CHAPTER
28

Taxonomic Preparedness: Are We Ready to Meet the Biodiversity Challenge?

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Taxonomic and genetic diversity—essential for human health, agriculture, and ecosystem function—are being eroded as wildlands are converted to other uses. Many species already have become extinct as a result, and thousands, perhaps millions, of others soon face a similar fate. Equally alarming, the rate of habitat conversion is accelerating, along with—by implication—extinction of species. Consider, for example, the approximate doubling of the estimated annual rate of tropical deforestation in the 1980s (Myers, 1991), which has led some to predict that one-fourth or more of our planet's species may disappear within a few decades (National Science Board, 1989).

Humans use tens of thousands of species in their daily lives for food, shelter, medicines, and diverse forms of commerce. As population pressures increase and more and more people must make use of other species for subsistence, managing these resources in a sustainable manner will become increasingly difficult. Modern forms of transportation have reached all corners of the globe so that people, whatever their economic circumstances, are now more mobile than at any other time in human history. As a consequence, thousands of species are being transported around the world, both intentionally and unintentionally. New diseases are emerging; agricultural systems are being exposed to a multitude of new crop pests; the natural structure and function of ecological communities are being torn apart by the introduction of exotic species; and intricate distributions of species produced over thousands or millions of years are rapidly being shuffled. Laissez-faire public policies regarding the management of natural ecosystems that once were considered benign now are seen to carry serious societal consequences that seldom can be reversed, and then only at substantial expense.

Discovering new biological resources and managing existing ones depend on access to reliable scientific knowledge about biodiversity. Yet as implied above, the challenges to effective management of the world's species are multiplying at a rate that far outstrips our acquisition of the information needed to confront them (Cracraft, 1995; Systematics Agenda 2000, 1994a,b). Ironically, the biodiversity crisis has emerged as a global issue at the same time that support for basic research and training in the biodiversity sciences has declined sharply (Holden, 1989; House of Lords, 1991; Nash, 1989; Schrock, 1989; Wheeler, 1995a). The absence of adequate scientific infrastructure in most countries, especially in those that are species-rich, constitutes a major impediment to an international response by the scientific community. Even those countries with substantial scientific resources cannot meet their management needs (National Research Council, 1993). In these countries, for example, systematic collections are not funded at a level that is capable of keeping up with the existing rate of specimen acquisition, let alone at a level appropriate for the biodiversity crisis. Existing data in herbaria and museums remain largely inaccessible by modern technologies for data management. Funds available for investigating fundamental questions about biological diversity are severely limited relative to the task at hand. And, finally, the numbers of students trained in systematics and organismal biology have diminished, contributing to what many, including the DIVERSITAS program of the International Union of Biological Sciences, the Scientific Committee on Problems of the Environment, and the United Nations Education, Scientific, and Cultural Organization, have called the "taxonomic impediment."

Of all the biological information that is needed to manage the world's species, the most fundamental is that provided by the discipline of systematic biology. The four primary components of systematics—discovery and description of species, phylogenetic analysis, classification, and biogeography—provide basic biological information about species, including their name, characterization, relationships to other species, and geographic distribution, thus establishing the foundation for all the other biodiversity sciences, such as ecology, population biology, genetics, and behavior. Taken in aggregate, these components support the ultimate aim of systematics to know and understand the taxonomic and phylogenetic diversity of life on Earth.

The need for systematics has never been greater. Despite having accumulated significant knowledge about the world's species over the past 2 centuries, we still cannot provide accurate answers to the simplest of all questions about biodiversity. How many species are there? Estimates vary from 3 to 100 million species. What are the relationships among species? Except for a small number of taxa, the pattern of life's history remains an enigma. Where among the myriad of Earth's habitats are these species distributed? Detailed answers exist for no more than a few species; indeed, the distributions of many of the most thoroughly studied vertebrates, including groups such as birds, remain imprecisely known.

The continuing loss and degradation of the world's biological resources compromises the ability of nations to create a sustainable future for their citizens. Managing these resources will necessitate an increased commitment on the part of the world community to support the biodiversity sciences, especially in the species-rich countries where scientific capacity is least developed. This should include programs to build new or to improve existing infrastructure, enhance human resources, and establish a world-wide biodiversity information network.

The systematics community, through its initiative *Systematics Agenda 2000*, has established a framework that can be used to develop the science of systematics world-wide (Systematics Agenda 2000, 1994a,b). Advances in the theory and methods of systematics, computer management of vast collections of specimens, and existing descriptions for more than a million of Earth's species provide a context and starting point for creating the knowledge-base in systematics that will be required to confront the challenges of managing species and their ecosystems.

