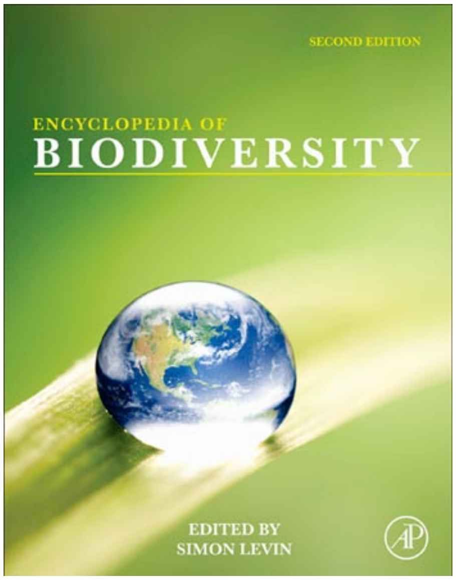
The Role of Museums and Institutions in Biodiversity Science and Education

Chapter · January 2013

2 authors:

Michael J Novacek
American Museum of Natural History

Suzann L. Goldberg
American Museum of Natural History



Novacek Michael J., and Goldberg Suzann L. (2013) Museums and Institutions, Role of. In: Levin S.A. (ed.) Encyclopedia of Biodiversity, second edition, Volume 5, pp. 404-420. Waltham, MA: Academic Press.

Museums and Institutions, Role of

Michael J Novacek and Suzann L Goldberg, American Museum of Natural History, New York, NY, USA

Glossary

Bioinformatics Technology and research aimed at clarifying, coding, organizing, and analyzing biological data through use of computing hardware, software tools, web applications, and theoretical and computational science.
Curation The scholarly study, care, management, documentation, and maintenance of a scientific collection.
Curator A scientist responsible for curation.
Lot A specimen or set of specimens generally stored and studied together, such as individuals of a single species from a single site collected at a single point in time.
Parataxonomist A layperson trained in basic sciences and methods that allow him or her to identify species and higher taxa and conduct biodiversity surveys and inventories.
Phylogeny The evolutionary and kinship relationships of species or the taxa that contain them, usually depicted as branching, tree-like diagrams.
Specimen The whole or a part of an individual organism with a unique data identifier formally added, or accessed, to the institution's collection.
Systematics The study of the evolutionary and kinship relationships of species or the taxa that contain them. Many systematic studies yield results represented by tree diagrams that depict phylogenies (see above).
Type specimen A particular specimen chosen to be the "name bearer" of a species. The characters that diagnose a given species are to be found in the type.
Vouchered specimen A specimen that serves as the basis for extended study and is retained as a reference specimen. A type specimen is a particular vouchered specimen that serves as the basis for taxonomic description and diagnosis of a species. Another example of a vouchered specimen is the one retained as a reference source for tissues used in DNA studies.

Natural history museums (NHMs) and related institutions such as botanical gardens, zoos, and aquaria are devoted to the exploration and study of the biological world, both past and present, and through these efforts provide, with their vast collections, the primary record of life's history and diversity. It has been estimated that some 6700 institutions worldwide serve as the biological repositories for more than 2 billion biological specimens (Duckworth *et al.*, 1993; OECD, 1999; Chapman, 2005; Ariño, 2010). Many of these institutions are also committed to the twin mission of science and education: The research, collecting, curation, and exhibition and educational programs they sponsor serve to enlighten, inspire, and inform a broad public about the richness and wonder of life on earth. In recent decades, these twin missions have taken on a special urgency due to the rapid global degradation and destruction of rain forests, coral reefs, wetlands, and many other natural habitats and the concomitant loss of biological species. That loss, estimated to be at levels 100–1000 times the normal or background rate of extinction recorded in the fossil record (Pimm *et al.*, 1995), constitutes what many biologists call the current biodiversity crisis, an event that possibly could result in loss of anywhere between 30% and 50% of all living species during the twenty-first century, a biological catastrophe approaching the level of the five major mass extinction events in the past 500 million years (Leakey and Lewin, 1996).

