoming accessible through the Internet, at the rate of Exabytes per day (McAfee *et al.* 2012). Big data is thus a label applied to bodies of knowledge that are digitized, so large that they require distributed or specialized storage facilities, are updated very frequently, and require special methods to be analysed. In biology, leaving aside the already vast holdings of the molecular communities (Stephens *et al.* 2015), the largest data repositories are the museum and herbarium holdings, that contain a few thousands of millions of records (Edwards 2004), and the holdings of observations recorded by amateurs (Dickinson *et al.* 2012). Although these data sources are 'big' in some sense, of the order of Terabytes, and growing reasonably fast [Megabytes per day; Soberón & Peterson 2004], they fall short of the spectacular volume and speed of change of other fields.

In view of the above, it is probably premature to assign the label of 'big data,' sensu stricto, to biodiversity data. However, it is undeniable that the organismic disciplines of biology, like taxonomy, systematics, ecology, biogeography and other similar ones, are experiencing an explosion on the amount of data digitally available (Kelling *et al.* 2009) and new technologies will increase this rate even more (Hampton *et al.* 2013). This creates challenges for our disciplines. In what follows I will explore two of them: the growing utilization of 'machine learning' methods that emphasize extracting patterns from large quantities of data, and the related question of whether that would imply that we are moving towards a different form of thinking and theorizing in organismic biology.

## Machine Learning Methods in the Biodiversity Disciplines

The very large quantity of data available now, in the form of taxonomic authority files, occurrence data, very large phylogenetic trees, sequence data, and soon image data, are difficult to organize, search, visualize and analyze without using very advanced computational methods. The sheer volume of data together with the complexity of the non-parametric algorithms that are now available (neural networks, maximum entropy, decision trees, genetic algorithms, etc.) indeed suggests that a black box approach to science, whereby patterns are found by software, and then applied to prediction without much human intervention will become the rule. For instance, simply by sequencing huge volumes of genetic materials found in seawater samples, Venter *et al.* (2004) found 148 unknown bacterial phylotypes as well as a very large amount of variation on rhodopsin receptors. Based on this type of research some have claimed that "the data deluge makes the scientific method obsolete" (Anderson 2008).

Closer perhaps to organismic biology, the area of species distribution modelling makes full use of the hundreds of Gigabytes of occurrence data, as well as advanced and complex algorithms that extract patterns from the databases. For instance, the GARP (Genetic Algorithm for Rule Production) algorithm has been used as the engine of Lifemapper (Stockwell *et al.* 2006) to create a library of hundreds of thousands of unsupervised species distributions models. GARP is the ultimate 'black box' algorithm in the sense that it outputs long lists obtained by establishing a stochastic competition among different modelling algorithms (Stockwell 2007). The output is a set of rules that describes the pattern, but not all implementations of GARP provide access to the rules! Lifemapper later substituted Maxent (Phillips *et al.* 2006) for GARP, and although Maxent is well described theoretically, and calculates a relatively simple and well defined object (a Gibbs distribution, see Merow *et al.* 2013), it is clear that many, if not most of its users, simply "… fail to interpret the original algorithms, much less understand how they were implemented in the … code" (Joppa *et al.* 2013).

Is the big data, 'machine learning' approach to science a new paradigm for the biodiversity disciplines? Kelling *et al.* (2009) believe this is the case, arguing that the complexity of ecological systems make difficult posing and testing hypothesis using parametric statistics. They describe an alternative methodology where big datasets are analyzed using sophisticated software, patterns are found, and then the patterns are tested in confirmatory analysis. Leaving aside problems with the uneven quality of big data data per se, and most relevantly, its biased (in time, space, and taxa) nature (Soberón *et al.* 2007; Engemann *et al.* 2015), and the need to deal with such biases using theoretical tools, the communities engaged in the biodiversity disciplines need to ponder in a serious way how it is that large quantities of digitally available data are changing the way we manage the relationship between the data provided by our instruments and senses, and the models, concepts, and theories that we use to describe, predict and understand the phenomena represented by the data. In the last section I will provide some reflections on this problem.

## The Role of Theory in the Data-rich Disciplines

There is no doubt that science advances by a continuous interplay between observations of phenomena and our conceptual representations of them. This is well illustrated by a famous, and contradictory (Ayala 2009), pair of statements of Darwin: "I am turned into a kind of machine for grinding general laws out of large collections of facts" (Darwin, in Barlow 1958). This would be the 'machine learning' paradigm, whereby big data is grinded into patterns. However, the same Charles Darwin also stated: "How odd it is that anyone should not see that all observation must be for or against some view if it is to be of any service!" (Darwin, letter to H. Fawcett, 18 Sept 1861, in Darwin Correspondence Project, University of Cambridge https://www.darwinproject.ac.uk/), and this second statement corresponds to the conventional scientific paradigm, of contrasting hypotheses and models against data, for the purpose of understanding (Pigliucci 2009), as well as for the purpose of pattern discovering. Moreover, without understanding, in some theoretical sense (that goes beyond the mere description of the patterns), there is no trust in prediction, another essential scientific objective.

This point is well illustrated by using an example of the Mexican Biodiversity Commission. When CONABIO started, its mandate was to create a database of the Mexican biodiversity. This lead to a large scale effort to digitize the data in national, and foreign, scientific collections. One of the first questions that the Mexican government wanted to address was how to identify suitable regions in which to create protected areas, and this in turn required them to be able to compile species' lists of arbitrary regions. Since large parts of the country are still unexplored, short of a full scale – and hugely expensive – field explorations program, the databases of specimens could be used to find patterns of high number of endemic species, and extrapolate them to unexplored regions. As soon as the specimen data started coming in large numbers (big data in relative terms), this question could be explored using Species Distribution Modeling (SDM). By 1994, CONABIO was resorting to the software called GARP, which at that time ran in the San Diego Supercomputing Centre, in California. One by one species were modeled, and although generally speaking the models made sense to the eyes of experts, they tended to overpredict, in the sense that the software often highlighted areas where the species had never been observed as part of the area of distribution. This problem was not due to lack of data. Even on a 'gedankenexperiment' with a perfect set of occurrence data, GARP (and many other algorithms) would still overpredict, but it was only later, thanks to theoretical understanding, that it became clear that the problem of overprediction was not really a problem. Theoretical understanding allowed scientists to realize that correlative species distribution algorithms (software quintessentially for pattern recognition) model something intermediate between an actual area of distribution and a potential area of distribution (Soberón 2010), and that the overprediction was actually very useful for the purpose of assessing potential impacts of invasive species, or any other species out of dispersal equilibrium (Peterson *et al.* 2011).

The morale that I would like to extract from this story is that, although the pattern looking exercise, based on large quantities of data and complicated software was indeed useful, and only possible in the era of large quantities of digitally available data and powerful software, the full comprehension, correct interpretation of the results, and an awareness of the possibilities and limits of extrapolation was the result of a conventional theoretical analysis of the problem.

## Conclusion

In organismic biology we are now fully immersed in an era of exploding growth of digitally available data. This is a novel and exciting area for the biodiversity disciplines, one that will enable both fundamental discoveries and useful applications. However for the biodiversity disciplines it would be a serious mistake to accept the simple 'pattern discovery' paradigm that is so useful in commerce, banking, and other similar activities. Science is, at its core, about not only describing and predicting, but also about understanding. Leaving aside philosophical discussions, history shows that the most interesting and deep scientific advances are associated to an attempt to understand, in some of various senses, the patterns that are discovered, or why predictions are successful. This should not be left to machines or to algorithms. In the biodiversity disciplines, theoretical developments are more necessary than ever.

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# Tropical Plant Collections and Drug Discovery

# The Future of Drug Discovery: Are collections needed?

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## Abstract

Collections serve as repositories documenting the distribution of plants across time and space. At the same time, collections, both living and preserved, are an immense source of 'big data' for a wide range of research applications from the core discipline of taxonomy to testing evolutionary relationships in the 'genomics era', drivers of biodiversity, and the highly topical impact of environmental change. In this paper, we argue that collections are also essential for medicinal plant research and have the potential to significantly impact modern drug lead discovery. Collections are, at the very least, needed to allow authoritative identification and documentation of medicinal or any other plant material. Additionally, collections provide a powerful framework for understanding variation of natural products at all scales from ecological or chemical types within species, to chemical diversity within lineages and across the entire plant domain. Examples from recent studies are that DNA barcoding can be used for authentication of *Equisetum arvense* products, and collections can provide easily accessible high quality samples for creating barcoding reference libraries. Medicinal uses of *Aloe* has been correlated with the phylogeny and succulence of the leaves, and the origin of now globally popular *Aloe vera* could be traced to the Arabian Peninsula, suggesting a connection with ancient trade routes. Using collections provide easy access to biodiversity for improving selection and focusing drug lead discovery efforts, avoid destructive collection of rare and threatened species, and provide added value to collections. However, new collections are needed in medicinal plant research, requiring additional efforts and permits to ensure compliance with international conventions and creating added synergy of North-South collaborations.

**Key Words:** authentication, herbaria, medicinal plants, phylogenetic selection, intra-specific variation

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In the face of a long list of unmet medical needs one of the grand challenges for society today is the identification of new leads by pharmaceutical companies, which can improve and restore health and welfare. Historically, plants have been very important sources of medicine, but most companies now focus entirely on synthetic libraries to identify new leads. At the same time, the number of new drugs brought to the market is steadily declining, notwithstanding the progress in design and discovery technologies during the recent decades (Scannell *et al.* 2012). Nevertheless, among twenty new chemical entities launched worldwide to the pharmaceutical market in 2010, ten (50%) are natural products (Newman & Cragg 2012). This trend is evident also in the longer perspective, as shown by Newman, Cragg and co-workers in a series of papers (Cragg & Newman 2009, 2013; Newman & Cragg 2012) and demonstrates that modern natural product based drug-discovery programs are highly productive and competitive when compared to other drug discovery technologies.

Plants provide healthcare worldwide. Twenty-five percent of modern medicines originate from plants originally used in traditional medicine, and as much as 50% of all drugs can be traced back to natural resources (Cragg & Newman 2009). A recent example is ingenol mebutate (from *Euphorbia peplus* L.) registered as a drug for treatment of actinic keratosis by LEO Pharma A/S (Berman 2012). Evolutionary processes have led plants and other organisms to develop a diversity of chemical defenses selected for their biological activity (Ehrlich & Raven 1964). Furthermore, plant metabolites are made by living organisms and consequently have an affinity for functional proteins from the outset. It is also shown that chemical diversity found in natural sources greatly outperforms that of the synthetic libraries, thus increasing the likelihood of new drug lead discovery from nature (Larsson *et al.* 2007). However, there is a range of challenges associated with drug discovery from biodiversity resources. Identification and isolation of bioactive compounds are both time-consuming and costly and the number of known as well as yet unclassified biological species, including plants, is enormous.

Whereas methods for isolation and identification of natural products have greatly advanced in recent decades, methods for the selection of target plants have hardly developed. Large-scale drug discovery programs such as the one run by the National Cancer Institute (USA) during the period 1960–1982 basically screened material from all plants available to them at random. The important new drug paclitaxel (taxol, from the Pacific Yew tree, *Taxus brevifolia* Nutt.) used in anticancer treatment, emerged from such programs (Cragg & Newman 2009; Newman & Cragg 2012). Although this is a success story of random screens, this approach can be extremely inefficient as there is no indication on the potential bioactivity of the selected plant material. To increase efficiency, academic efforts have largely focused on taking advantage of knowledge from traditional medicine to choose plants for further investigation (Bohlin *et al.* 2012). By using a systematic and integrative approach to explore the great inventiveness and diversity of nature, we may potentially provide a more efficient way of finding new and improved leads for drug development from biodiversity resources (Rønsted *et al.* 2008, 2012; Bohlin *et al.* 2012). As biodiversity is decimated by changing land use, climate change and over-exploitation, identifying the species most likely to contribute to future health needs and at greatest risk could hardly be more urgent or significant. Botanical collections contribute to addressing the grand societal challenge of improving health through supporting natural product drug discovery efforts in a variety of ways.