DEVELOPING A SYSTEMATIC UNDERSTANDING OF THE WORLD: LIMITATIONS OF THE ECOLOGICAL APPROACH

Maintaining global ecological systems and achieving sustainability of biological resources are now widely recognized goals of the world's nations. For this to happen, however, each nation must adopt management policies that are based on, and consistent with, credible scientific knowledge. A key component of this knowledge is derived from systematic biology. Unfortunately, sufficient systematic information neither exists today in the quality or quantity required, nor does the scientific community have the capacity to acquire it rapidly.

Given that systematics is of clear importance for successfully managing global biodiversity, and that resources to support systematics science will need to be increased, we may ask "What is the most cost-effective and efficient means of developing a systematic understanding of biodiversity?" The broad, comparative scope of systematics research is unique among the biological sciences (Nelson and Platnick, 1981), suggesting that the best returns will be gained from strategies that meet its special needs for research resources.

Perhaps no more than 5% of the world's species have been discovered, described, or classified. There is broad agreement that human societies would benefit immensely from having knowledge of this unknown diversity, yet until recently no coherent research programs have been proposed to address this problem.

One approach to providing a taxonomic understanding of global biodiversity has been developed largely from an ecological perspective on diversity. It begins with the concept of an All Taxa Biodiversity Inventory (ATBI) at a single, geographically localized site, in which an effort is made to collect and identify "all" the species at that site (Janzen and Hallwachs, 1994; Janzen, Chapter 27, this volume). The overriding purpose of an ATBI is to contribute to the sustainable development activities of the country in which the site is located, and for that purpose an ATBI has obvious potential. Because of the substantial systematic activity necessary to undertake and support an ATBI, global knowledge of biodiversity seems certain to increase, and the results of such an exercise are likely to have important benefits for basic and applied biology, as well as for conservation and economic development. But are ATBIs the most logical and efficient way to approach an inventory of Earth's biological diversity (Wheeler, 1995b)?

In addition to their function in the development of nations, ATBIs also are being proposed as a model for achieving a systematic understanding of global biodiversity (Janzen, 1993; Langreth, 1994). It has been suggested that a dozen ATBIs, carefully sited and successfully completed, would sample as much as 40-50% of the world's species diversity and could be undertaken for about $1 billion (Janzen, quoted in Langreth, 1994:81). Leaving aside the fact that we currently do not have the necessary collections-based infrastructure or systematic expertise to complete a single ATBI, the application of what is essentially an ecological approach to sampling will result, over the long term, in an ineffective and cost-inefficient program, whether the goal of that program is to develop a systematic understanding of the world's species or a credible and predictive understanding of the local biodiversity.

The reasons for this are several. First, a dozen ATBIs barely would begin to provide the geographic coverage necessary to discover a sizable percentage of the world's estimated species diversity. This follows from the fact that when groups are investigated in detail, it is found that most species are rather narrowly distributed (see also Reaka-Kudla, Chapter 7, this volume). To sample the Earth's diversity adequately, therefore, would require an ATBI in each of the major areas of endemism in the world. A dozen ATBIs, in fact, would be a small number for some continents. In Australia, for example, the vertebrate fauna is partitioned into many areas of endemism, and an ATBI in only one of them would recover a very small portion of the Australian biota (Cracraft, 1991). As a consequence, an ATBI in one country will have limited utility for representing the diversity of other countries, including in many cases those in relatively close proximity to the ATBI site. An ATBI in one country, moreover, often will have limited relevance for the development process in others, except perhaps in the sense that they contribute to global systematic knowledge. Because adequate knowledge for any given taxon may dictate studies in a unique number and combination of geographic locations and habitats, it is doubtful that any finite number of ATBI sites ever would prove to be fully adequate for a detailed systematic understanding of more than a few taxa. While periodic collecting at known sites is a prerequisite for documentation of the status and trends of biodiversity, the very notion of long-term study at a few anointed sites is inherently an ecological approach while the resolution of fundamental questions about biodiversity require answers grounded in a systematic biological approach.

Ironically, were most species found to have broad geographic ranges, in contradiction to 2 centuries of experience and observation, then comparative studies throughout their ranges would be of critical importance. Widespread species often can be recognized definitively only after their full range of genetic variation has been studied (Mayr, 1963). The history of taxonomy suggests that the isolated description of local floras and faunas frequently results in confusion about species identities and a proliferation of redundant names. If most species actually were narrowly distributed, perhaps this problem could be avoided and provincial ATBIs could succeed in recognizing endemic species without creating such confusion. But then the assumption that species are widespread would be violated, and the ATBI model would fail to capture a significant representation of the world's biological diversity.

