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Part I

Introduction

1

Taxonomy and the future of plant diversity science

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taxonomy . . . the lonely voice speaking on behalf of an interest in diversity
V. Heywood, 1967

In the last 50 years, science has experienced a remarkable period of rapid and irreversible growth. There are more scientists alive today than all those that have lived in previous generations. More money is now being spent on science than has ever been the case in the past; and new knowledge is being created at an unprecedented rate. However, over these five decades, science has not only grown, it has also changed. It has become increasingly fragmented into ever-narrower specialisms. It has become increasingly reliant on sophisticated instrumentation. It has become highly internationalised. It has also become ever-more dependent on the coordinated activities of multiple practitioners working together in teams to make real progress in many areas.

All these factors, together with many other changes in society, mean that science is now more central in the lives and thoughts of people and governments than it has ever been in the past. But as science's prominence has grown, public demands on science and scientists have also increased. Governments and tax payers want to know what they are getting for their money. Many areas of society are also beginning to question why they need such knowledge in the first place, and to what uses that knowledge will be put. The science of plant diversity has not been immune from these changes or these pressures; and among the world's leading practitioners few have seen these decadal trends so clearly, and anticipated their outcomes so effectively, as Vernon Heywood.

As observers of just part of Vernon Heywood's career, it seems to us that much of what he has accomplished – and much of his success – has been based on four key 'principles' that have allowed him to anticipate, or stay abreast of, broader changes in science: the importance of synthesis, to make sense of knowledge that is increasingly information-rich, but also increasingly fragmented; the necessity of broad collaboration to complete significant tasks; the imperative of taking an international perspective to frame and accomplish important goals; and the need, at all times, to continue to build worldwide capacity in plant diversity science. These principles have been embedded in Vernon Heywood's career for decades but they remain important and will become even more relevant in the future. The enormous potential for scientific advancement in the field of plant diversity will not be fulfilled without such an approach, nor will we be able to respond effectively to increasing societal demands.

Forty years ago, Vernon Heywood – together with his colleague Peter Davis – provided a classic synthetic perspective on plant taxonomy that summarised progress in the first half of the twentieth century (Davis & Heywood, 1963). *Principles of Angiosperm Taxonomy* is still essential reading for any serious student of plant diversity science. It starts from the perspective that '[taxonomy] extends beyond the frontiers of biology' and that 'there is surely no aspect of biology more deeply intertwined in man's history, economy, literature, aesthetics and folklore' (Davis & Heywood, 1963). Davis and Heywood emphasised that taxonomy, the science of naming and identifying species,[1] is the foundation of all biology. They also articulated the view that taxonomy is fundamental to communication and research in all areas of plant science including ecology. Today, we also understand that taxonomy has a central role to play in the contemporary environmental arena. Taxonomy is inextricably linked to the study of biodiversity, defined as variation among organisms and the ecological complexes of which they are part, and hence to issues of conservation and sustainability. Even in the face of rapid expansion in technology, an estimated 40% of the global economy is still based on biological products and processes (WEHAB, 2002). In this context, as Davis and Heywood emphasised more than 40 years ago, taxonomy remains of central importance, but it will only flourish if it continues to evolve and rise to the challenge presented by its new context.

The origins of plant diversity science

The origins of taxonomy are rooted in informal folk taxonomies, as well as the works of early biologists and herbalists who were concerned mainly with ethnobotanically important species (Davis & Heywood, 1963). Later – through the 'Enlightenment' – the exploration, description and naming of the exuberant diversity of organisms came to be seen both as intellectually and economically important. At the close of the seventeenth century, de Tournefort stabilised what in hindsight became the

[1] The terms 'taxonomy' and 'systematics' are used today more or less synonymously. However, in the narrow sense, taxonomy refers to classification and all that that entails (e.g. nomenclature and types). Systematics is the broader science of biological diversity that seeks to describe not only the kinds of diversity of organisms, but also the relationships among them (Simpson, 1961).

concept of the genus. He recognised 698 genera (de Tournefort, 1700). By the mid eighteenth century, Linnaeus, the founder of the binomial system of naming species, recognised 1313 genera (Jarvis *et al*., 1993). Today we recognise about 14 000 genera (Brummitt, 2001).