Natural history institutions continue to add to their collections and expand on their biological surveys, research, and training. Despite this effort, museum scientists and their colleagues at universities and other institutions still face the enormous challenge of producing a comprehensive census of life's diversity. Between 1.5 and 1.8 million species have been named, described, and classified (May, 1988; Wilson, 2003), but this, by any estimate, is far short of the actual diversity of species living at present. A recognition of our incomplete knowledge of some highly diverse groups such as insects, and our extremely poor knowledge of many groups of invertebrate animals, fungi, algae, plants, and especially diverse bacteria, protists, and other microbial organisms, suggests that the total number of species could range notably upward from at least 10 million species (Wilson, 2003). The challenge of mustering a better accounting of biodiversity is compounded by the current rate of environmental degradation and the loss of species: Many of these species will doubtless be extinct before scientists have a chance to account for them. Thus the work of NHMs and related institutions is critical to our understanding of both the scope and richness of life and the magnitude of the impacts on the natural world resulting from land degradation and loss, climate change, pollution, invasive species, overharvesting, and other drivers caused by human activities.

History: The Emergence of Natural History Institutions

The motivations for establishing museums devoted to natural history are deeply rooted in human culture. The desire to observe, contemplate, and memorialize nature is represented in some of the oldest evidence of human thought and expression, including the elegant wall paintings of animals in the 17,000-year-old paintings in the caves of Lascaux. In the less-distant past, the emergence of a place for scientific collections, study, and enlightenment is certainly apparent. Aristotle's "peripatetic school," formally established in 335 BC at the site of the even more ancient Lyceum, was the base camp from which the philosopher and his students roamed the world collecting animals, plants, and other natural objects (Ross, 1995). Aristotle indeed intended to catalogue the whole of life's diversity, a task whose difficulty, as we know in hindsight, far exceeded his enthusiasm for it.

 http://dx.doi.org/10.1016/B978-0-12-384719-5.00420-2

Yet such motivations in the ancients clearly inspired what followed. History is replete with entities that share many of the qualities and objectives of what we recognize currently as NHMs, botanical gardens, and zoological parks. Although such establishments were not, until more recently, characteristic of eastern societies such as those in India and China, their rise and proliferation in western societies coincided with the cultural fruition spawned by the Renaissance that ushered in the Age of Enlightenment. The transition from the seventeenth century inventions of Galileo, including his improvements on the telescope and his design and fabrication of the geometric compass and the thermoscope, to the eighteenth century refinements of the compound microscope, thermometer, and barometer is vividly represented in original collections of the newly renovated and reopened Museo Galileo in Florence.

The European Model for NHMs

Throughout the eighteenth and nineteenth centuries, the great centers for natural history collections were established to provide a home for the specimens avidly collected from the far corners of the world. In most instances, the passions for collecting by wealthy, influential, and in many cases, aristocratic individuals led to the formation of societies or academies devoted to collections and research. Such developments anticipated, sometimes by many years or decades, the actual acquisition of a facility and the attainment of a scientific program adequate to care for such collections (for a review, see Kohlstadt and Brinkman, 2004). The British Museum, established in 1753, housed (in fact in a private house) the natural history collections that were originally amassed by Sir Hans Sloane, who acquired specimens from many of the British colonies and other parts of the world. Within a few decades, the British Museum could not accommodate the rapidly accumulating collections, a period accompanied by a notorious phase of disarray, where specimens were lost, sold, and even burned in bonfires. Order was imposed by the renowned comparative anatomist and paleontologist Sir Richard Owen, who was appointed superintendant of the natural history departments in 1856. Owen spearheaded the effort to move the collections to a new, appropriately designed building. The resulting grand Romanesque structure, the NHM in South Kensington, opened in 1881. Kew Gardens (or more formally the Royal Botanic Gardens, Kew), established in 1759, grew from the exotic gardens of Lord Capel John of Tewksbury into the world's largest collection of living plants. Some of Kew's most important additions, such as the iron and glass-clad Palm House, came many decades later. Complementing these developments was the establishment of the Oxford University Museum of Natural History in 1860.

Other major museums on the European continent were also established through a prolonged period of gestation. The Muséum national d'Histoire naturelle (MNHN) in Paris was formally founded in 1793 during the French Revolution but was a product of a much earlier, venerable establishment, the Jardin royal des plantes médicinales (Royal Medicinal Plant Garden) created by King Louis XIII in 1635. During much of the eighteenth century the Jardin des plantes was under the directorship of the preeminent naturalist George-Louis LeClerc, Compte de Buffon. The later-established Muséum national d'Histoire naturelle was also home to such influential scientists as Georges Cuvier, Jean-Baptiste Lamarck, and Geoffrey Saint-Hilaire. The largest NHM in Germany, the Museum für Naturkunde, Berlin, associated with the great eighteenth century German explorer and naturalist Alexander Von Humboldt, was established in 1810, but many of its collections date back to the 1700s. More a product of European, rather than Asian, influences is the Zoological Museum of the Zoological Institute of the Russian Academy of Sciences in St. Petersburg. The Zoological Museum is rooted in developments that took place as far back as 1724 and at present functions as one of the world's largest NHMs.