Second, ATBIs are particularly inefficient for setting global priorities for systematic research or for facilitating the growth of systematic knowledge, being biased as they necessarily are by the geographic location of the site and by the development and conservation needs of that particular country. Systematics can contribute far more to meeting the international need for knowledge by working with all nations to set priorities for revisionary studies, such as on those groups that are important for agriculture, human health, ecosystem function, and growth of scientific knowledge. Designing a global program to target such groups and to share the resulting discoveries would more efficiently meet diverse international needs for knowledge of biodiversity than investment of human and financial resources in documenting the biodiversity at a limited number of sites. For taxa of demonstrated economic or societal relevance, it is unlikely that either the majority of species or the most promising underutilized species will be found in a handful of ATBI sites, regardless of how carefully they are identified. For taxa of unsuspected or unappreciated importance, a worldwide perspective is even more essential. No one yet can predict where valuable discoveries will take place. Opportunities are enhanced by assuring an exploration of the most disparate branches of the evolutionary tree of life, rather than restricting our discoveries to the species and clades that happen to live in a dozen or so places on Earth.

Third, collecting organisms is typically the easiest, least labor-intensive aspect of systematic activity. Specimens cannot be identified reliably to species without access to synoptic collections of previously described species, specialized expertise, and extensive comparative analysis. This takes considerable time and access to resources for systematic study. Thus, current conceptual schemes for ATBIs significantly underestimate the time and scientific resources that will be required to identify and classify specimens collected during the ATBI process. With the exception of a few well-known groups, or species that are widespread or "weedy," identifications frequently will be a slow process, if they can be done at all. As is well known, there is exceedingly little taxonomic expertise or background knowledge for many groups of organisms.

Finally, ATBIs will not fulfill their potential for many development purposes until the relationships of the species are understood, inasmuch as it is the knowledge provided by an understanding of the close relatives of species and their biological characteristics that makes newly discovered species useful to society. Unless studies of phylogenetic relationships go hand-in-hand with the inventory process, we will neither make maximal use of these discoveries, nor will we be able to construct maximally efficient and useful information systems or predict where research, development, or conservation dollars are most profitably spent. Thus, systematic research is a prerequisite for the successful completion of any ATBI and as a consequence should have priority when building scientific capacity.

Drawing on extensive experience in the discovery, description, and classification of biodiversity and a remarkable recent theoretical revolution within the discipline, systematists are uniquely qualified to propose an alternative strategy for inventorying biodiversity that draws on what we already know and takes full advantage of research expertise and resources.

REALIZING *SYSTEMATICS AGENDA 2000:* AN ACTION PLAN FOR MEETING THE BIODIVERSITY CHALLENGE

In contrast to a world-wide network of ATBIs, the most efficient and cost-effective mechanism for developing a systematic understanding of the world's biodiversity is to promote capability in systematics for all nations (Systematics Agenda 2000, 1994a,b). This entails an integrated research program of global inventories, revisionary taxonomy and phylogenetic analysis, and electronic access to this knowledge via a biodiversity information system. It also involves setting priorities for research that benefit all nations, not just a few, which can be accomplished within a time-line that meets the needs of countries over the short term.

It is impossible to identify, classify, or understand the biota of one nation without also knowing and studying the same or related taxa from other countries. Assessing variation within species or the diversity of characters among species necessitates access to correctly identified specimens of all species of the group under study world-wide.

Because it is impractical to house a complete collection of the world's species in each country, comparative systematic research will rely on a limited number of institutions focused on particular groups and networked electronically and programmatically. By creating such centers with special expertise on specific taxa, resources for research can be concentrated at that location. Such resources would include collections, systematic experts, specially trained support staff, and databases. This results in cost-effectiveness for original research as well as training new generations of experts, validating and updating data included in vast databases, and providing a source for taxonomic expertise and services wherever they are needed around the globe. Such laboratories typically would be located within museums and universities that at the same time support reference collections of the species indigenous to their own countries. Because no country can support experts on all groups living within its borders, each country must depend on a network of international scientists in order to have duplicate, accurately identified specimens of as many of their species as possible.

For many branches of science, such global vision and international cooperation are taken for granted. Imagine astronomical, seismological, or global change research without data gathered world-wide or without relatively open exchange of data and scientists among nation states. In each case, data must be gathered at many sites around the globe and integrated in order to make sense of the local data. At the same time, budgets for such "big science" are assumed to be a shared, multinational responsibility. Similarly, an understanding of the Earth's species diversity will require no less than a globally conceived research effort.