## The Role of Natural History Collections in the 21$^{st}$ Century

Historically, plant systematics and herbaria have roots in the first herbals or pharmacopoeias, catalogues of medicinal plants with names and descriptions of the plants and their uses, often richly illustrated (Anderson 1977; Friis 2017). Until the 17$^{th}$ century, botany and medicine were largely integrated sciences and plants were primarily categorized based on their uses. Traditional herbal medicine is probably as old as mankind, passed on through oral tradition and later through written texts (Leonti *et al.* 2015). Early herbarium collections were in the form of preserved specimens mounted on sheets bound together in a book for reference and teaching (Nesbitt 2014; Ahmed & Hasan 2016). Classical herbals such as Dioscorides' *De Materia Medica*, written between 40 and 90 Current Era, included around 500 medicinal plants and influenced European medicine for a thousand years (De Vos 2010). Currently, about 13,500 plant species are recorded in the Medicinal Plant Names Services, a global resource for medicinal plant names, assembled by the Royal Botanic Gardens, Kew (Medicinal Plant Names Services 2016). However, the estimated number of higher plant species alone used worldwide for medicinal purposes is more than 50,000 (Schippmann *et al.* 2002). The history of botanical collections, both living and preserved, is rooted in the use of plants for medicines and other purposes, and also today, and in the future, collections are essential for medicinal plant research and have the potential to significantly impact modern drug lead discovery. Collections are, at the very least, needed to allow authoritative identification and documentation of medicinal plant material. Additionally, collections provide a powerful framework for understanding variation of natural products at all scales from ecological or chemical types within species to chemical diversity within lineages and across the entire plant domain. In the era of Big Data and genomics, botanists of the 21$^{st}$ century can set the agenda by taking advantage of collections, collaboration, and an interdisciplinary approach to help develop new understanding, tools, better medicines and policies for sustainable and ethically responsible biodiversity use.

## The Importance of Collections in Natural Products Research

### *Collections are repositories and reference for identification*

A specimen deposited in a recognised herbarium serves as documentation of the identity of plant material used for natural products research and allows for later confirmation of authoritative identity of the material (Hedberg 1993; Bussmann 2015). However, herbaria are not only repositories of vouchers, but they also contain reference specimens and type specimens that can be used to verify the identity of newly collected plant material or material received from collaborators or commercial suppliers. Authoritative and verifiable identification ensures that substantial amounts of time and money are not invested in investigating plant material that may later turn out to be a different and inactive species - or may be active but cannot be identified due to lack of a voucher specimen. This may have been a real shortcoming of natural product research in past decades. An early survey by Farnsworth and Bingel (1977) concluded that out of 2399 novel chemical compounds reported in the scientific literature in 1975, only 160 of them indicated voucher specimens for future reference. The situation has improved considerably and voucher specimens are now required by journals, but the example illustrates the historical gap between natural product research and botanical methods and expertise.

Natural product researchers should consider the importance of providing vouchers of high quality with informative labels deposited in herbaria, enabling them to be more useful for other studies (Bussmann 2015). At the same time, some herbaria today are reluctant to accept sterile or other hard to identify material as well as cultivated material. However, a sterile voucher is, in any case, better than no voucher, and even the use of material from living collections in botanical gardens need vouchering rather than just reference to an accession number in the living collection. Whereas DNA barcoding inherently will allow reliable identification of sterile and other difficult to identify material in the future, the quality of accompanying information provided on the labels as well as in the materials description in the scientific publications cannot easily be improved or retraced retrospectively. Researchers should, therefore, consider including as much information as possible directly on the labels of the voucher specimens allowing specimens to be of use for future reference as well as for other types of studies.

### *Collections are a representation of biodiversity*

Collections in herbaria and botanical gardens have been assembled over centuries and often contain a good representation of all plant families and most genera. For natural product and bioactivity screening, collections are therefore an invaluable resource of authentically identified material allowing selection and study design to maximize taxonomic diversity or diversity with respect to habitat, life form or other specific traits. However, destructive sampling is always problematic, but in larger collections, there are often several specimens to choose between, and often loose material to be found in envelopes on some of the specimens or duplicates of accessions of plants in other preserved or living collections. Furthermore, modern hyphenated analytical methods and bioactivity screens require only small amounts of material (100–1000 mg of dried plant material) making highly informative screenings from collections possible without compromising the collections significantly although not all chemical markers are well preserved in dried material (Kongstad *et al.* 2014; Okutan *et al.* 2014; Liu *et al.* 2015). Researchers must also consider any potential effect of chemicals sometimes used for preserving specimens and, if relevant, avoid such specimens. Needless to say, permission to remove any part of a specimen in a collection must always be sought from the herbarium curator.

However, selection of plant material for screening studies should also consider any known information from traditional medicine or previous studies indicating which plants are most relevant to screen. The emerging approach of phylogenetic selection is discussed below. Traditional uses are sometimes recorded on the labels of the specimens or may be found in literature or through databases such as the NAPRALERT® database of natural products (*www.napralert.org*) maintained by the University of Illinois, Chicago. For DNA barcoding, studies relevant to authentication of medicinal plants are discussed below, 10–20 mg dried plant material is sufficient (Saslis-Lagoudakis *et al.* 2015a). In addition to using herbarium specimens, other types of collections such as seeds (which often have better preserved DNA) (Fordyce *et al.* 2013; da Fonseca *et al.* 2015), or wood collections (which often allow for sampling larger quantities), may be considered for some studies.

### *Collections are a source of natural variation*

Documented sourcing of material of consistent quality is required as part of the regulatory guidelines for herbal products (Council of Europe 2015), yet within-species variation is a largely neglected problem in natural product research today. It is well known that the same species may express different amounts or combinations of compounds dependent on seasonality, age, geographical origin, habitat use or other variables (Gatehouse 2002; Agrawal & Fishbein 2006; Moore *et al.* 2014). Specialized compounds are not continuously expressed, but may be produced as a response to herbivory or other damage and stress including the environment. However, most screening studies for activity only include one representative per species and subsequent identification of active compounds usually does not revisit intraspecific variation. Whereas it may not be feasible to consider intra-specific variation in large scale screening studies focusing on inter-specific diversity, collections are easily available and well-documented resources for studying both quantitative and qualitative chemical diversity within species (Berkov *et al.* 2004; Yilmaz *et al.* 2012; Saslis-Lagoudakis *et al.* 2015a). Such chemical diversity screens may subsequently help selection of the best starting material for further bioactivity studies, or hyphenated techniques may be used directly as discussed above. However, many natural products may be broken down over time compromising the value of dried and older collections for general screening.

### *Collections provide a window into the past*

Collections are of age. They provide time referenced data points which can be used to document domestication (da Fonseca *et al.* 2015), changes in distribution associated with climate (Calinger 2015), or human interaction (Dodd *et al.* 2015; Martin *et al.* 2014), flowering times (Davis *et al.* 2015; Munson & Sher 2015; Park & Schwartz 2015), or other morphological traits (Dalrymple *et al.* 2015; Everill *et al.* 2014). Using collections to look into the past can also document the history of plant pathogens (Yoshida *et al.* 2014) such as the Irish potato famine pathogen (Martin *et al.* 2014; Yoshida *et al.* 2014), mildew (Choi & Thines 2015) or rust fungi (Braithwaite *et al.* 2009; Haudenshield & Hartman 2015). Time referenced collections may also be used for exploring chemical variation over time. Whereas records in time can be readily used and morphological traits can be measured, obtaining DNA sequence data from historical herbarium samples has been difficult using classical DNA extractions and sequencing techniques as elaborated on in relation to authentication of herbal products discussed below. However, the rapid development of so-called ancient DNA techniques (Willerslev & Cooper 2005; Sarkissian *et al.* 2015) continues to open up new opportunities for including significantly older historical samples in evolutionary studies as exemplified by several centuries old rag-weed samples (Martin *et al.* 2014) and 700 year old maize kernels (da Fonseca *et al.* 2015). Surviving plant DNA has even been retrieved from more than 20,000 years old lake sediments from Greenland (Parducci *et al.* 2012).

## Examples of Collection-based Natural Product Research

### *Authentication of herbal products*

The safety of medicinal plant use is compromised by alteration and substitution, and by the availability of prohibited plants or restricted species, which can lead to severe side effects due to the presence of toxic compounds (Gilbert 2011) or raise conservation concerns. Authentication of the qualitative and quantitative composition of herbal products is regulated by international and national guidelines such as the European Pharmacopoeia (Council of Europe 2015), which provides a series of monographs for quality control of herbal products, including recommended tests for identification. However, macroscopic or microscopic identification of plant species requires considerable expertise to differentiate between closely related or similar looking species. Furthermore, morphological characters may be indistinguishable in bulk, pulverised or otherwise processed material (Han *et al.* 2013; Kool *et al.* 2012; de Boer *et al.* 2014). Authentication therefore normally includes chemical tests, typically simple chromatographic assays, which can be applied to crude drug samples in pulverized form to verify specific chemical profiles. Chromatographic techniques may also be used to reveal adulteration as demonstrated for the Ashoka bark (*Saraca asoca* (Roxb.) Willd.), which is used in Ayurvedic medicine (Beena & Radhakrishnan 2012). However, based on chemical profiles that may not be unique to a species and may be compromised by intraspecific variation, such assays rely on the existence of well-defined chemical profiles of possible adulterants for comparison and may not always confidently verify the botanical identity of the sample.

DNA-based identification methods or barcoding have often revealed adulteration in traditional medicinal preparations and herbal products (de Boer *et al.* 2015). For example, potentially toxic *Ephedra* L. and *Asarum* L. material was found in traditional Chinese medicinal products administered in Australia (Coghlan *et al.* 2012), and several adulterant plant species were found in herbal products from North America (Newmaster *et al.* 2013). However, DNA barcoding also has limitations. Depending on the condition of the plant material, amplification of the target DNA marker may not be practically possible. In a study including 100 museum medicinal specimens and herbal products from 92 species representing five orders, Han *et al.* (2013) were able to recover ITS2 from 90% of the museum specimens, suggesting ITS2 as a mini-barcode to effectively identify species in a wide variety of specimens and medicinal materials. DNA barcodes may also lack interspecific variability, particularly among closely related species. Finally, because DNA barcoding relies on the presence of a reference database, the absence of a species from the database will impede its identification success (Stoeckle *et al.* 2011; Saslis-Lagoudakis *et al.* 2015a).

The common horsetail, *Equisetum arvense* L., is used in numerous herbal products for mild urinary and renal conditions and as skin, hair and nail remedies, but it can be adulterated with closely related species, especially *Equisetum palustre* L. that produce toxic alkaloids. The potential of using DNA barcoding for identifying *Equisetum* L. species using material from herbarium collections and commercial herbal products was tested by Saslis-Lagoudakis *et al.* (2015a). Using herbarium collections from herbarium C, it was possible to include in this study all 15 species of Equisetum and a broad geographical representation of both *Equisetum arvense* and *Equisetum palustre*. This study showed that DNA barcoding could be used for authentication of *Equisetum arvense* products, and that collections can provide easily accessible high quality samples for creating barcoding reference libraries (Saslis-Lagoudakis *et al.* 2015a). Other examples are provided by market surveys of the drug trade of *Phyllanthus* in India (Srirama *et al.* 2010) and a broad spectrum of medicinal plants traded in Morocco (Kool *et al.* 2012).

Looking ahead, phylogeny and comparative sequence analysis made possibly by sampling collections, opens up the possibility of enhanced regulatory control. Additional opportunities could be tracking the supply chain to elucidate the drivers and the extent of substitution and adulteration – data that could provide significantly more effective monitoring to protect health of consumers on one hand, and health of the wild biodiversity resource on the other hand.

### *Phylogenetic selection of medicinal plants and new leads*

During evolution, plants and other organisms have developed a diversity of chemical defense compounds leading to the evolution of various groups of specialized metabolites, such as alkaloids, terpenoids, and phenolics, selected for their endogenous defense function (Ehrlich & Raven 1964; Becerra 1997). Intuitively, a correlation between phylogeny and biosynthetic pathways is sometimes assumed (Ehrlich & Raven 1964; Hegnauer 1962–1973) and could offer a predictive approach enabling the elucidation of biosynthetic pathways (Rodman *et al.* 1998; Rønsted *et al.* 2003), insights into defense against herbivores (Wink & Mohamed 2003; Becerra *et al.* 2009), more efficient selection of plants for the development of traditional medicine and lead discovery (Rønsted *et al.* 2008, 2012; Zhu *et al.* 2011; Grace *et al.* 2015; Saslis-Lagoudakis *et al.* 2015b) as well as inform conservation policies (Forest *et al.* 2007).