Museums of the Americas

In the western hemisphere, the transition from naturalists' interest to the formation of societies that ultimately sponsored and promoted the establishment of museums was very much in the European mould (Kohlstadt and Brinkman, 2004). Indefatigable collecting and a passion for collections led Charles Wilson Peale and his colleagues to ensure that the comparatively young USA had its own NHM. This effort resulted in Philadelphia's Academy of Natural Science, founded in 1812 but not rehoused in a proper building until 1840 (and later in a building opened in 1876). During the 1850s, massive collections of specimens were stored in the Smithsonian's Castle building in Washington, DC but were not transferred to a newly constructed National Museum of Natural History (NMNH) until 1881. Similarly, the American Museum of Natural History (AMNH) in New York founded in 1869 moved in 1877 from its crowded, temporary home in Central Park to a newly constructed, fireproof building adjoining the Park. Soon to follow were the New York Botanical Garden (NYBG) and the Bronx Zoo (later under the management of the Wildlife Conservation Society) opened in 1891 and 1899, respectively, on land purchased from Fordham University.

Beyond the eastern seaboard, institutions sprouted with American expansionism. The Missouri Botanical Garden, St. Louis, the oldest in the USA, was established in 1859 to encompass its ancestral home, the original estate of Henry Shaw, botanist, and philanthropist. The Field Museum in Chicago founded in 1893 first occupied the Palace of Fine Arts, a magnificent structure built as part of the ''White City'' for the Chicago Columbia Exposition (1893) but one wholly inadequate for housing museum collections. It was not until 1921 that the Field Museum relocated in its present habitat, the massive neoclassical building on Lake Shore Drive. San Francisco's natural history museum, the California Academy of Sciences (CAS), was founded as a society in 1853 and located in a commercial building whose rental income allowed Academy members to build their own facility in 1891. The latter was destroyed in the great fire of 1906 and the Academy moved to its present location in Golden Gate Park. Its facility there was succeeded by a strikingly modern, environmentally friendly, and energy efficient building that opened in 2008.

These institutions were mainly independent entities, meant to mark the cultural attributes of a city or a particular region. Nonetheless, some of the most important natural history museums and botanical gardens are actually a part of university campuses, including Harvard's Museum of Comparative Zoology (established, 1859), Harvard's Arnold Arboretum (1872), Yale's Peabody Museum (1866), and The University of California at Berkeley Museum of Vertebrate Zoology (1908).

Outside the USA, the roster of North American museums would not be complete without the mention of Mexico's very important Museo de Historia Natural de la Ciudad de México, Mexico City (MNH). Although the newest instantiation of the MNH dates back to only 1964, when it expanded its active research and education programs in biological subjects, this museum's origins can be traced back to 1790, as one of the Americas' first institutions devoted to curatorial research in natural history. At higher latitudes, Canada has had a long commitment to natural institutions. Among the oldest and most prominent of these are the Royal Ontario Museum (ROM) in Toronto, established in 1912, and the Canadian Museum of Nature in Ottawa, launched with the construction in 1912 of a famous gothic revival structure, the Victoria Memorial Museum Building.

This small sample of established museums and related institutions in North America should not exclude other major museums of the western hemisphere. Some of the latter were indeed established concurrently or prior to those mentioned above. Prominent among South American museums are the Bernardino Rivadavia Natural Sciences Museum, Museo Argentino de Ciencias, Buenos Aires (established in 1826, with the first of its current buildings opened in 1929), Museo del Mar, Mar del Plata (1888), Argentina, and the Museu Nacional, Rio de Janeiro, Brazil (1818).