Acceptance of the premise that research should be organized around particular groups affects virtually every aspect of research in biodiversity. Research centers should be structured and staffed so as to maximize and take full advantage of accumulated knowledge of a taxon. Field inventory work must be organized to document all species of a group throughout its geographic range rather than to concentrate efforts at one or a few study sites. Ultimately, this information needs to be summarized, interpreted, and communicated—in either printed or electronic form—through comprehensive monographs. Databases should be kept current and accurate by locating them where experts, libraries, and voucher specimens exist. In each case, research, funds, and personnel would be organized around the unique requirements for the study of specific taxa.

What kinds of research infrastructure are necessary in order to mount an effective scientific response to the biodiversity challenge? While existing numbers of specialists, institutions, and funding sources are grossly inadequate to address the biodiversity challenge, there is little doubt about what needs to be done or that the organizational components of an effective scientific program exist. Theoretical advances in systematic biology over the past 3 decades have revolutionized and rejuvenated the field, arming it with the ideas and methods appropriate for the exploration and analysis of biodiversity (e.g., Eldredge and Cracraft, 1980; Forey et al., 1992; Nelson and Platnick, 1981; Schoch, 1986; Wiley, 1981). Collection and data management practices have incorporated modern computational capabilities so that they are prepared for the acquisition of large numbers of specimens and vast quantities of data. The tragic erosion of systematic expertise, moreover, could be reversed in a single generation of scholars, given adequate resources to recruit, train, and employ such scientists.

PLANETARY EXPLORATION: TAXON INVENTORIES

The process of discovering, discriminating, and describing the world's species is an enormous undertaking, amounting to the scientific exploration of all forms of life on an entire planet (Raven and Wilson, 1992). In order to accomplish this ambitious undertaking efficiently and rapidly, it is critical that such work be approached so as to take full advantage of current taxonomic expertise and research resources. What does this mean?

Just as systematic research is focused on taxa, as opposed to geopolitical areas or ecosystems, so too an efficient scientific program must be aimed at generating systematic knowledge of Earth's species. Scientists studying a particular group must collect specimens from wherever on the globe such organisms live. Short-term or intermittent study sites in diverse geographic locations are most appropriate for meeting the global needs for systematic knowledge. In essence, systematics views biodiversity differently than experimental or functional biology by making broad comparisons across all species of a clade. The following, then, represent top priorities:

- **Action Item 1:** Provide for diverse world-wide inventorying efforts, each of which is directed at one (or several related) taxa, making full use of specialized expertise and research resources.
- **Action Item 2:** Increase the effectiveness of the inventorying effort, and the systematic research derived from it, by expanding support for the construction, improvement, management, and growth of natural history collections in museums, botanical gardens, and universities. These should include institutions that build comprehensive, global research collections as well as reference collections that hold representatives of the species indigenous to each nation.
- **Action Item 3:** Establish international networks of taxonomic experts with the goal of ensuring that there is open access to expertise for every group of organisms somewhere in the world. Each country should have sufficient systematics expertise to coordinate cooperative international research and to link with and interpret existing data.

DOCUMENTING DIVERSITY: MONOGRAPHY, REVISIONARY TAXONOMY, AND PHYLOGENETIC ANALYSES

The scientific documentation of biodiversity goes far beyond the description of species, and ultimately extends to providing access to all that is known about related species in larger taxa as well as enabling a logical classificatory scheme to be constructed from which predictions about their properties, distributions, and attributes can be made.

Drawing on powerfully predictive phylogenetic analyses, monographers pull together, analyze, and interpret all that is known about the species of a taxon, elucidate the clade's evolutionary history, and produce a classification that makes data easily retrieved and understood. Consequently, the following is imperative:

- **Action Item 4:** Competitive research funds should be made available to support comprehensive, comparative revisions and monographs that are focused on taxa at all levels from individual genera to phyla.

ACCESS TO KNOWLEDGE ABOUT BIODIVERSITY

Because more and more nations, managers of natural resources, and scientists will make ever-increasing demands for accurate and detailed knowledge about biodiversity, it is critical that what is learned from this global inventory effort and subsequent systematic analysis be accessible as part of the world's emerging information highway. Much of the information on biodiversity that is housed in the world's collections remains inaccessible electronically. Furthermore, descriptions of the approximately 1.5 million existing species are widely scattered in the technical literature, making an accurate count of species, not to mention retrieval of the descriptions themselves, problematic. Two hundred million specimens exist in natural history collections in the United States alone (Edwards et al., 1985), yet databases permitting access to their data do not yet exist. Therefore, the following must receive priority attention:

- **Action Item 5:** A network of world-wide taxon databases should be created which make specimen-based knowledge accessible and guarantee that those data are maintained by institutions possessing the collections, libraries, and taxonomic specialists necessary for ensuring their integrity over time.
- **Action Item 6:** An international effort should be made to electronically capture the specimen-based information in major natural history collections of the world and to make that information freely available to all nations for their use and benefit.