How can we implement a phylogenetic selection of medicinal plants? One approach may be to identify 'Hot Nodes' of bioactivity. By exploring plant uses in a phylogenetic context, based on plant molecular phylogenies that were generated largely from herbarium collections, Saslis-Lagoudakis *et al.* (2011, 2012) demonstrated that certain nodes are significantly overrepresented by species with different medicinal properties.

Another approach is to better understand the correlation between phylogeny, chemistry and bioactivity. Alkaloids occurring in Amaryllidaceae subfamily Amaryllidoideae are known to possess central nervous system activities (Jin 2011) including galanthamine originally isolated from snowdrops (genus *Galanthus* L.), which is registered as a drug for the inhibition of acetylcholinesterase associated with the progression of Alzheimers disease (Heinrich & Theo 2004). Taking advantage of collections, Rønsted *et al.* (2008, 2012), explored the phylogenetic correlation of alkaloids with central nervous system activities in Amaryllidaceae subfamily Amaryllidoideae. They found significant correlation of alkaloid diversity and in vitro inhibition of acetylcholinesterase and binding to the serotonin reuptake transporter, but the effect was not strong.

Phylogenetic studies can also provide insights into the origins and explanations of the uses of medicinal plants. *Aloe vera* L. supports a substantial global trade, but both its natural origin and explanations for its popularity over 500 related *Aloe* species in one of the world's largest succulent groups, have remained uncertain. Comparison of monosaccharide profiles of 30 species representing the diversity of aloes (Grace *et al.* 2013) found the common glucose-mannose-xylose profile identified in *Aloe vera* and other commercially important species, to be shared by many other *Aloe* species. Using a phylogenetic approach and published medicinal uses, Grace *et al.* (2015) constructed a phylogenetic hypothesis including over 200 species from a combination of curated living collections and wild origins. They found that medicinal use was correlated with the phylogeny and succulence of the leaves, and for the first time, the origin of *Aloe vera* was traced to the Arabian Peninsula, suggesting a connection with ancient trade routes as an explanation for the global popularity of *Aloe vera* today.

With almost 2000 species and only about 5% of species in the genus chemically investigated (Vasas & Hohman 2014), *Euphorbia* exemplifies the need for a systematic approach to plant-based drug discovery an effort currently being undertaken as part of the MedPlant International Training programme (Ernst *et al.* 2015). The genus *Euphorbia* (spurges, Euphorbiaceae) is the third largest genus of flowering plants, with a near-cosmopolitan distribution and remarkable morphological diversity, including annual herbs, succulents and large trees, united by a unique, flower-like inflorescence and often poisonous, milky latex. Medicinal uses have been identified for >5% of the species in the genus (Ernst *et al.* 2015) and ingenol mebutate (Picato®), a diterpenoid isolated from *Euphorbia peplus* L. is marketed for the topical treatment of actinic keratosis (Berman 2012). Given the high number of chemically unexplored species, and the signature diterpenoid chemistry of *Euphorbia* latex (Vasas & Hohman 2014), species with a higher production of compounds of interest or new drug candidates with therapeutically relevant activity profiles await discovery.

Despite these few examples, the predictive power of phylogenies is still not fully explored, and there are no standard methods for application of phylogenetic selection (Saslis-Lagoudakis *et al.* 2015b). Development of new approaches and technologies for selection of biodiversity resources for lead discovery is also one of the objectives of the MedPlant International Training Network, *www.MedPlant.eu*, which aims at training a new generation of young scientists in interdisciplinary approaches to explore medicinal plant diversity.

## Future Directions

### *An interdisciplinary approach*

Science today has become a collaborative and highly interdisciplinary effort, where scientists work together and take advantage of highly specialised complementary expertise to gain as much information as possible from their data (Van Noorden 2015). Such interdisciplinary science is not only necessary because the amount and types of data we can obtain continues to increase, but also because new exciting research questions may be addressed. To solve the grand challenges facing society today – energy, water, climate, food, and health – scientists and social scientists must work together (Ledford 2015).

The MedPlant programme synthesizes and takes advantage of botany, phylogeny, bioinformatics, ethnobotany, natural products chemistry and bioactivity studies to take a fresh look at the evolution of chemical diversity, the development of pharmacopoeias, and sustainability and safety, to develop and refine new approaches and technologies for selection of biodiversity resources for lead discovery. However, interdisciplinarity takes time and requires a mutual mission and the will to understand and overcome different paradigms, theoretical, and methodological traditions (Ledford 2015; Van Noorden 2015).

Collections are at the heart of these interdisciplinary efforts by providing material and data, which may be used for addressing a plethora of research questions. Botanists and curators working with collections are at an advantage by knowing the collections and being able to define exciting new research questions that can be addressed with the collections and by joining forces with relevant colleagues in other scientific fields such as ecology, genetics, bioinformatics, history, ethnopharmacology, natural products research, as well as with governmental agencies, NGOs, or industry as relevant. In the era of Big Data, botanists and curators of collections also have an important role in securing high quality data for interdisciplinary studies, including the curation of the ever growing public databases (Maldonado *et al.* 2015).

### *Merging collections and archives*

The value of collections is related to the associated information, such as the name of the collector, the date, locality and recorded field data. Additional information may be accompanying collections, such as expedition journals, letters and lists from the collector, card catalogues, field images of plants and scientific publications. However, a clear link between the collections and scientific publications or archives is not always present, but may be retrieved through additional research. A classical example is the lack of assigned type specimens to species named by Linnaeus. The Linnaean Plant Name Typification Project is now addressing this by establishing type specimens retroactively for the 9000 plant names of species established and named by Linnaeus, so that the names can be correctly used (*http://www.nhm.ac.uk/our-science/data/linnaean-typification/*; accessed 16/1-2016).

The possibility of obtaining DNA sequences from herbarium specimens also allows for better identification of specimens that are difficult to identify either because of the quality or incompleteness of the specimen or because of uncertain species concepts or complexes. Thapsigargin from the Mediterranean *Thapsia garganica* L. is currently being developed into a product for treatment of certain cancer forms, and alternative production methods are being investigated to overcome expected supply problems (Andersen *et al.* 2015). However, the biosynthetic pathway to thapsigargin and the species concepts in the genus *Thapsia* L. are not well understood, impeding prediction of a more productive better source for the production of thapsigargin. In a phylogenetic study of *Thapsia* (Weitzel *et al.* 2014), it was possible to link published chemical screening data (Rasmussen *et al.* 1981; Christensen *et al.* 1997) with the original voucher specimens, thereby allowing reassessment of the original identifications in a difficult plant genus. Reassessing published chemical distribution data in a phylogenetic context allows us to both improve our chemotaxonomic understanding and to evaluate the taxonomic value of chemical markers, as well as to take advantage of the published data to predict biosynthetic pathways or select clades of interest for further chemical studies (Rønsted *et al.* 2008; Larsson & Rønsted 2014; Weitzel *et al.* 2014). Linking specimens with archives or published data improve the value of collections but also of the aforementioned, or even leftover material or other biocultural collections (Hedberg 1993; Salick *et al.* 2014; Maldonado *et al.* 2015; Soelberg *et al.* 2015).

Soelberg *et al.* (2015) discovered archived historical documents from the colonial days of Ghana, describing medicinal plant uses among the Fante, Ga and Ashanti people of present-day Ghana. These historical medicinal uses could be linked to original botanical specimens in European herbaria and provided a unique opportunity to gain insight to the historical Materia Medica of Ghana. By comparison to contemporary medicinal plant uses, this study provided the foundation to reconstruct forgotten medicines, i.e. lost or discontinued Ghanaian plant uses in local or ethnopharmacological contexts. The scientifically strong voucher material allowed for authoritative identification of a high number of historical medicinal plants and their roots in traditional Ghanaian medicine systems 200-300 years ago. Of the 134 specific historical uses, 41 (31%) were traced to contemporary medicinal plant uses in Ghana and represent some of the most important Ghanaian medicinal plant species. However, 93 (69%) of the historical uses could not be traced and appear to have been discontinued or forgotten. Among the Ga people, only two medicinal plants species have become rare or locally extinct, thus the vast majority of the loss of knowledge appears to be due to cultural extinction. This conclusion confirms current awareness that traditional languages and practices and thus knowledge about how to use the plants may be disappearing faster than the plants themselves (e.g., Alves & Rosa 2007).

### *Aligning with international regulations*

Along with the potential discovery of new medicinal uses of plant species based on collections, two potential problems related to the conservation and intellectual property rights arise. When paclitaxel (taxol) from the Pacific yew tree, *Taxus brevifolia* Nutt., was discovered as a cure against various forms of cancer in 1962 through a large screening programme conducted by the National Cancer Institute (Wani *et al.* 1971), the pacific yew tree was already becoming threatened, but a more stable resource of the drug was secured through chemical semi-synthesis from the common yew, *Taxus baccata* L. (Malik *et al.* 2011). However, a survey by the Botanic Gardens Conservation International (Hawkins 2008), warned that 'cures for things such as cancer and HIV may become extinct before they are ever found'. They identified 400 medicinal plants at risk of extinction from over-collection and deforestation. A recent example is *Hoodia gordonii* (Masson) Sweet ex Decne from Namibia and South Africa, which became threatened by collectors after it was advertised as a potential source of weight loss drugs (Vermaak *et al.* 2011).

Whereas taxol was discovered through a random screening programme, the benefits of *Hoodia* was based on the San peoples' use of this plant, but without seeking prior informed consent from the San (Vermaak *et al.* 2011). Since the 1980s, the use of biological resources and indigenous peoples knowledge has been addressed by international conventions, such as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES; www.CITES.org) and The Convention on Biological Diversity (CBD; *www.cbd.int*) and the recent addition, the Nagoya Protocol (https://www.cbd.int/abs/doc/protocol/nagoya-protocol-en.pdf).

Researchers working on drug discovery from collections must, therefore, be aware of international regulations, as well as consider solutions to potential supply problems and conservations issues. Embracing and consolidating strong North-South collaborations is part of a forward-looking solution. Doing so, botanists of the 21st century can set the agenda by taking advantage of collections, collaboration, and an interdisciplinary approach to help develop new understanding, tools, better medicines and policies for sustainable and ethically responsible use of biodiversity resources.

### *Medicinal plant research can also benefit collections*

Although the prospect of developing new drugs improving human health is in itself worthwhile, medicinal plant or natural products research can also benefit collections, through increased public awareness and appreciation of both biodiversity and the importance of collections – if facilitated through public dissemination and engagement activities. Collection-based drug discovery programs, big or small, may also help raise funds for taxonomic and curatorial work in connection with medicinal plant research projects. New collections or fieldwork may also provide new specimens to the collections and other additional information or samples can be collected simultaneously for uses other than drug discovery (e.g., Maldonado *et al.*

2015). Collections have their roots in herbals and finding new exciting ways of integrating collections with modern drug discovery, through interdisciplinary collaborations, is highly timely and will likely provide new synergy and results benefitting both our collections and our health.

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# Tropical Plant Collections and Molecular Systematics

# Herbarium Genomics, Skimming and Plastome Sequencing

*Freek T. Bakker, Di Lei and Rens Holmer*



## Abstract

Herbarium genomics is a promising field, as next generation sequencing approaches are well suited to deal with the usually fragmented nature of archival DNA. We show that routine assembly of plastome sequences from herbarium specimens is feasible, from total DNA extracts and apparently only slightly depending on specimen age. We used genome skimming and an automated assembly pipeline, iterative organelle genome assembly (IOGA), that assembles paired-end reads into a series of candidate assemblies, the best one of which is selected based on assembly likelihood estimation. We used 93 specimens from 12 angiosperm families, 73 of which were from herbaria with specimen ages up to 146 years old. For 84 specimens, a sufficient amount of paired-end reads were generated (at least 50,000), yielding successful plastome assemblies for 74. Differences in plastome assemblies between herbarium and fresh specimens were modest, but the same assembly lengths were obtained. Specimens from wet-tropical conditions appear to have a higher number of contigs per assembly and lower median contig length, indicating they need more editing compared with specimens collected from dry areas. Using fungal rDNA sequences as reference in IOGA we retrieved limited anounts of reads from our samples, both silica-gel dried and herbarium, and find that fungal rDNA is not easily assembled. We conclude that routine plastome sequencing from herbarium specimens using genome skimming is feasible and cost-effective and can be performed with highly limited sample destruction.