Museums in Africa, Oceania, and Asia

Outside of the Americas, many museums were originally products of colonialism, subsequently reshaped and renovated with new programs after their home countries became independent. Examples include the Nairobi National Museum of Kenya, anticipated by a modest two-room building opened in 1911, moved to the new Coryndon Museum in 1930, and, following the country's independence, renamed and reconceived as the National Museum in 1963, attracting its famous director Richard Leakey in 1968. South Africa has several important natural history institutions that currently carry on very active research, including the Ditsong NMNH (formerly Transvaal Museum) in Pretoria, South Africa, founded in 1892. Other African natural history museums, in various states of modernization and improvement, can be found in Ethiopia, Egypt, Botswana, Tanzania, and Zimbabwe.

In Oceania, the most expansive museums are located in Australia and New Zealand. Australia's oldest, the Australian Museum in Sydney, founded in 1854, currently supports very active research – including new research centers devoted to biodiversity and conservation – as well as collections growth in keeping with Australia's particular emphasis on studying and sustaining its remarkable, and in many cases unique, biodiversity. But that country can claim a number of important institutions, including the Museum Victoria in Melbourne (founded in 1854), the Queensland Museum in Brisbane (1862) and several others. New Zealand's major institution covering its equally remarkable natural history is the Museum of New Zealand Te Papa Tongarewa, located in Wellington. Its ancestral home was the Colonial Museum founded in 1865, which expanded and moved during subsequent decades culminating in the modern Te Papa that was established in 1992. The Te Papa, which can claim among its arresting exhibits the world's largest specimen of the rare colossal squid (*Mesonychoteuthis hamiltoni*), is particularly notable for integrating themes relating to natural history and biodiversity with the traditions, perspectives, and practices of New Zealand's indigenous peoples.

As noted, Asia historically lacked the longstanding traditions that gave rise to the natural history institutions in Europe, North America, and elsewhere. For example, one of the continent's principal museums, the Beijing Natural History Museum (BMNH), was founded in 1951. Nonetheless, Beijing's museum and many others were direct descendents of China's research institutes established several decades earlier. Indeed, some of Asia's prominent museums, such as the National Museum of Nature and Science in Tokyo, Japan took form as early as 1871. There are a number of other important institutions in Japan as well as other countries that include Israel, India, Malaysia, Pakistan, Philippines, Singapore, South Korea, Taiwan, Thailand, and Jordan. Notable is the growth of relatively new museums as part of the cultural and economic surge in some of the Arab countries. Examples include the Qatar National Museum in Doha and the Sharjah Natural History Museum and Desert Park in the United Arab Emirates.

The Evolution of the Museum Mission

The eighteenth and nineteenth centuries thus marked the emergence and rise of the natural history institutions that still maintain major collections, support active research, and attract tens of millions of annual visitors. Yet the conditions and the premises under which these institutions were originally established were radically different from what they are at present. Although by 1800, the global human population reached 1 billion, the planet still seemed an expansive, mysterious, even intimidating place. Huge areas were poorly known or not known at all. Antarctica, an entire continent larger than Europe and only slightly smaller than South America, was not seen by humans until 1820. Not until well along in the nineteenth century did western scientists encounter, describe, and name the Sumatran rhino, the blue whale, the two living species of tree sloths, the wombat, the pigmy hippo, the spider monkey, and huge numbers of insects and plants. Museums, botanical gardens, and zoos thus sponsored elaborate expeditions to exotic locales, the essence of the so called ''Golden Age of Exploration'' that marked the 1800s and carried on well into the twentieth century.

Yet even in these early times, museums, explorers, and collectors began to reflect on the diminishing populations of wildlife and the encroachment on natural habitats by people and cities. Several of the great diorama halls, such as the Akeley Gallery of African Mammals in the AMNH in New York that opened in the 1936 (**Figure 1**), were not only a testament to the grandeur of wildlife but were also intended to

Figure 1 A museum's homage to a vanishing world: The Akeley Hall of African Mammals at The AMNH in New York.

memorialize natural settings destined to disappear in the decades ahead. Museums indeed early on fostered a conservation ethic, one, for example, that embodied the concepts and actions of none other than Theodore Roosevelt, the 26th president of the USA, a Harvard graduate with a strong interest in and knowledge of biology and a life long connection to the AMNH and other like institutions. This legacy of environmentalism set the foundation for the expansive research, educational, and exhibition programs in biodiversity and related themes carried out by present-day museums and other collections-based institutions.