HUMAN RESOURCES AND TRAINING: MEETING NEEDS FOR TAXONOMIC EXPERTISE

A major challenge facing the study of biodiversity is the creation, reestablishment, and expansion of taxonomic expertise on neglected taxa, thus confronting the "taxonomic impediment." Evidence from around the world indicates that taxonomic expertise has declined and continues to do so at just the time when the world is expressing its desire for credible taxonomic knowledge (e.g., Edwards et al., 1985; National Science Foundation, 1990). In the United Kingdom, for example, about one-half of the botanical taxonomists teaching in leading universities have disappeared in recent years (House of Lords, 1991). A recent survey of universities in the United States which offer doctoral degrees in systematic entomology shows that 60% of existing faculty have an average of one Ph.D. student and the remaining 40% have none (Daly, 1995). In many universities, faculty positions in systematics have been replaced by non-taxonomic, often molecular, ones (Holden, 1989; Nash, 1989). And even in museums, efforts to be "modern" and compete for limited research dollars have resulted in the de-emphasis of traditional taxonomic research, particularly monography.

Steps must be taken immediately to train and support experts on diverse taxa, to clarify the unique responsibility of museums, herbaria, and universities to conduct taxonomic research, and to educate administrators to understand that good biology involves asking and answering questions at many levels of organization using a wide range of techniques. Each nation and its systematics institutions must accept responsibility for facilitating taxonomic work that is not only relevant to its own interests and objectives but which also contributes to the global knowledge-base.

Despite the urgency for additional systematic expertise, the contributions of the limited number of taxonomists working today can be increased immediately and significantly to meet the demand for knowledge about biodiversity if given the requisite support. Support personnel who are knowledgeable about the group being studied can multiply the productivity of single or teams of scientists. Collectors, preparators, curatorial assistants, illustrators, database managers, laboratory technicians, and others can perform tasks that today occupy a significant proportion of systematists' time. Such personnel, familiar with common species, proper collecting protocols, and procedures for handling specimens, also could extend the field activities of a taxonomist to many sites simultaneously.

EPILOGUE: AN OPTIMISTIC FUTURE

Systematics Agenda 2000 must be seen for what it is: big science. It is nothing short of planetary exploration, requiring the resolve to understand the biota of Earth for the future benefit of humanity and the conservation of the natural world. The use of biodiversity already contributes trillions of dollars to the world economy through the goods and services it provides. Thus, it is not only a good investment to have scientific knowledge about the world around us, it is a matter of survival.

Because many aspects of taxonomic research are not perceived as being expensive or technologically intensive, it has been falsely assumed that the missions of systematics do not meet the contemporary criteria for status as "big science." Yet the missions of systematic biology constitute an immense and complex scientific enterprise, ultimately accounting for the biodiversity of the present and past world (see Systematics Agenda 2000, 1994a,b). The dimensions of the biodiversity crisis are immense, and the extinction of several million species over the next few decades seems certain unless nations respond forcefully. This, and the lack of sufficient scientific information to confront the biodiversity crisis with effective policies, contributes to a sense of doom. We are, nonetheless, cautiously optimistic. Whereas taxonomic expertise has declined sharply, the field is more intellectually vibrant and exciting than ever, and existing scientists are eager to train a new generation of experts. With adequate resources for the kind of research taxonomists do, positions would open, and students would gravitate to the field. Given successful examples of the knowledge and understanding that would emerge from world-wide inventories of targeted taxa, benefits to nations participating in this global exploration of biodiversity would become evident.

In the industrialized countries, at least, construction of a massive scientific infrastructure from scratch to meet the biodiversity challenge would not be necessary. A first step would be to expand, amplify, and support more fully those scientists and infrastructure that are already in place and to make accessible data from the hundreds of millions of specimens already housed in our museums. Recent advances in the theory of systematics have been rapid and profound, giving a promising conceptual context for understanding the origin and diversification of organisms on Earth. New and diverse sources of comparative data have been developed, extending and enhancing our means of critically testing phylogenetic hypotheses. The expanding capacities of computational tools provide hope for managing facts about tens of millions of species around the globe. Systematic biologists thus know what must be done in response to the biodiversity challenge and have the conceptual and practical tools to accomplish it. Society now needs the courage and foresight to invest in the growth of the fundamental taxonomic knowledge that will make scientifically informed decisions about resource management and conservation possible in the future.

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