**Key Words:** DNA sequence data, herbarium specimens, IOGA, museomics, organellar genomes

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Obtaining DNA sequence data from museum specimens has been an intriguing endeavour ever since the first attempts proved successful in the 1990s (Pääbo 1989; Savolainen *et al.* 1995; Shapiro *et al.* 2002). The notion that museum collections actually represent 'dead DNA repositories', hence enabling the testing of historical biological hypotheses, has inspired many workers to exploit collections further (e.g. Neubig *et al.* 2014) whilst minimising destructive sampling. This has led to an increase in activities in optimising sampling DNA from museum specimens, as for instance in the EU FP7-funded SYNTHESYS II programme (see http://www.synthesys.info/joint-research-activities/), where efforts have focussed on such issues as optimising DNA extraction from muco-polysaccharide-rich tissues, or minimising sampling damage (by taking small samples) from rare archaeological bone fragments. In addition, modeling of DNA decay in such material enabled quantifying the risks associated with destructive analysis of specimens prior to DNA extraction (Smith *et al.* 2003; see thermal-age.eu). All in all, the term 'museomics', i.e. the large-scale analysis of the DNA content of museum collections, has become established in several research programmes (e.g. Der Sarkissian *et al.* 2015; Gushansky *et al.* 2013; Chomicki & Renner 2015; Fabre *et al.* 2014), in addition to 'palaeogenomics' (Hofreiter *et al.* 2015).

Over the past decades museomics has been primarily focussed on improving polymerases and PCR reagents used in working with archival DNA (e.g. Hajibabaei *et al.* 2005). Efforts included developing (recombinant) polymerases with lower error rates than is typical (1 in 10,000–50,000 base pairs, which is too high for most applications), by revisiting hot springs and hydrothermal vents from where the original *Thermus acquaticus* was isolated (Chien *et al.* 1976) in persuit of thermostable polymerases with 3'-5' exonuclease proofreading capacity. Or using Restorase (Sigma-Aldrich, St Louis, MO, USA), capable of handling fragment lengths from 200–20,000 bp, in case of damaged DNA. Whereas these efforts have had mixed succes, and PCR inhibition in ancient DNA samples remains a significant problem (Kemp *et al.* 2014), this has now all been taken over by the emergence of next generation sequencing (NGS) technology. 'Suddenly' the fragmented nature of archival DNA is not a problem anymore as the massive parallel sequencing approach followed in most 'second generation' sequencing platforms uses a fragmented template anyway (Metzker 2010); in contrast, 'third generation' sequencing involves single molecule sequencing instead (Hörandl & Appelhans 2015), making it less suitable for archival DNA.

Since the application of NGS, spectacular results have been obtained in museomics, with, e.g. discovering new hominids from sequencing of small bone fragments (Reich *et al.* 2010), sequencing genomes from extinct lineages such as the Tasmanian tiger (Miller *et al.* 2009), or placing Caribbean endemic lineages of rodent (Fabre *et al.* 2014). All in all, next-generation sequencing has opened up tremendous possibilities for sequencing museum specimens due to increased output and power, but also because of ever-decreasing costs (Millar *et al.* 2008; Metzker 2010; Glenn 2011; Rowe *et al.* 2011; Buerki & Baker 2015).

## The Botanical Perspective

From a botanical perspective, things are a little different given that, apart from the presence of a third genomic compartment, the plastid genome or 'plastome', the angiosperm nuclear genome is usually of much larger size than that from animals or fungi (Gregory *et al.* 2007; and see also below) and contains many repeats, which hampers genome sequence assembly. Nevertheless, herbaria do take a special place in museomics as the possession of cell walls in plant (and fungal) material provides much better protection for DNA than is the case in animal tissues (Mateiu & Rannala 2008; Roldán-Arjona & Ariza 2009), for instance for damage due to oxidative stress. On the other hand, herbarium specimens are often dried with heat, which can have adverse effects on the immediate survival of DNA. It is fairly well understood that applying heat to DNA when it is in a desiccating specimen is not favourable and can cause a range of irrepairable damage, both single- and double-stranded (Staats *et al.* 2011; Bakker 2015). Double-stranded damage causes the number of amplifiable template molecules to be reduced, as herbarium DNA is typically highly degraded into low molecular weight fragments (Doyle & Dickson 1987; Pyle & Adams 1989; Harris 1993). Single-stranded damage, however, leads to the generation of erroneous sequence information or mis-coding lesions. Thus, damaged nucleotides in herbarium DNA may result in damage-specific nucleotide mis-incorporations (miscoding lesions) by DNA polymerases during amplification (Hofreiter *et al.* 2001; Gilbert *et al,* 2003; Stiller *et al.* 2006). This includes the occurrence of a-puric sites, de-aminated cytosine residues, and oxidized guanine residues, as found in studies in vivo and on ancient DNA (Lindahl

1993; Pääbo *et al.* 2004). This type of damage is in principle polymerase-bypassible, leading to incorrect bases in the inferred sequence. Studies involving experimental preparation of herbarium specimens and the use of next generation sequencing (Staats *et al.* 2011, 2013; summarised in Bakker 2015) indicated no evidence for increased post-mortem single-stranded damage in herbarium specimens up to 100 years old. These specimens were compared with fresh DNA of the same individuals (trees growing in the Botanical Garden Leiden, The Netherlands), allowing the assertion that herbarium DNA sequence data are accurate. Whereas quantitative PCR assays indicated 90% of the DNA to be inaccessible to polymerases, probably due to double-stranded breaks directly after heat treatment, the remaining molecules are sequenced without apparant mis-coding lesions (single-stranded damage) irrespective of specimen age (Staats *et al.* 2011). Based on these data, 'DNA repair protocols' such as those suggested by Yoshida *et al.* (2015) for herbarium DNA are therefore probably not nessecary.

In a follow-up study, Staats *et al.* (2013) demonstrated that by using Illumina HiSeq technology, herbarium DNA is perfectly amenable to plastome sequencing (in spite of the 90% DNA 'lock-up'), and in case of a 43-year-old *Arabidopsis thaliana* (L.) Heynh. specimen, a full nuclear genome was sequenced as well (at 12 × average coverage). Indeed, herbarium genomics has already yielded valuable data and contributed importantly in testing historical biological hypotheses: for instance, genomes were sequenced from type specimens and rare or extinct species stored in herbaria by Zedane *et al.* (2015). Herbarium DNA was used for finding previously unknown sister groups for important crops (Sebastian *et al.* 2010; Chomicki & Renner 2015), or in SNP analysis in genotyping by sequencing of species in *Solidago* (Asteraceae) (Beck & Semple 2015). To study historical pathogens, Yoshida *et al.* (2014, 2015) determined the genotype of the *Phytophtera infestans* (Mont.) de Bary strain that caused the great Irish potato famine in the 19$^{th}$ century. Likewise, herbarium DNA was crucial in discovering ancient alleles in *Alopecurus myosuroides* Huds. that are relevant to herbicide resistance but pre-dating human influence (Délye *et al.* 2013). Reconstructing the shift to C4 photosynthesis in grasses could be conducted using DNA from a 100 year old Malagasy herbarium specimen for which both its phylogenetic placement and its 'genetic make-up' with regards C4 photosynthesis could be assessed (Besnard *et al.* 2014). For taxonomy and DNA barcoding herbaria collectively represent a potential treasure trove ready to be exploited (e.g. Xu *et al.* 2015). Bebber *et al.* (2010) estimated that around 70,000 new species are already in herbarium collections, 'waiting to be described'.

Therefore, it is probably fair to say that we are currently at the dawn of a herbarium genomics era (Buerki & Baker 2015), and chances are high that a large body of plant archival genomic data will be generated in the years to come. This can only underline the vital importance of securing our herbarium collections for further molecular exploitation. In addition, there is an unprecedented need for more or less automated bioinformatics pipelines for genome sequence assembly as well as for annotation and gene sequence compilation and alignment. Obviously, such tools will greatly expedite the process of massive herbarium plastome sequencing (and of other genomic compartments).

In this chapter, we discuss recent findings on generating plastome sequences from a range of fresh and herbarium angiosperm specimens, and outline challenges and issues relating to assembly accuracy, possible contamination and the use of (tropical) plant specimens.

## Herbarium DNA Extraction: Garbage in, garbage out?

Challenges to extracting genomic data from herbarium specimens abound, starting with DNA extraction. Various studies (Erkens *et al.* 2008; Särkinen *et al.* 2012; Drábková *et al.* 2002; Telle & Thines 2008) focus explicitly on the efficiency of extraction and on the quality of herbarium DNA, mostly measured by PCR amplification. The expectation was that heat treatment (see above) but also the 'Schweinfurth method' (Schrenk 1888), which includes spraying specimens with ethanol in order to stop fungal growth, prior to heat treatment, will have been used in preparation of herbarium specimens. The general consensus is that when extracting DNA from herbarium leaf material, most commercially available solutions are fine as long as some combination of CTAB protocols (Doyle & Dickson 1987; Doyle & Doyle 1987) and anion exchange purification is applied. Yields are usually low, which can obviously be a problem when dealing with small, historic specimens, especially types.

In addition, and perhaps not unexpectedly, short PCR fragments were always found to amplify better using herbarium DNA (Särkinen *et al.* 2012) which is due to the fact that extracted herbarium DNA is almost always highly fragmented (Staats *et al.* 2011). As mentioned above, this double-stranded type of damage is most likely the result of herbarium specimen preparation, which is known to induce high levels of metabolic and cellular stress responses and ultimately cell death (Savolainen *et al.* 1995). The high temperatures (60–70 °C) at which herbarium specimens are typically dried cause cells to rupture quickly, releasing nucleases and other cellular enzymes (Gill & Tuteja 2010), as well as reactive oxygen species. Such physiological conditions resemble necrosis, and this cellular stress typically causes DNA to degrade randomly into smaller fragments, running as a smear on agarose gels (Reape *et al.* 2008; McCabe *et al.* 1997).

## After the PCR Era

Precisely this aspect, fragmentation of herbarium DNA, transfigured from 'nuisance' to 'blessing in disguise' in the NGS world, as targeted (Sanger) sequencing of amplified fragments has been replaced by massive parallel sequencing (Metzker 2010), which requires fragmentation of the template genomic DNA. Therefore, the problems associated with traditional herbarium DNA extraction in the PCR era, i.e. low yields and DNA fragmentation, came into a new light with fragments now being incorporated directly into NGS libraries, and the generally low yields sometimes being overcome by whole genome amplification (WGA). Whereas WGA can help obtaining enough DNA strands for proper library building, it can in principle, however, cause artefacts in the representation of the target genomes and hence in genome sequence assembly. The alternative is to use more starting herbarium material, but generally speaking, for plastome sequencing one square centimeter of herbarium leaf tissue suffices for successful extraction, library preparation and (Illumina) sequencing, which will be feasible for most specimens.

On the other hand, herbarium DNA fragmentation can sometimes have happened to such an extent that the efficiency of paired-end sequencing using Illumina HiSeq is affected. In such cases, the effective insert size in the sequencing libraries becomes so small that the actual sequencing reads 'meet in the middle' of the insert and start to overlap, therefore reducing the power of the paired-end information used in the assembly. Furthermore, it is clear that in such cases the use of third generation technologies such as provided by Pacific Biosciences (www.pacb.com) using whole molecule sequencing is prevented.

## Genome Skimming

The angiosperm genome size ranges from a minute 65 Mb (parasitic *Genlisea*, Lentibulariaceae) up to a staggering 150,000 Mb (octaploid *Paris japonica*, Melianthaceae) and is on average considered to be 6000 Mb long (Litt 2013). Well over half the angiosperm genomes estimated to date were found to be smaller than 5000 Mb and about one-third to be under 1000 Mb (Murray *et al.* 2010). Therefore angiosperm genome sequence assembly represents a huge challenge (e.g. The Tomato Genome Consortium 2012) and is by far not as routine an undertaking as it is in animal and fungal genomics. Some parts of the angiosperm genome, however, are present in high copy number, notably the rDNA cistron repeats, the organellar genomes, i.e. the plastome and the chondrome (mitochondrial genome), and the different classes of highly repeated elements among which we distinguish microsatellite regions and long terminal repeats or transposable elements. Because of their repetitive nature, such regions will collectively be relatively well represented, even in a limited or 'skimmed' second generation sequencing sample that, by itself, would be too small to cover the entire nuclear genome. 'Genome skimming' has therefore been coined for the approach where superficial sequencing is performed and only genomic repeats or organellar genomes are represented with sufficient sequencing depth (Straub *et al.* 2012; Dodsworth *et al.* 2015). Usually this results in relatively low costs compared with full genome sequencing (although the cost for sequencing library preparation remains the same), and therefore it is an approach well suited for comparative studies involving many specimens. Another advantage of a skimming approach is that it prevents introducing rare variants and errors from various sources (Lonardi *et al.* 2015), whilst at the same time maintaining sufficient coverage for each repetitive genomic compartment. In a sense, it makes genome skimming comparable again with Sanger sequencing, in which 'rare variants' are marginalised in light of a main, average signal peak in Sanger trace files.