Collections

The organization of institutional collections follows several prescriptions. A fundamental unit is of course the specimen, the whole or a part of an individual organism, living or preserved, fossil or recent, with a unique data identifier formally added, or accessed, to the institution's collection. Specimens vary in completeness and mode of storage according to the nature of the material. A specimen may be a single fossil tooth of an individual dinosaur, a herbarium sheet, a sample of frozen tissue, a pinned butterfly, or each tiny fly in a vial holding hundreds of flies. Specimens are often grouped in a lot, a specimen or set of specimens generally stored and studied together, such as individuals of a single species from a single site collected at a single point in time.

The Size and Scope of Natural History Collections

The accumulated collections of the world's natural history institutions and related biological repositories are of course enormous in size but for a variety of reasons it is difficult to reliably estimate this figure. Collection records vary in precision from institution to institution and discipline to discipline. Although formal accession records and actual specimens are interchangeable in many herbaria, this is often not the case with zoological collections. Moreover, the very large collections of highly diverse groups such as insects are customarily catalogued with reference to the published literature rather than by individual specimens. Notwithstanding this variation in curatorial methods, total holdings are reasonably well known for some of the major museums (**Figure 2**). Unfortunately, this is not the case for a large number of other institutions, including those in developing countries, where resources for collections-based institutions can be very limited. A mandatory register of biodiversity-related collections does not yet exist.

Well known estimates for total worldwide collections size, primarily in museums, that account for animal, plant, fossil, and mineral specimens range between 2.5 and 3 billion (Duckworth *et al.*, 1993; OECD, 1999; Chapman, 2005). Newer data sources, such as the Global Biodiversity Information Facility (GBIF) (2003), record lower figures, ranging from 407 to 737 million in holdings, but many data rich institutions are not yet members of GBIF. The application of probabilistic and distribution models and case studies to data derived from GBIF and other sources, such as the Biodiversity Collections Index, yields estimates of total worldwide biological collection size ranging between 1.2 and 2.1 billion units, with a unit equaling a single specimen or a group of specimens registered as a single data record and treated as a whole (Ariño, 2010).

Relative biological collection sizes for 10 major museums, which include among them the largest such institutions (**Figure 2**), represent in aggregate more than 426 million biological specimens (both fossil and extant), and thus a large portion of worldwide holdings. With respect to extant species, all of these collections, and those of many other museums, share some of the same characteristics (**Figure 3**). By far the