In 2003, we celebrated the 250th anniversary of the publication of Linnaeus' *Species Plantarum* (1753). In this landmark attempt to document all the world's known species, Linnaeus produced one of the most enduring syntheses in the history of botany; and, like many works of synthesis, it provided the foundation for subsequent rapid scientific advances. Linnaeus' work was both a summary of existing knowledge and a catalyst for future research. But Linnaeus was also unaware of the scale of the task before him. He declared confidently: 'That the number of plants in the whole world is much less than is commonly believed I ascertained by fairly safe calculation, in as much as it hardly reaches 10,000.' (Linnaeus, 1753). Today, some estimates suggest that there may be about 420 000 described plant species (Govaerts, 2001; Bramwell, 2002).

Throughout the lifetime of Linnaeus, and the rest of the eighteenth century, European plant hunters explored the newly accessible interiors of North America, they first encountered Australia, and they also began to penetrate parts of Africa and Asia. They were motivated both by a desire for scientific discovery and the potential economic rewards from horticultural novelties or other plants of practical value. In the nineteenth century these explorations continued, especially in western North America, South America, Africa and over larger parts of Asia. Vast collections of herbarium specimens and living plants were accumulated, and the transfer of plants around the world took place with extraordinary speed.

Until the mid nineteenth century, most of the science of biological diversity focused on documenting the variety of life. But attention then turned to understanding how this diversity may have arisen. Darwin first presented his ideas about evolution by natural selection in a joint paper with Alfred Wallace published in 1858 (Darwin & Wallace, 1858), and this was quickly followed by the publication of *The Origin of Species* (Darwin, 1859). Supplemented by an increased understanding of genetics during the twentieth century, this theory has been refined and has come to be widely accepted as the explanation for how biological diversity has been generated. However, as Davis and Heywood (1963) pointed out, this huge theoretical advance brought with it no new approaches or techniques to assist practising taxonomists in their work.

Plant diversity science, 1960–2000

In their review of developments in taxonomy up to the mid twentieth century, *Principles of Angiosperm Taxonomy*, Davis and Heywood (1963) drew together the theory and methods underpinning the classification of plants. Davis and Heywood (1963) brought plant taxonomy up to date, made its principles and methods more accessible, and sought to place them in the context of contemporary science. They noted that the 1940s and 1950s brought taxonomy a wealth of new techniques and theories in fields such as cytology, ecology, genetics and evolution. As early as the 1960s they pointed out how the face of taxonomy might change in the future from being purely 'intuitive' or 'taught by imitation' to greater maturity as a repeatable, and even experimental, science based on a multidisciplinary approach that draws evidence not only from morphology, but also from a myriad of other sources.

After the publication of *Principles of Angiosperm Taxonomy*, during the 1960s, practitioners in taxonomy experimented with a wide range of ever more sophisticated techniques. The widespread use of scanning and transmission electron microscopy allowed plant and pollen surfaces to be examined in detail for the first time. Advances in gas–liquid chromatography and mass spectrometry enabled phytochemistry to be studied in unprecedented detail (Harborne, 1970). As a result a great new range of potential taxonomic characters were uncovered.

In addition, in the late 1960s (e.g. Heywood, 1968), the first inklings of new quantitative approaches – as exemplified in Sneath and Sokal's *Numerical Taxonomy* (1973) – were beginning to permeate botanical consciousness. To quote Heywood (1968, p. 7): 'The last preserve of the taxonomist – the taxonomic eye, the so-called intuition – is being probed and analysed into its components with a view to machine copying.' Numerical taxonomy introduced new ideas, new analytical approaches and fresh debates. It subsequently exploded as the aspirations of its theory were gradually matched by DNA technology and the increased sophistication and capacity of computers to process and analyse large data sets.