## IOGA

In a paper in a special issue on 'Collection-based research in the genome era' in the *Biological Journal of the Linnean Society* we described an automated bioinformatics assembly pipeline for angiosperm organellar genomes, including iterative organelle genome assembly (IOGA) based on genome skimming data (Bakker *et al.* 2016). Our approach is similar to the 'baiting and iterative mapping' MitoBIM pipeline described by Hahn *et al.* (2013) for mitochondrial genomes, the difference being that IOGA does not require closely related reference organelle genome sequences, and in addition that best assemblies are selected from multiple candidate assemblies. The IOGA Python script can be obtained from Github (https://github.com/holmrenser/IOGA), and is usually run after first taking a random subsample of reads *R* from the overall read pool in order to avoid excessive plastome coverage (and hence excessive processing time); the subsample typically includes 1M forward and 1M reverse reads. *R* is then subjected to IOGA which includes the following steps : (1) low quality, adapter and other Illumina-specific sequences are trimmed from individual reads; (2) plastid genome-derived reads ('$R_{Pl}$') are filtered out of *R* by aligning the latter to a panel of reference angiosperm (and land plant) plastid genome sequences, using Bowtie (Langmead *et al.* 2009). $R_{Pl}$ is then subjected to the following steps: (3) using SOAPdenovo2 (https://github.com/aquaskyline/SOAPdenovo2) assemblies are made from the filtered, trimmed and corrected plastid reads contained in $R_{Pl}$, using k-mer values ranging from 37–97; and (4) 'best assemblies' are selected using the N50 criterion and then used as a 'new reference' in order to find target-specific reads from *R* that were not selected in the first iteration. (N50 is defined as the median length-weighted contig length or the length for which the collection of all contigs of that length or longer contains at least half of the sum of the lengths of all contigs.) Step (4) is then repeated until no further $R_{Pl}$ reads are found, followed by (5), assembly of the final set of reads with SPAdes3.0 (Bankevich *et al.* 2012). This assembler applies a bi-directional De Bruijn graph, solving 'complex knots', under a range of different k-mer settings. Finally, (6) in order to select among candidate assemblies from SPAdes (step (3)) we apply a 'read'-driven test named 'assembly likelihood estimation' (Clark *et al.* 2013), which calculates the likelihood of the fit of the original reads to each candidate assembly, using a model that includes parameters such as 'read quality', 'mate pair orientation', 'read alignment' and 'sequence coverage'. The ALE test therefore assures assembly quality at the read level (Clark *et al.* 2013) and the one with the best -LnL score is selected as final assembly, (5), which is then subjected to further genome annotation (for instance using DOGMA; Wyman *et al.* 2004). After scaffolding, i.e. correcting the relative orientation and order of contigs using 'map to reference' in Geneious (www.geneious.com), final assemblies are then compared with available 'nearest' reference plastome sequences in order to check accuracy of our assemblies. This is done in pair-wise alignments using MUMmer plots (Kurtz *et al.* 2004), as implemented in MAFFT using default settings (Katoh & Standley 2013); basically, one would expect co-linearity of assembly and reference plastome in case of conspecifics. For further technical information on IOGA, scripts, updates and programmes used, see the Github mentioned above and Bakker *et al.* (2016).

## A Herbarium Genomics Test-case

Using the IOGA pipeline described above, we compared 93 specimens from 12 angiosperm families, 73 of which were herbarium specimens up to 146 years old, to explore the feasibility of herbarium genomics (Bakker *et al.* 2016). After DNA extraction and quantification, carried out under standard conditions (i.e. not in an ancient DNA lab), sequence library preparation, index PCR and equimolar pooling of indexed libraries were conducted and all libraries were then sequenced on four lanes on an Illumina HiSeq 2000 platform using paired-end chemistry. For 84 out of our 93 specimens, sufficient numbers of paired-end reads were generated (at least 50,000), with all but two of the failed specimens being from historical herbarium material. A significant negative correlation was found between total reads per sample and specimen age, indicating that despite PCR enhancement of poor samples in the library preparation, older specimens still give fewer reads. The 84 successful samples were then subjected to IOGA, which yielded (after filtering out all contigs < 1000 bp) successful plastome assemblies for 74 specimens (80% of the specimens), at a rate of approximately one hour per specimen using IOGA on a 64GB RAM Linux workstation with 16 cores. The fact that 19 of our 93 specimens did not yield plastome assemblies we feel may have been due to the fact that not enough copies of these plastomes were present in the first place or the required equimolar mixing of specimens in the Illumina flow cell may have been unsuccessful, causing libraries for those specimens not to be sequenced successfully.

Assembly lengths varied from 6–220 kb with an overall average total assembly length of 136,167 bp, which is consistent with reported average angiosperm plastome length, 120–170 kb (e.g. Downie & Palmer 1992), including two inverted repeat (IR) regions of, on average, 25 kb each. In one case, *Pelargonium elegans* Willd., a 117-year-old herbarium specimen, using only 24 ng of herbarium DNA, yielded a 167,770 bp assembly; from another, *Aethionema membranaceum* DC., a 146-year-old herbarium specimen, a complete plastome sequence was obtained. After checking pair-wise alignments (MUMmer plots) of best assemblies in selected samples, we found good co-linearity with the published reference plastome sequence in cases for which reference and target were the same species, indicating accurate plastome sequence assembly. Reduced co-linearity was found in case of congenerics, which reflects phylogenetic distance between target and reference rather than mis-assembly.

When comparing fresh and herbarium specimens in terms of plastome assembly, it was found that differences were modest, with herbarium specimens yielding lower fractions of plastome-derived reads (4%) compared with those from fresh and silica-gel dried specimens (13%; Fig. 1). This would suggest that plastids may be lost preferentially, after herbarium specimen fixation with high temperatures. This seems to contradict the studies by Staats *et al.* (2011), who did not find evidence for preferential degradation of organellar DNA in herbarium tissue based on quatitative PCR assays. In any case, herbarium specimens appear to yield enough reads for effective plastome assembly; we found that total assembly length did not differ significantly between fresh and herbarium specimens, but that fresh samples on average yielded longer individual assemblies. This indicates that the specimen preparation process, which often included heat treatment, causes plastome assemblies to be more fragmented compared with fresh samples, possibly in additional fragments <1000 bp. Nevertheless, total assembly length from herbarium DNA is the same, and herbarium assemblies just need slightly more more editing and 'scaffolding'.

Unexpectedly, specimen age per se does not seem to correlate with plastome assembly succes. Of the 74 succesful specimens in Bakker *et al.* (2016), there were eight specimens older than 80 years, half of which gave plastome assemblies (>125kb) that may be complete (or excluding one IR region). For all other spec-

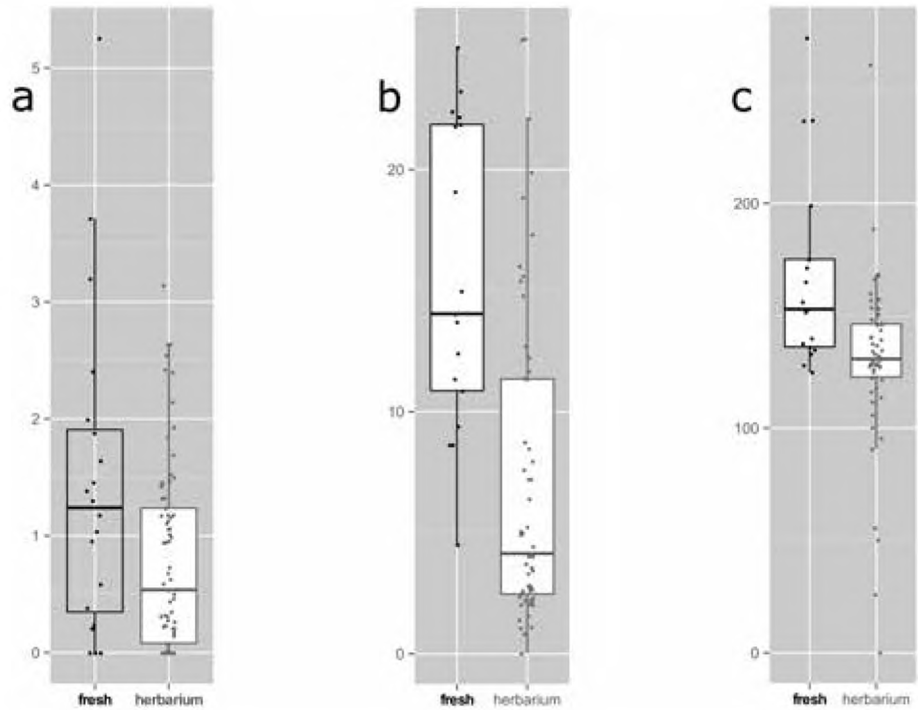


Fig. 1. Median, first and third quartile and 95% confidence interval of median of total number of reads (× $10^7$) for fresh or silica-dried samples vs. those from herbarium samples (a); the same for plastid-derived reads $R_{\mathrm{Pl}}$ (b); total assembly length (in kb) for 74 successful assemblies derived from fresh or silica-dried vs. herbarium specimens (c). Re-drawn from Bakker *et al.* (2016).

imens (i.e. younger than 80 years), this proportion was just over half (55%). Although there were more young than old specimens, which prevents making direct comparisons, it still appears that assembly success does not depend on specimen age. This is of course promising for the near-future further exploitation of herbarium collections world-wide, as many older (type) specimens are available.

A special note needs to be made about herbarium specimens from wet-tropical conditions, of which there were 13 included in our study. Given the potentially different conditions under which these specimens have been collected and preserved, it is worthwhile determining if this correlates with herbarium genomics success, i.e. plastome assembly efficiency. Whereas 'dry collected' specimens sometimes may not even have been subjected to heat treatment (other than the sun) and ususally do not get 'Schweinfürted' (Schrenk 1888) i.e. sprayed with ethanol in order to stop any fungi growing, for wet-tropical specimens this may be the opposite. It appears that preserving such specimens by immersion in ethanol prevents any DNA from being recovered later on (Mark Chase *pers. com.*). Bressan *et al.* (2014) however, found no difference in neither quality nor quantity of nuclear DNA recovered from tropical plant leaf tissue stored in liquid nitrogen versus 96% ethanol, but also show how storage in ethanol causes cytoplasmic contents (including plastids) to be cleared from the leaf tissue cells. Therefore, in our opinion ethanol preservation is best to be avoided for herbarium genomics when targeting plastomes or chondromes. The Schweinfürth treatment in wet-tropical conditions nowadays usually entails keeping specimens inside a plastic bag under a saturated ethanol atmosphere, which can last for days before a drier is reached. Alternatively, specimens are somtimes dried directly on a kerosine or gas-stove (Jan Wieringa *pers. com.*).