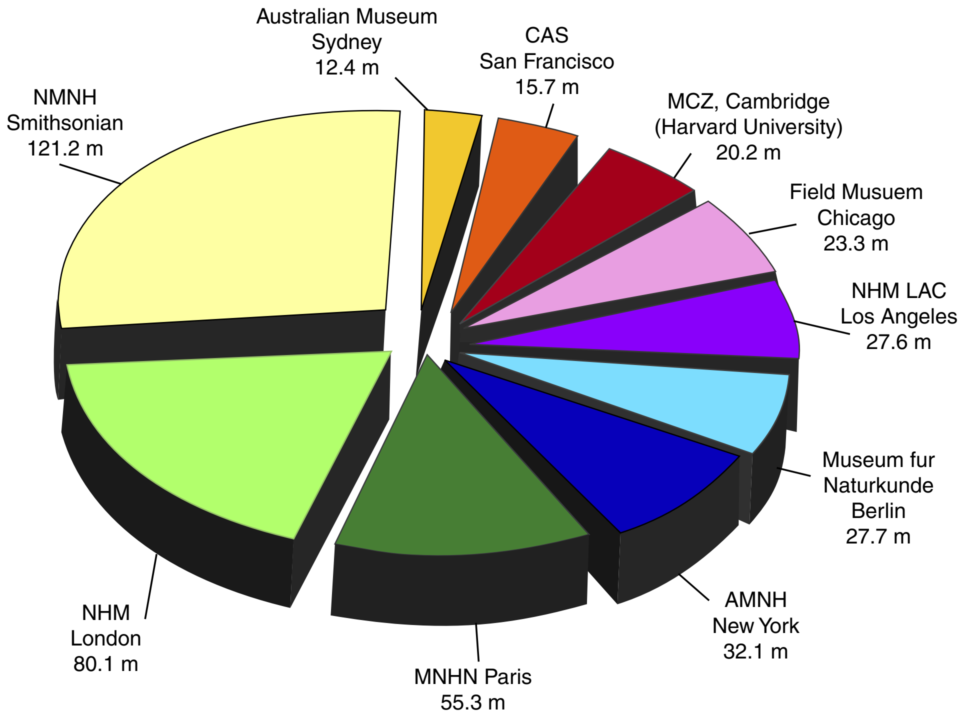


Figure 2 Total size (in millions of specimens) of biological collections (extant and fossil) of several major natural history museums. Abbreviations are: AMNH, American Museum of Natural History; CAS, California Academy of Sciences; MCZ, Museum of Comparative Zoology; MNHN, Muséum national d'Histoire naturelle; NHM, Natural History Museum; NHM LAC, Natural History Museum, Los Angeles County; NMNH, National Museum of Natural History. Data are from institutional websites accessed November and December, 2011 updated through direct communications with collections personnel at several institutions.

largest portions of collections in terms of numbers of specimens contain insects and other invertebrate groups. This fittingly reflects the vastly greater diversity and abundance of these species in nature, although based on this criterion one might judge most museums as having disproportionately large collections of vertebrates.

In other respects, collections in museums can differ markedly. Thus museums such as the Smithsonian, Field, California Academy, and London have substantial collections of plants, whereas others, such as New York's American Museum, do not (Figure 3). In some cases, this is due to the presence in the same region of sister institutions, such as the NYBG. The latter and other major botanical gardens, such as Missouri Botanical Gardens, Saint Louis, and Kew Gardens, London, combine preserved plant collections (herbarium sheets of plant parts stored in drawers and cabinets) with elegant collections of living plants more familiar to the public. A comparison of collections for some of the major botanical gardens is shown in Figure 4. Zoological parks as well often incorporate notable collections of living plants on their grounds. The San Diego Zoo, for example, is also an officially registered botanical garden, with representatives of more than 6500 plant species.

Most of the figures given above refer to the more traditional collections – namely skins, skeletal elements, shells and other hard parts, whole bodies preserved in alcohol, pinned insects, pressed or living plants, and related specimens. In recent years, a very important new kind of collections has been added to this list. Frozen tissues supercooled in liquid nitrogen represent a significant new component of collections at certain institutions. Such frozen, or cryogenic, facilities provide tissues highly suitable for sampling deoxyribonucleic acid (DNA), ribonucleic acid (RNA) (where tissues are fresh and rapidly frozen), and proteins. With the proliferation of comparative genetics and genomics at many collections-based institutions, these cryogenic collections have become a core resource for modern collections-based research. Such collections are already substantial and growing at several institutions, including the Museum of Vertebrate Zoology at Berkeley, the Australian Museum in Sydney, the Louisiana Museum of Natural History at LSU, and the AMNH in New York. At AMNH, the cryogenic collection as of 2011 contained 71,000 specimens and is rapidly increasing to fill a facility designed to house more than a million specimens. Other institutions, such as the Smithsonian's NMNH, are launching major efforts to build facilities for this purpose.

Another noteworthy category, culture collections, not typically held by museums and gardens are important resources provided by centers and laboratories specially designed to hold them. Notable here are the American Type Culture Collection and the Provasoli–Guillard National Center for the Culture of Marine Phytoplankton, also in the USA along with satellite collections in developing countries (see also Henderson and Chalmers, 2001). Finally, a few institutions have important seed banks, collections extremely relevant to biodiversity related strategies as they maintain storage for live seeds that can be used to propagate endangered or even plant species recently extinct in the wild. It is estimated