Over the last 40 years, advances in phylogenetic theory (e.g. Hennig, 1966), continued increases in computational power and an improved understanding of DNA and the genome, have together fuelled a new revolution in taxonomy. Taxonomy has developed to levels of sophistication that were simply unimaginable at the beginning of Vernon Heywood's career. Perhaps most significantly, the invention of the polymerase chain reaction (PCR) (Saiki *et al*., 1988) allowed plentiful amounts of DNA to be obtained from small amounts of plant material (including herbarium specimens). This has permitted the development of 'high-throughput' methods and, together with increasingly sophisticated computer analyses, has revolutionised our ability to analyse the relationships between different groups of plants. To a very large extent (although not entirely), subjectivity has been reduced. Different regions of the genome can now be examined to reveal different aspects of evolutionary history, the combined use of morphological and molecular data – when analysed in computationally intensive ways – now results in explicit, repeatable, testable and robust phylogenies. Before the current molecular age, Davis and

Heywood (1963) regarded classifications based on phylogeny as completely unrealistic in groups with an inadequate fossil record. The prevailing view was that classifications should be based on overall resemblances, 'which may then be interpreted in phylogenetic terms'. Today's phylogenies are still models that need to be interpreted, but they are models that rest on a more sophisticated theoretical and empirical base. Phylogenetics has breathed new life into taxonomy. It has also stimulated botanists to expand their horizons and their methods to encompass a world-view that taxonomy too can be 'big science'.

Plant diversity science in the twenty-first century

Even though the scientific study of plant diversity began well before words such as evolution, genetics, ecology or DNA were ever used in a scientific context it is perhaps surprising that at the beginning of the twenty-first century, after more than 300 years of effort, the basic process of discovering plant diversity is still far from complete. We now find ourselves in the extraordinary situation where some branches of taxonomy are highly developed, while others have clear deficiencies in even the most basic information. Perhaps most worryingly of all, we remain uncertain about what it is that we actually do know, largely because much of the practice of systematics – which is classically a decentralised scientific activity – is surprisingly unsystematic.

It is also clear that we still have much to learn about even the basic units of botanical diversity. Entries in IPNI (the International Plant Names Index) (2004) reveal that over 2000 new species are described each year; a large proportion of which come from the tropics, the most botanically diverse, unique and undercollected areas of the world. Here, the practical difficulties of exploratory fieldwork are often exacerbated by the fact that many of the new species now being discovered exist only in small populations with very narrow distributions (Prance *et al*., 2000). For example, the Wollemi Pine (*Wollemia nobilis*) – a new genus in a family in which two genera were known previously – was discovered in 1994 in a canyon of the Wollemi National Park about 150 km northwest of Sydney, Australia. This remarkable living fossil was found growing in the bottom of a canyon where the microenvironment was moist and protected from bush fires; today it persists as a population of only 43 individuals (Botanic Gardens Trust, 2004). Similarly, the recent rediscovery of *Takhtajania perrieri* in Madagascar, 85 years after its original discovery (Schatz & Lowry, 1998), exemplifies the difficulties of locating small populations in remote areas. In Brazil alone, one of the world's centres of plant diversity (Davis *et al*., 1997) which contains significant hotspots of biodiversity (Myers *et al*., 2000), 39 000 new species names have been described from type specimens and listed in *Index Kewensis* since 1898.

It is also very obvious that there is currently insufficient taxonomic capacity to keep up with the rate of discovery of new species. An increase in taxonomic capacity is needed even to process the outputs of current fieldwork. Building up human capacity, requiring a major increase in training programmes for taxonomists throughout the world, needs to remain a high priority. Vernon Heywood expended enormous effort in this area throughout his career and this important work must continue.

It is also crucial to recognise that even in countries where capacity for plant diversity research has been increasing (e.g. Brazil), a persistent major impediment to taxonomic work is that the key literature and specimens, which are needed to understand both new and previously described species, are not easily available to the in-country scientists who need them to do their work. Efforts devoted to capacity building should therefore include digitising and increasing online availability of scientifically important historical information, including images of type specimens and primary literature. Much of this material is physically located in the 'North', but is needed in the 'South'. New initiatives to make such information electronically available point the way for other efforts around the world (e.g. the Australian Virtual Herbarium (2004), the International Plant Names Index (2004), digitisation of the Missouri Botanical Garden's nomenclatural database and associated images VAST (VAScular Tropicos) (2004), the Herbarium of the New York Botanical Garden (2004) and the electronic Plant Information Centre (ePIC) of the Royal Botanic Gardens, Kew (2004)).