When we compare our wet-tropical samples with the rest, we see generally a higher number of contigs per assembly and lower N50 values (Fig. 2). When plotted against specimen age it appears as if the wet-tropical specimens seem to 'age' more quickly in terms of increased plastome assembly fragmentation

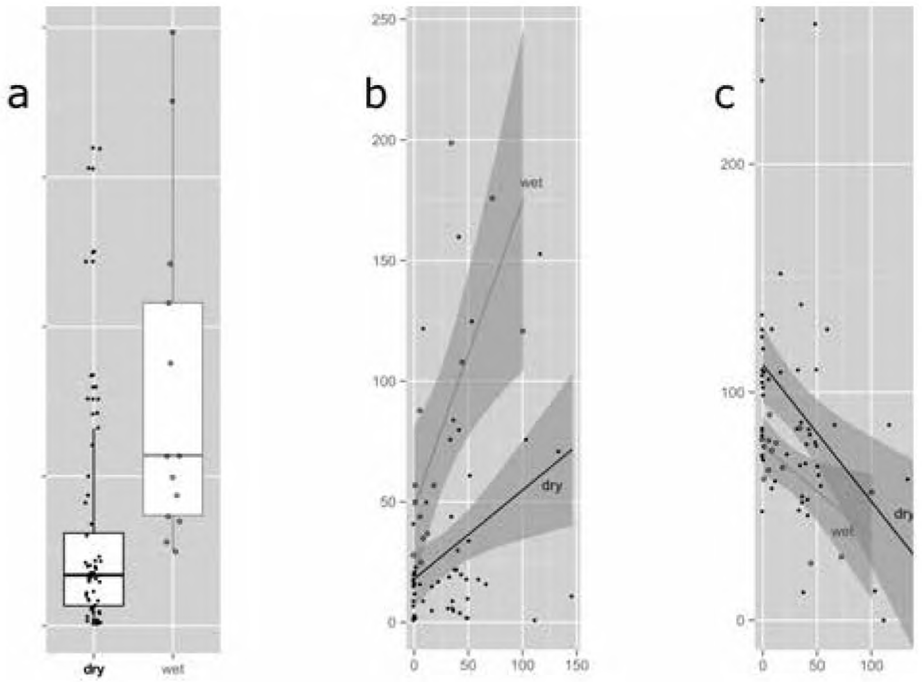


Fig. 2. A comparison between specimens collected from wet-tropical and dry conditions with regard to success in plastome assembly, in terms of number of contigs (a), number of contigs plotted against specimen age in years (b), and (c) N50 (in kb) plotted against specimen age in years. Darker shaded areas indicate confidence intervals of the linear model fitted. Re-drawn from Bakker *et al.* (2016).

when compared with dry habitat specimens. As the exact preservation histories cannot be reconstructed for most herbarium specimens, we cannot draw firm conclusions here but suggest that wet-tropical herbarium specimens may need some extra effort in terms of plastome assembly and possibly require more additional Sanger sequencing-based confirmation of assembly boundaries.

## Worry about Contamination?

Another concern with using harbarium DNA could be the presence of contaminant DNA in samples, for instance from either endophytic or 'post-mortem' fungi. In case of post-mortem contamination of the specimen, we would expect the contaminant DNA to be much less fragmented than that of the specimen, as only the latter would have been heat-treated. Fungal contamination in plant (herbarium) samples has been reported to be fairly widespread (Álvarez & Wendel 2003; Miranda *et al.* 2010), and the extent to which plant rDNA ITS sequences in public databases such as GenBank are actually fungal can be questioned. Because the genome skimming/IOGA approach is in theory suitable for other high copy number compartments such as chondromes and rDNA, it is relevant to know to what extend non-target rDNA could be picked-up using this approach. Therefore, to assess the proportion of fungal-derived reads in a selection of our samples we re-ran IOGA using a panel of fungal SSU rDNA and ITS1-5.8SrDNA-ITS2 sequences, comprising both asco- and basidiomycetes. In case fungal ITS sequences were assembled, they were identified using the UNITE database (Köljalg *et al.* 2013) that currently holds 354,465 annotated fungal rDNA ITS sequences (http://unite.ut.ee/). BLAST was used to match our target ITS sequences against a subset library of 20,000 fungal ITS sequences from UNITE.

The results (Lei 2015) were unexpected in that only modest numbers of reads (ranging up to appr. 73,000) were found in the selected herbarium specimen read samples by using these fungal references, and when assembled into rDNA sequences, the majority of contigs turned out to be plant rDNA not fungal rDNA. In only a minority of cases were 'non-plant' contigs found, usually of <2 kb, which could only in some cases be identified as fungal. In addition, when repeating the analyses, but this time using plant rDNA sequences (both SSU and rDNA ITS), in some cases a minority of fungal contigs were assembled that could be identified using the UNITE data base as *Cladosporium*, *Aureobasidium*, *Fibulobasidium* species and in one case a 'human skin community' type fungus. Whereas the first three matches would make sense given the ecology of these fungi (leaf parasites or endophytic fungi), the latter would be consistent with a scenario of human fungal contamination. The cross-assembly results can probably be explained by the high conservation at the nucleotide sequence level of parts of the fungal and plant rDNA cistron. However, in practical terms, given the difficulty we encountered in obtaining fungal reads and assembling fungal rDNA from these herbarium samples, and in the same time given the ease with which plant rDNA reads and assemblies could be obtained, we consider fungal cross-contamination artefacts in herbarium DNA to be of minimal importance.

## Conclusions

We conclude that effective plastome sequence assembly using genome skimming is feasible using small amounts of herbarium specimen tissue, roughly one square centimetre of leaf, and show that the results are only in some aspects different from those obtained from fresh or silica-gel-dried material. We are confident that most of our specimens have been sampled non-destructively and therefore are optimistic that this approach can be used more widely for future genomic exploitation of herbarium collections.

The IOGA automated pipeline established previously in Bakker *et al.* (2016) appears to be working effectively, with draft plastome assemblies being completed in one or a few hours only. Obviously, subsequent gene annotation and quality check of contigs, which may include Sanger verification of contig boundaries, is still a formidable task but is (time-wise) probably less so than the curation of a large scale comparative sequence project using traditional Sanger sequencing. Using a panel of land-plant-wide plastome sequences as reference proves to be efficient, and no closely related reference plastome is needed. For instance, no Brassicaceae reference plastome was included (*Medicago* was probably the closest reference included phylogenetically), but all Brassicaceae samples in our study were assembled correctly. The fact that our IOGA plastome assemblies could be aligned without any problem to their reference plastome sequences indicates that assembly was accurate. Nevertheless, additional analysis by re-mapping reads to finally selected assemblies and checking whether anomalies exist is still important, but this is general 'good genomic practice'. For specimens collected and preserved in wet-tropical conditions we conclude that more effort into contig assembly, scaffolding and editing of plastome sequences is probably required but is expected to yield fully comparable final results compared with dry-collected specimens. Finally, we found possible contamination of herbarium specimens with fungal DNA not to be an (important) issue. Therefore, herbarium genomics is promising and further makes continued support and curation of herbarium collections around the world important.

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# Tropical Botanical Gardens

# The Future Role of Botanical Gardens

*Stephen Blackmore*


## Abstract

Historically, botanic gardens have used their living collections of plants for a wide variety of purposes and those purposes have evolved through time to continue to meet the changing needs of society. I argue that, building on and going far beyond their success to date, the future role of botanic gardens should be nothing less than shaping and contributing to a sustainable future for humanity. A sustainable future can only be one in which plants are placed at the heart of the web of life and recognised as our life support system. Botanic gardens, as popular places in which people chose to spend their time, are better placed than other kinds of institutions to engage with society and mobilise support for the protection of plant diversity through powerful, positive messages that empower citizens to be involved in shaping the future. Botanic gardens already work together through national, regional and international networks but need to achieve a step change in the level of the strategic action they take together. Of the Post-2015 Development Agenda, the UN Secretary-General has said, "Our goal is simple but daunting - prosperity and dignity for all in a world where humankind lives in harmony with nature." Botanic gardens have a key role in delivering this vision of the future.



**Key Words:** global change, sustainable development agenda, Anthropocene



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We live in a world that is changing more rapidly than ever before in human history, confronting a set of interconnected challenges arising from the growing demands we make on the biosphere (see, for example, Rockström *et al.* 2009; Mooney 2010; Ellis 2011; Brook *et al.* 2012; Ellis *et al.* 2013). Botanic gardens, with their living collections, expertise and close engagement with wider society, have the potential to be key players in meeting the major challenges of the times and contributing to a sustainable future (Blackmore 2001, 2009, 2016; Blackmore & Paterson 2005; Marris 2006).

Before making the case for botanic gardens in the Anthropocene as agents for change and pathfinders into the future I will briefly consider the origins and historical roles of botanic gardens. My purpose in doing this is to show that botanic gardens are evolving entities, capable of adapting their mission and roles to meet the changing requirements of the communities they serve.

## The Evolutionary Nature of Botanic Gardens

Neither the origins nor the earliest history of plant collections that would today be considered botanic gardens can be known with certainty. We can, however, speculate that organised, purposeful collections of plants began to be made around the time when people made the transition to practicing settled agriculture. The early recorded history of botanic gardens was reviewed by Hill (1915) in an excellent account, proceeding from the garden of Shen Nung, Emperor of China in 28th Century BC, to the Royal Garden of Thotmes III at the Temple of Karnak, to Aristotle's Garden at Athens and onwards into modern times. In Europe, botanic gardens arose as off-shoots of medicine, as physic gardens, for the provision of medicinal plant materials and the training of physicians (Hill 1915; Stearn 1962; Stafleu 1969). The scope of botanic gardens, their collections and their work expanded enormously as they embraced the Linnean endeavour of classifying and documenting diversity. In the eighteenth and nineteenth centuries, in particular, a strong emphasis was placed on utilitarian plants other than medicines and botanic gardens became important as institutions of colonial power (Prain 1925; Holttum 1970; Radding 2005). Botanic gardens also came to be regarded as important cultural institutions, expressions of a civilised society, and this was an important motivation for the establishment of many public botanic gardens in America (Coulter 1917; Brockway 1979; O'Malley 1996). Writing on the history of botanic gardens in America, O'Malley (1996) described them as "... the quintessential expression of both garden art and scientific inquiry" embodying "...the fundamental belief in the perfectibility of man and the optimism of the founders in the future they were creating for the new republic." The justification for regarding botanic gardens as cultural institutions alongside the great museums and galleries of the world has been strengthened by their growing commitment to public education and outreach. Education now plays an important part in almost every botanic garden, including many that do not sustain their own research programmes (Wyse Jackson & Sutherland 2000).

Perhaps the greatest redefinition of role in botanic gardens has been the focus on plant conservation which emerged as a major concern during the twentieth century (Heywood 1990; Barthlott *et al.* 2000; Heywood & Iriondo 2003; Powledge 2011) especially since the introduction of the United Nations Convention on Biological Diversity (CBD) (Williams *et al.* 2003). A further impetus was provided by The Global Strategy for Plant Conservation (GSPC) (Blackmore 2005; Wyse Jackson & Kennedy 2009; McNeely 2011) which exerted considerable influence of the development of the strategic plans of many botanic gardens (see, for example, Hopper 2010). Initially, the main responses of botanic gardens focused on *ex-situ* conservation (Havens *et al.* 2006; Li & Pritchard 2009). Botanic gardens, with their living collections and seed banks for threatened plants have come to be been seen as 'modern-day arks' (Oldfield 2010; Pennisi 2010). They have also led the development of protocols for the reintroduction of plants from botanic gardens into the wild (see, for example, Akeroyd & Wyse Jackson 1995). More recently the ability of botanic gardens to contribute to ecological restoration, coupled with growing recognition of the urgent need to restore degraded landscapes has led to the launch of the Ecological Restoration Alliance of Botanic Gardens (Havens *et al.* 2006; Aronson 2014) under the auspices of Botanic Gardens Conservation International (BGCI).

The conclusion I draw from this brief historical introduction to botanic gardens is that they are resilient and persistent institutions capable of changing through time and adapting to continue to meet the needs of the society they serve.

## The Geographical Distribution of Botanic Gardens

Before turning to explore what it is that society might require of botanic gardens in the future, I want to consider the global distribution of botanic gardens. The GardenSearch Database developed by BGCI currently holds records on 3392 botanic gardens in around 150 countries (Fig. 1). It is clear that the vast majority of botanic gardens are situated in the temperate regions of the world, with a preponderance in Europe and the United States (Chen *et al.* 2009).