Much of the current interest in taxonomy, especially from governments, is driven by the relevance to plant conservation of the data contained in such electronic resources. The link between plant diversity science and conservation biology is also encouraging the development of new scientific approaches. Computer map-based geographic information systems (GIS) are used increasingly to understand environmental information and to manage and process spatial data (Burrough & McDonnell, 1998). These approaches are now being used increasingly to integrate biological and ecological information. At the same time, population genetics is also becoming increasingly important to conservation biology. Genetic diversity within species (Guarino *et al.*, 1999) is an often-neglected aspect of biodiversity. Before the advent of DNA-based techniques, morphometric and protein-based analyses were commonly used to assess levels of genetic diversity at the population level; now, however, DNA sequencing, amplified fragment length polymorphism (AFLPs, a PCR-based method) and plastid microsatellite-based techniques can all be used to identify isolated lineages, determine genetic diversity within and among populations, and hence guide conservation science. The data provided by such techniques are increasingly important in guiding management decisions focused on small populations of key species.

The impact of the Convention on Biological Diversity (CBD)

Increased concern about the conservation and sustainable use of plant diversity has been driven by significant changes in the political and social spheres over the last 30 years. In turn, this has changed the context in which plant diversity science is pursued. During the 1960s, concern about the impacts of humans on the environment increased dramatically, and culminated in the 1992 United Nations Conference on Environmental Development (UNCED) in Rio de Janeiro, more commonly referred to as the 'Earth Summit'. At Rio, world governments sought to find ways to halt the destruction of natural resources by committing to the CBD, as well as the associated need for national strategies of sustainable development. For plant taxonomy, adoption of the CBD was a key event. The Convention established three main goals: the conservation of biological diversity, the sustainable use of its components, and the fair and equitable sharing of the benefits from the use of genetic resources (UNEP, 1992). The CBD recognised that biodiversity is a natural resource that needs to be managed in a sustainable way. It also recognised that sustainable use of biodiversity, and the opportunity to benefit from biodiversity in an economic as well as an aesthetic way, creates incentives for conservation, especially among the poorer countries of the world.

The Sixth Conference of the Parties to the CBD (Decision VI/8) recognised 'taxonomy to be a priority in implementing the Convention on Biological Diversity' and endorsed the Global Taxonomy Initiative (GTI) (UNEP, 2002a). The framework of the GTI aims to support maintenance of reference collections and taxonomic-capacity building, to improve accessibility of taxonomic data and to generate taxonomic information to underpin decision making concerning species conservation and sustainable development. As no formal knowledge assessment was carried out before the negotiation of the CBD, the UN Environment Program (UNEP) commissioned the *Global Biodiversity Assessment*, edited by Heywood and Watson (1995). This effort was a global synthesis of the state of the global biodiversity knowledge created from the peer-reviewed contributions of more than 1500 experts from the world of academia and international organisations, from developing and developed countries alike.

The *Global Biodiversity Assessment* undertook a key scientific analysis of the issues surrounding biodiversity under five main headings: (i) agriculture, fisheries and the over-harvesting of resources; (ii) habitat destruction, conservation, fragmentation and degradation; (iii) introduction of exotic/invasive organisms and diseases; (iv) pollution of soil, water and the atmosphere; and (v) global change. The ideas that the book contained helped to lay the foundation for the 2002 World Summit on Sustainable Development (WSSD, 2002).

The Hague and Johannesburg 2002

During the preparations for the WSSD in Johannesburg in late August and early September 2002, biodiversity was identified as one of five areas in which action must be taken to help alleviate poverty and to achieve the broad aim of sustainable development. Discussions at the WSSD emphasised the five crucially interrelated areas of Water, Energy, Health (and the Environment), Agriculture and Biodiversity (and Ecosystems Management). This was the first crystallisation of an increasingly influential international view that highlighted the importance of biodiversity in the context of poverty alleviation, and the importance of biodiversity in preserving the integrity of other vital resources.