It has been well known since the observations of Alexander von Humboldt that plant diversity is much greater in the tropics (Humboldt 1845-1858; Dobzhansky 1950; Barthlott *et al.* 2007) than at higher latitudes and a variety of hypotheses have been developed to explain this marked gradient in plant

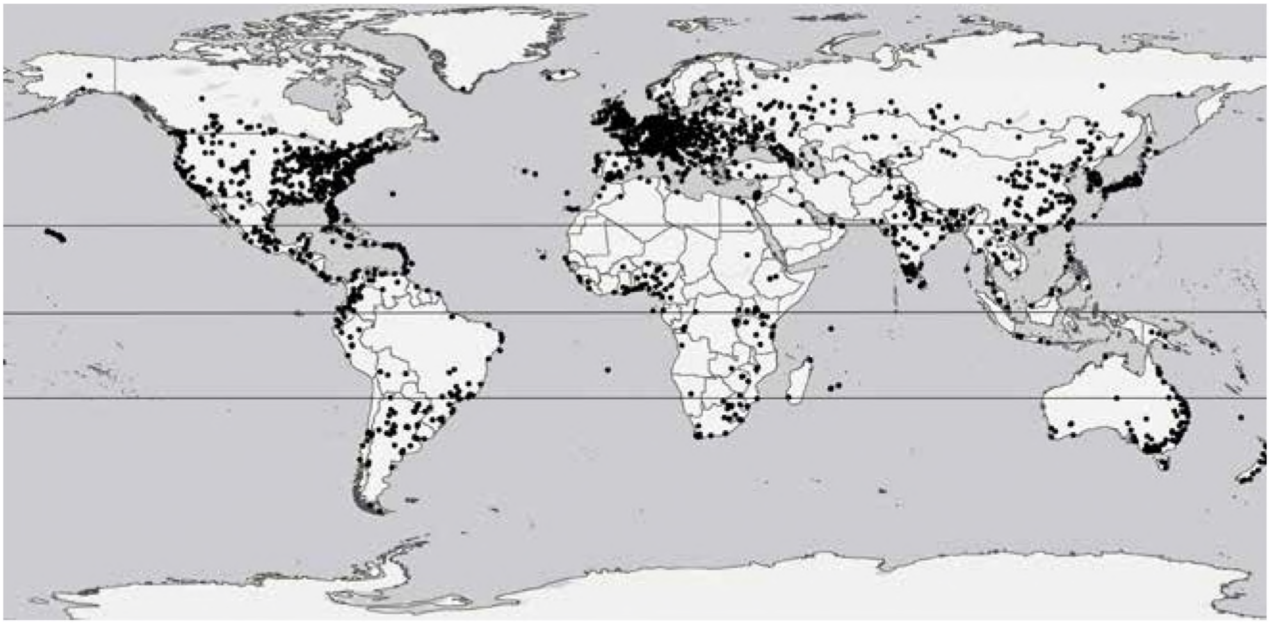

Fig. 1. Global distribution of botanic gardens based on the GardenSearch Database of Botanic Gardens Conservation International (BGCI in 2015).

biodiversity (Davies *et al.* 2004; Fine & Ree 2006; Hawkins *et al.* 2011). There is therefore a marked discrepancy between the distribution of botanic gardens and the distribution of plant diversity which reflects the historical development of formal, scientific botanic gardens in Europe discussed earlier. Barthlott *et al.* (2000) made the point that, "… the earth's Botanic Gardens are distributed inversely to the natural phytodiversity". The consequences of this for the patterns of diversity within the living collections of botanic gardens have been analysed by Parmentier and Pautasso (2010). In this symposium which focusses on tropical collections, it is clear that, in order to conserve and restore plant diversity for the future, many more botanic gardens need to be established in the tropics. More tropical botanic gardens are also needed in order to correct the imbalance in the delivery of the educational and wider social programmes which are much more readily available to people in temperate regions. There are, as will be mentioned later, other societal benefits to be realised through the creation of more botanic gardens in the tropics. It is important, however, to recognise that there are important botanical gardens in the tropics, a number of which have long and distinguished histories. Holttum (1970) presented a review of the significance of tropical botanic gardens in South East Asia, emphasising the gardens of Calcutta (established 1786), Bogor (established 1817), Peradeniya (established 1821) and Singapore (established 1874). Other important examples include the Sir Seewoosagur Ramgoolam Botanic Garden at Pamplemousses in Mauritius, (established 1770, the earliest botanic garden in the Southern Hemisphere) and Rio de Janeiro Botanical Garden which was founded as an acclimatisation garden in 1808. Mexico and China, two megadiverse countries which include tropical regions within their territories, have increasingly well-networked botanic gardens delivering coordinated, strategic work programmes. The Mexican Association of Botanic Gardens includes 40 partners (Dávila *et al.* 2011) while the botanic gardens of China are working together on a shared vision for conservation and sustainable use of plants (Huang 2011). Of course, in correcting the mismatch between the distribution of plant diversity and the distribution of botanic gardens, it is not simply a question of where in the world the collections are. As Gibson and Raven (2013) point out, tropical research exhibits a similar pattern of historical legacy with European researchers carrying out most of the research in the former colonies of the Old World tropics and scientists from the US dominating research in the Neotropics (Clark 1985). An analysis by Fazey *et al.* (2005) showed that fewer than half the papers on conservation biology in the Carribbean, Central America and South America had first authors from countries in those regions. Similar findings were reported by Griffiths and Dos Santos (2012), who highlighted both the need to build capacity in developing countries and the difficulties of doing so.

The development of human capacity within tropical, and subtropical, botanic gardens is therefore a priority for the future. It is likely that for more botanic gardens too be developed in the tropics, they will need to be seen to contribute directly to national development plans, as those of Mexico and China clearly do (Dávila *et al.* 2011). Furthermore, tropical botanic gardens are increasingly engaged in wider conservation efforts (Chen *et al.* 2009), also at the *in situ* ecosystem management. As will be discussed later, an even wider, universal agenda, to which botanic gardens can contribute, will be provided by the 2030 Sustainable Development Goals (SDGs).

## The Future

If botanic gardens have evolved to meet the changing needs of the communities they serve and if, as I imagine they will, they continue to evolve, what directions might they be expected to take in the future? Different answers suggest themselves at the local level and the global level.

## Meeting the Needs of the Local Community

When it comes to meeting the needs of their local community, botanic gardens, in common with many cultural_institutions and visitor attractions, generally use visitor footfall as a simple measure of their relevance. In addition, many use surveys and questionnaires to determine what it is that visitors value most and what they would like to see more of in the future. Often it is simply the peaceful, green ambience of the botanic garden that visitors value most highly. Although it is the raison d'être for most botanic gardens, the presence of a diverse, well-interpreted collection of plants, displayed in an attractive manner, tends to come lower on the list of priorities for visitors. At the Royal Botanic Garden Edinburgh I encountered one regular visitor who insisted that they did not come to look at the plants, but only to see grey squirrels and to watch tractors at work. I was asked where else, in the city, could their grandchildren see working tractors? What I found helpful about this interaction was the salutary reminder that what botanic gardens value most about themselves (the richness of their living collections or the vigour of their research programmes) might seem unimportant to some visitors but that even those with little appreciation of plants can find interest in the place, its wildlife and its work. Simply existing as pleasant and interesting place might not be sufficient justification for the existence of a botanic garden, but it is much more important than it may seem and in ways that will become more significant in the future. Botanic gardens, by their very existence, provide significant benefits to the health and well-being of their visitors. And although displaying agricultural machinery at work is unlikely to feature as an objective in the corporate plan, we should cherish the opportunity to show and celebrate the working skills of botanic garden staff. In an increasingly urban world (Victor 2006; Elmqvist *et al.* 2013a), with more than half of humanity already living in cities, experiences of urban green space are of growing importance. Elmqvist *et al.* (2013a) refer to both the hardware of cities, their physical infrastructure, and their software, their cultural life. They point out that less emphasis has been placed on recognising the ecological infrastructure of cities: their parks, gardens, open spaces and water catchment areas. Given that many botanic gardens are situated in cities, they are perhaps unique in that they contribute to both the hardware and software of the city. At the same time, albeit on a relatively small scale, they even contribute ecosystem services, including fresh air, carbon sequestration, groundwater management and reducing the urban heat island effect. Most importantly, an urban botanic garden can communicate with and influence a large number of people and serve as source of expertise and plant material to enrich the planted landscape within and beyond its boundaries. The opportunities to do this are increasing. People are continuing to move into cities and the trend of urbanisation is accelerating in many regions. As Seto *et al.* (2013) pointed out, the geography of urbanisation has shifted, with the fastest growing urban centres now being in Asia and Africa (in particular in China, India and Nigeria) rather than in Europe or the Americas. The predicted growth in cities and megacities is yet another argument in favour of the development of more botanic gardens in tropical and subtropical centres of urban expansion.

The fact that many botanic gardens are urban oases, engulfed by the city they serve, makes them of enormous value, offering contact with nature and bringing mental and physical health to citizens. A growing body of research makes it increasingly possible to document and quantify these benefits (see for example, Maller *et al.* 2005; Bowler *et al.* 2010; Keniger *et al.* 2013). The idea that gardens are, in themselves, places of healing (Hartig & Cooper-Marcus 2006) rather elegantly reflects that earlier chapter in history when, as physic gardens, they provided medicines. Some botanic gardens still do produce medicinal plants for consumption, but almost all could now claim to improve the health of their visitors. Furthermore, the fact that gardening is, in itself, both a leisure activity and a source of mental and physical health benefits to its practitioners, especially the elderly (Milligan *et al.* 2004), suggests an increasingly important role for botanic garden outreach programmes in response to the demographic changes of an aging society. In Tokyo, currently the world's largest megacity, Takano *et al.* (2002) found an increase in longevity associated with access to walkable greenspace such as parks and gardens and argued for the importance of greenspace in city masterplans. Keniger *et al.* (2013) grouped the benefits of contact with nature under four headings: psychological well-being benefits, cognitive benefits, physiological benefits and social benefits. Little wonder then that in many cities, including both London and New York, the most expensive real estate is next to, or has views over, a botanic garden or park. A growing number of botanic gardens offer programmes, from mindfulness to horticultural therapy, which promote and deliver health benefits to their audiences.

Such programmes already deliver real benefits to botanic garden visitors but urbanisation is creating new, unprecedented challenges for humanity. As Maller *et al.* (2005) and others have pointed out, humans have only lived in urban environments for a small number of generations, having previously become adapted to natural ones over many thousands of years. Botanic gardens have, it seems to me, the opportunity to be at the frontline of discovering how it is possible for humans to live healthy and satisfying lives in cities of increasing size and population density. There are many challenges to be addressed because cities will be heavily affected by global climate change (World Bank 2010), changes in sea level (McGranahan *et al.* 2007), pollution and other environmental impacts. The urban heat island effect, for example, is even more intense in tropical cities than temperate ones, and can create temperatures as much as 10 °C higher than in the surrounding countryside (Kovats & Akhtar 2008). Urban green spaces, including green roofs and walls, provide practical forms of ecosystem-based adaptation (EBA) (Colls *et al.* 2009) that can benefit greatly from the involvement of botanic gardens. Botanic gardens can, for example, promote the use of native species in urban greens spaces and facilitate the provision of suitable plant material, as in ecological restoration efforts (Aronson 2014). In developing this wider impact on the landscape of cities, botanic gardens may need to forge new partnerships, beyond their traditional alliances, such as engaging with the efforts emerging from the Mayors' Climate Protection Agreement (Bulkeley 2013). It would not be as novel as it may seem for botanists and botanic gardens to engage actively with architects, engineers and city planners. The botanist Patrick Geddes (1854–1932) was a pioneer of social improvement in cities and one of the founders of modern city planning (Geddes 1915; Meller 1993). Geddes lived in a world with two billion human inhabitants, there are now more than seven billion of us, with a projected 9.5 billion by 2050 (Ehrlich *et al.* 2012). Consequently, there is a greater need than ever for plant-based solutions to feeding humanity, sustaining ecosystem services and maintaining the ecological resilience that comes from a biodiversity rich biosphere (Cardinale *et al.* 2012). In these matters, botanic gardens have much to offer (see for example, Maunder 2008; Donaldson 2009).

Urban agriculture, including the growing of food in city tenements, was promoted vigorously by Patrick Geddes (Meller 1993) and has seen a great resurgence in recent years (Katz 1986; DeKay 1997). Botanic gardens, in their efforts to develop wider social roles (Vergou & Willison 2013), have been significant contributors, teaching people who are increasingly remote from the production of food how they can grow their own. Many botanic gardens now have programmes to support home gardening. When I joined the Royal Botanic Garden Edinburgh at the turn of the millennium, carrots and cabbages were nowhere to be seen. Now, a popular programme of 'Growing your own food' attracts volunteers, external sponsorship and course participants. A less chauvinistic attitude prevails towards growing the full diversity of plants. Vegetables and crop plants, precisely those plant species most essential for our daily lives, now flourish alongside systematic collections for research and threatened plants in conservation programmes. This is a healthy mix, offering a broader spectrum of opportunities to engage with and support the local community and removing a false dichotomy between plants used in agriculture and plants not used in agriculture.