Also in Johannesburg the world committed itself to a goal of '[achieving] by 2010 a significant reduction in the current rate of loss of biological diversity' – an ambitious target. However, the WSSD did not even begin to develop specific mechanisms to measure how much biodiversity we have, or the rate at which it is being lost. As a contribution on how to approach such a challenge, the Royal Society has published a framework for measuring biodiversity. This makes explicit existing best practice for carrying out long-term monitoring, so that we can apply consistent sampling methods for the collection of new biodiversity data, and address the gaps in our current knowledge (Royal Society Working Group, 2003). This has now been followed by an international meeting and workshop that drew together governments, non-governmental organisations and scientists to help develop proactive approaches to global-biodiversity measurement.

In the context of the post-Rio development of the CBD in 2002, we also saw for the first time clear recognition by the global community that a more comprehensive, synthetic and cohesive understanding of the plant world must be an international priority. In April 2002, the Sixth Conference of the Parties to the CBD in the Hague adopted a Global Strategy for Plant Conservation (GSPC) (UNEP, 2002b). This strategy outlines 16 clear, time-limited targets towards improving our understanding of, and conserving, the world's valuable plant resources (Table 1.1). The first and most fundamental of these sets down the challenge to produce, by 2010, a taxonomically standardised world checklist of plant species, as a first step towards completing a World Flora. Completing even this first step is a massive task that cannot be accomplished without synthesis, collaboration, an international perspective and expansion of the worldwide capacity in plant diversity science.

Science, conservation and sustainability

In spite of the remarkable theoretical and technological developments over the past few decades, the science of taxonomy is sometimes still criticised for being too inward looking. Increasingly, however, in light of the CBD process and the Rio and Johannesburg summits, taxonomists are now considering the wider conservation and sustainability management issues to which their work relates. The GSPC is the most obvious manifestation of the trend that recognises that taxonomy is the foundation on which wider issues and decisions regarding the future of plant diversity must be based. The formulation of the GSPC – largely by taxonomists and botanic garden specialists – and its acceptance by the international community, was a landmark accomplishment.

Anticipating these developments, in recent years there has been a significant increase in the extent to which conservation-orientated initiatives are being undertaken by traditional taxonomic organisations. At one extreme, new scientific research has been devoted to methods of prioritising conservation efforts more effectively. For example, the relative phylogenetic distinctiveness of taxa with respect to patterns of phylogenetic branching can now be approached objectively. The ongoing Natural History Museum-based 'Worldmap' project uses this approach to link problems in biogeography, biodiversity assessment and conservation needs at a variety of spatial scales (Williams, 1996). At the other extreme, traditional methods of *ex situ* conservation are being applied and developed in new ways and on an expanded scale. *Ex situ* conservation represents the mainstay of botanic gardens, and is a key way to educate the public and raise awareness of conservation and sustainability issues. The GSPC explicitly acknowledges the key role that *ex situ* conservation has to play in the conservation of species and genetic diversity. Botanic Gardens Conservation International (BGCI) has estimated that botanic gardens in the European Union alone represent living collections of up to 50 000 plant species, or almost 20% of the world's known flora (Cheney *et al*., 2000). It is also significant that *ex situ* collections comprise not just growing plants, but also seed banks, and cell and tissue culture collections.

The Millennium Seed Bank (MSB), based at Wakehurst Place, UK is the largest *ex situ* conservation project focusing on the preservation of wild plant species (Smith *et al*., 1998). All overseas projects undertaken by the MSB are carried out in collaboration with local partners and are regulated by formal Access and Benefit-Sharing Agreements, as recommended by the CBD. In some cases benefit-sharing constitutes a financial agreement, but it can also involve capacity building and a great variety of other initiatives, including training. For example, every year the MSB runs a two-week course in seed-conservation methods and in-country courses are also arranged with individual countries. Such efforts are also given increasing priority on an international scale. For example, at the Rio Summit in 1992, the UK Government introduced the 'Darwin Initiative for the Survival of Species' scheme which brings together individuals from biodiverse, but economically poor, countries and UK centres of expertise. Through grants provided by this scheme, the United Kingdom has been able to welcome many hundreds of individuals from developing countries and to participate in joint conservation projects, many of which include a significant training component.