The city of Chicago, described by Wang and Moskovits (2001) as "… a microcosm of some of the greatest challenges to the survival of Earth's biological diversity and to the quality of human life", provides outstanding examples of urban regeneration and urban farming. Since 1996, the Chicago Wilderness programme has brought together a large and diverse coalition of partners to document natural remnants of vegetation and then restore and reconnect them through greenways and wildlife corridors to create a regional nature reserve covering 81,000 hectares (Wang & Moskovits 2001; Moskovits *et al.* 2002). Chicago Botanic Garden, a key participant in the initiative, developed 'Plants of Concern' a state-wide citizen science programme to monitor threatened plants (Havens *et al.* 2012). Going far beyond its own boundaries, Chicago Botanic Garden also runs an impressive programme of rural agriculture called 'Windy City Harvest' (www.chicagobotanic.org/urbanagriculture) as well as programmes in horticultural therapy and a wide range of educational activities. To my mind, Chicago Botanic Garden's Strategic Plan (http://strategicplan.chicagobotanic.org/homepage) is a model for the botanic garden of the future. Chicago Botanic Garden states, "Our mission is clear: We cultivate the power of plants to sustain and enrich life." This mission is founded on three beliefs:

- "The future of life on Earth depends on how well we understand, value, and protect plants, other wildlife, and the natural habitats that sustain our world.
- Beautiful gardens and natural environments are fundamentally important to the mental and physical well-being of all people.
- People live better, healthier lives when they can create, care for, and enjoy gardens".

These core beliefs embody principles that are universal in their applicability to the botanic gardens of the future. At Chicago Botanic Garden they are matched by the ambition and leadership that makes the Garden one of the city's most influential institutions. It is perhaps ironic that these forward-looking initiatives are taking place in a city where, in the 1920s and 1930s, the Chicago School of urban sociology promoted a modernist perspective in which urban life was considered to be quite distinct from rural life (McDonnell 2011 cited by Elmqvist *el al.* 2013b) so that cities were essentially thought of as detached from their broader life-support systems in the hinterland. The growth of Chicago as a major hub in the US railways allowed the rapid expansion of the city and pushed its dependence on agricultural production further away. Today's green renewal shows the potential of botanic gardens to help to shape the quality of life in the future. No doubt, as they work to increase their impact, botanic gardens will need to extend the range of disciplines and skills they can draw on, either by direct recruitment of specialist staff or by developing new partnerships, for examples, with organisations with medical healthcare expertise.

Given our focus on tropical collections, I will take Singapore as another microcosm of the future. Established as an independent state in 1965 with five million people in just 580 square kilometres the national development strategy focused on creating 'a city in a garden' (Hean 2010). Singapore has no natural reserves of fossil fuels and limited land for the generation of renewable energy. Similarly, spaces for reservoirs of drinking water are limited and the government has therefore promoted energy efficiency, recycling and desalination of sea water. In developing the Marina Bay area, adjacent to the central business district, incentives were provided to encourage greenery and an inland reservoir captures and recycles the cities run-off (Hean 2010). The architecture of the Gardens by the Bay reflects these considerations (Davey 2011) with recycled vegetation providing biomass to combined heat and power energy plants that cool and dehumidify the substantial glasshouses (Davey *et al.* 2010; Koh 2012). Interpretation of these features raises the consciousness of visitors to sustainable technologies and the role of plants in the life of the city, becoming a source of civic pride to local inhabitants. The Gardens by the Bay also houses a rich and well-interpreted collection of plants in an exciting setting with futuristic 'supertrees', elevated walkways and the spectacular Flower Dome and Cloud Forest glasshouses. The latter houses a world class exhibit focussing on global change, setting out practical steps every visitor can take to reduce their own ecological footprint. Where better than the relaxing, yet stimulating, environment of a botanic garden to learn about and reflect upon the future of the planet?

## Meeting the Needs of the Global Community

Above and beyond the contribution botanic gardens make to the life of the immediate communities they serve, it is possible to consider how, collectively, they meet the needs of the global community through their relevance to the international development agenda (Blackmore 2016). At the Millennium Summit in 2000, the largest ever gathering of world leaders agreed to reduce poverty through the Millennium Development Goals (MDGs), eight ambitious targets running to 2015 (http://www.unmillenniumproject.org/goals/). These targets are, I would argue, the closest thing we have had to an internationally agreed agenda for the future of our planet. I regard them, therefore, as a proxy for what the world wants for the future. This is not to say that the MDGs provided an optimal or even an adequate vision for the future of the planet. They were, in effect, concerned only with those aspects of the future on which 191 world leaders could reach agreement. And although Millennium Development Goal 7 refers to environmental sustainability there is, for example, no specific goal concerning the condition of nature itself. The emphasis was firmly on what was referred to as the human environment. MDG 7 had three specific targets, to:

- "integrate the principles of sustainable development into country policies and programs and reverse the loss of environmental resources,
- Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation, and
- Have achieved by 2020 a significant improvement in the lives of at least 100 million slum dwellers".

It might be argued that the United Nations addresses biodiversity and the natural environment elsewhere, through the UN Convention on Biological Diversity (CBD). But the CBD contains no specific targets for action. The Global Strategy for Plant Conservation (GSPC) on the other hand, does have explicit targets (Blackmore 2005; Wyse Jackson & Kennedy 2009; McNeely 2011). However, as the Secretariat of the Convention on Biological Diversity (2009), McNeely (2011), Sharrock *et al.* (2014) and others have pointed out, progress towards these targets has been mixed and has undoubtedly been constrained by the lack of dedicated financial resources to support the strategy. The GSPC is now into its second term, but it remains the case that few governments have allocated funding to support it. Although the fundamental importance of plants to humanity is often stated (see for example, Sharrock *et al.* 2014), it seems that the message has not yet been taken to heart. One of the major challenges has been, and continues to be, establishing the links between biodiversity and poverty alleviation (Sachs *et al.* 2009). The links are there, whether recognised or not. But bringing about a wider understanding of this point is one of the most important contributions botanic gardens can try to make to wider society for the benefit of the future. Of the eight MDG targets some were more obviously connected with our dependence upon plants than others. Goal 1, to eradicate extreme poverty and hunger, and Goal 7, to ensure environmental sustainability, depend directly upon the state of the world's plants and vegetation. Other goals, concerned with human health, have a tangible but less direct connection with plants, especially given the importance of plant-derived medicines. These include Goal 4, to reduce child mortality, Goal 5, to improve maternal health and Goal 6, to combat HIV/AIDS, Malaria and other diseases. Arguably, however, none of the MDGs could be achieved in places where plant-derived ecosystem services have broken down completely (Blackmore in press). Now that we have passed the deadline for the achievement of the MDGs progress towards them has clearly been mixed, with the UN reporting that, "Despite many successes, the poorest and most vulnerable people are being left behind" (United Nations 2015).

As the deadline for the Millennium Development Goals drew closer, discussion on the Post 2015 Development Agenda began (see, for example, Griggs *et al.* 2013). One important document, The Future We Want (http://www.uncsd2012.org/thefuturewewant.htm), emerged from a wide consultation exercise and a summit in Rio de Janeiro in June 2012, twenty years after the 1992 Earth Summit. The Future We Want called for "....holistic and integrated approaches to sustainable development which will guide humanity to live in harmony with nature and lead to efforts to restore the health and integrity of the Earth's ecosystem." It introduced a new draft set of 17 Sustainable Development Goals (SDGs) which were put forward for agreement in September 2015, at the 70th session of the General Assembly of the United Nations in New York. The 2030 Agenda for Sustainable Development (https://sustainabledevelopment.un.org/post2015/summit) came into effect from the start of 2016. As with the earlier MDGs, achieving many of the 17 SDGs will require the careful conservation and stewardship of the Earth's botanical diversity. I identify five of them as having particular relevance to the future work of botanic gardens and to issues discussed earlier in this chapter:

- Goal 2. End hunger, achieve food security and improved nutrition and promote sustainable agriculture.
- Goal 4. Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
- Goal 11. Make cities and human settlements inclusive, safe, resilient and sustainable.
- Goal 13. Take urgent action to combat climate change and its impacts.
- Goal 15. Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss.

Of the SDGs, Goal 15, is most directly connected with the traditional work of botanic gardens and to their more recent aspiration to contribute to ecological restoration (Aronson 2014; Aronson & Alexander 2013). However, all five are worthy of review and consideration by botanic gardens when developing their plans for the future. By adapting their mission and roles to contribute to meeting the challenges of the global agenda defined by the SDGs, especially the goals highlighted above, botanic gardens can meet the needs of both the local and global communities and play a pivotal part in shaping the future.

## Conclusions

Thinking of botanic gardens as agents of change recognises the importance of both their advocacy and outreach programmes and of the direct actions they undertake in working with plants. A botanic garden is an ideal place in which to learn about and reflect upon global change and to become more aware of the UN's 2030 Sustainable Development Agenda. Securing the integrity of the biosphere and achieving the SDGs will depend not just on governments but upon the engagement of individual citizens around the world understanding how they personally can make a positive difference to the future. Recognising this, the role of botanic garden education and outreach programmes should be to focus on positive and practical messages that empower their visitors to live healthier and more sustainable lives. Botanic gardens can also build movements for change in society to replace the currently widespread perspective that there is little the individual can do to influence the future of the planet (Blackmore 2009). The United Nations' vision of "prosperity and dignity for all in a world where humankind lives in harmony with nature" requires changes in individual behaviour in addition to governmental programmes. Botanic gardens can contribute to creating such a world, especially if, and this will be my main conclusion about their future, they work together even more effectively than hitherto.

The direct action I refer to includes the research undertaken in botanic gardens, especially in the fields of taxonomy, systematics, conservation biology, ecology and other fields of biodiversity science. There is, of course, a real urgency to this research. As others in this conference have emphasised, the objects of this research are disappearing steadily in the biodiversity crisis. Our present efforts are inadequately resourced and, as a result, too slow. Fortunately, there is also good news. The internet enables rapid communication around the world and, with the digitisation of collections, is enabling the disproportionately rich herbaria housed in the temperate world to be accessible to all nations. Countries with emerging economies, including China and Brazil in particular, are expanding their workforces in the biodiversity sciences.

Nevertheless, applying our knowledge of biodiversity to the task of reversing the tide of environmental degradation in order to restore the health and integrity of the Earth's Ecosystems is an enormous challenge. Botanic gardens are now beginning to see their relevance to this task. The Ecological Restoration Alliance of Botanic Gardens is in its infancy, but it is clear that botanic gardens have a unique contribution to make. This special role reflects their rich collections of plant diversity coupled with their horticultural expertise to grow a wide spectrum of plants, including many that are rarely cultivated outside botanic gardens (Aronson 2014; Aronson & Alexander 2013). The scientific and technical skills available in seed banks and living collections represent essential knowledge for a sustainable future. Inappropriate, exotic plants continue to be used in reforestation programmes, often because native species are not readily available in commercial nurseries and seed stocks. Botanic gardens are perhaps the only agencies likely to be able to change this situation by providing native plant material. Doing so will build on the many successful programmes of ex-situ conservation carried out by botanic gardens in response to Target 8 of the Global Strategy for Plant Conservation (Blackmore *et al.* 2011). Such programmes focus on bringing locally threatened plants into the security of the living collection and, ultimately, using them to re-establish wild populations and to contribute to restoration projects.

Most importantly, for the future, we need to be better organised and more strategic if our actions are to be coordinated and scaled up in order to have a significant impact. We need what Paul Smith, Secretary General of Botanic Gardens Conservation International (BGCI), calls "a rational, cost-effective global system for plant conservation" (Smith 2017). He makes the point that such a system already exists for plants in agriculture, with an International Treaty on Plant Genetic Resources for Food and Agriculture (ITPGRFA) (www.planttreaty.org), a global plan of action, a network of international ex-situ collections, a global portal to accession data, advanced bioinformatics tools, and an endowment fund (The Crop Trust, www.croptrust.org) to conserve crop diversity in perpetuity. BGCI, as the global network of botanic gardens, is well placed to frame the debate and facilitate the establishment of an equally strategic approach to conserving plant species which are not necessarily important for food and agriculture. BGCI is developing its own strategic plan accordingly (www.bgci.org/about-us/mission).

Individually and, especially when working together collectively, botanic gardens have the opportunity to be agents for change transforming lives and pointing the way to a more sustainable relationship with the planet.

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