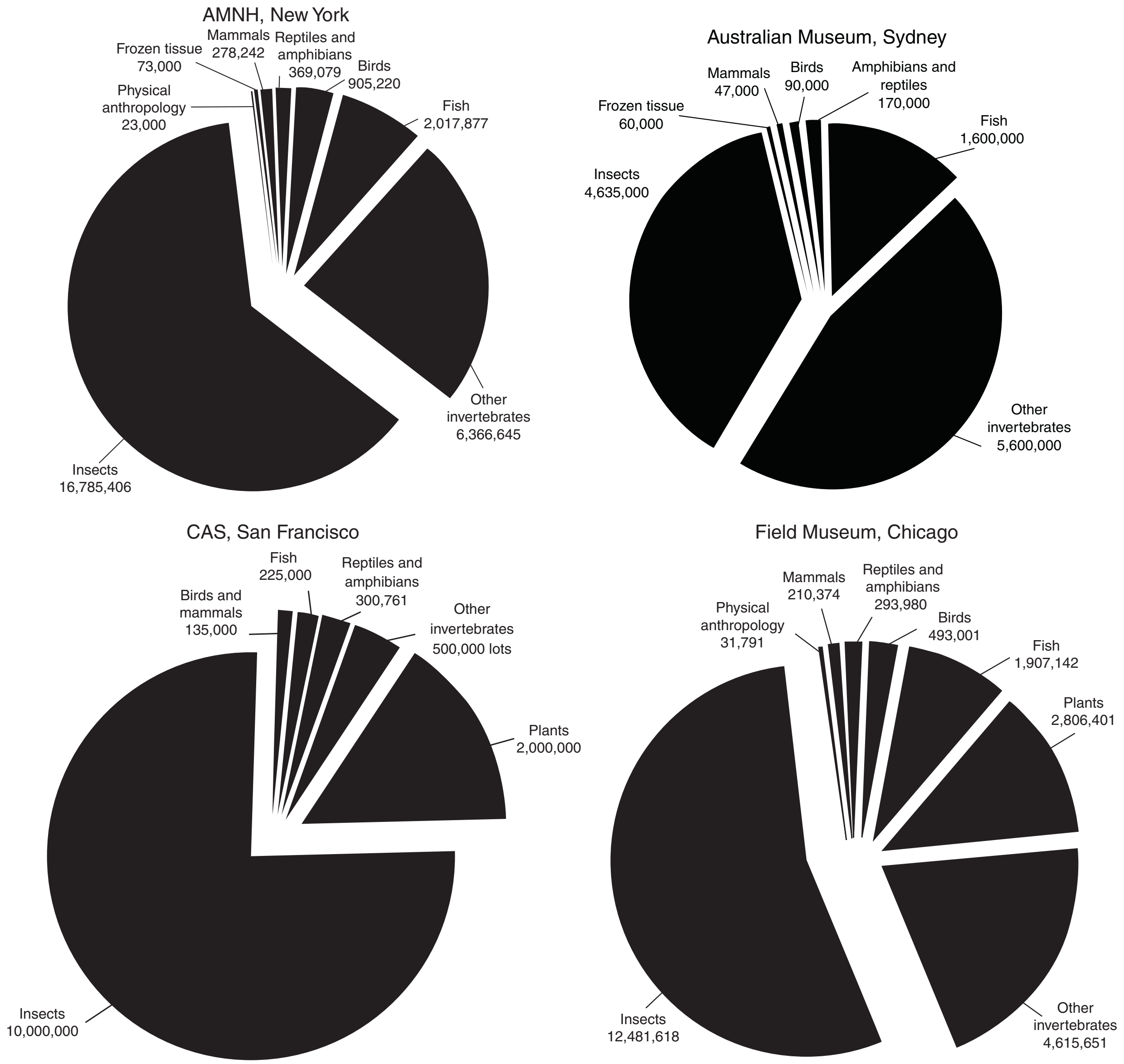


Figure 3 Total size of categories of biological collections (excluding fossils) for several major natural history museums. Abbreviations as in **Figure 2**. Data are from institutional websites accessed November and December, 2011 updated through direct communications with collections personnel at several institutions.

that between 60,000 and 100,000 plant species are threatened or highly endangered (Raven, 1987). Kew Royal Botanic Gardens maintains the world's largest seed bank through The Millennium Seed Bank Partnership (MSBP), a network of partner institutions and researchers across 50 countries. As of 2011, MSBP has successfully banked 10% of the world's wild species with a goal of reaching the 25% mark by 2020. Samples of this collection were used in a striking installation – the "Seed Cathedral" – designed by Heatherwick Studio for the UK Pavilion at the Shanghai World Expo 2010.

Because many museums and gardens are well more than a century old and their collections developed early and rapidly, it might be assumed that current collections growth is eclipsed by that resulting from the initial feverish period of collecting during the "Golden Age of Exploration." Although the more charismatic species of large mammals and other vertebrates, many of which are highly endangered, are not routinely collected at present, museum holdings are still growing at an impressive rate. On average, the AMNH, for example acquires more than 90,000 specimens a year – many of them are insects, spiders, and other arthropods – stemming from the work of more than 125 expeditions annually. Other institutions with comparable expeditionary programs show comparable growth.

Collections Digitization and Databasing

One advantage that comes with new collecting is that the incoming specimens are routinely recorded and catalogued into a highly usable digital database. However, retrospective

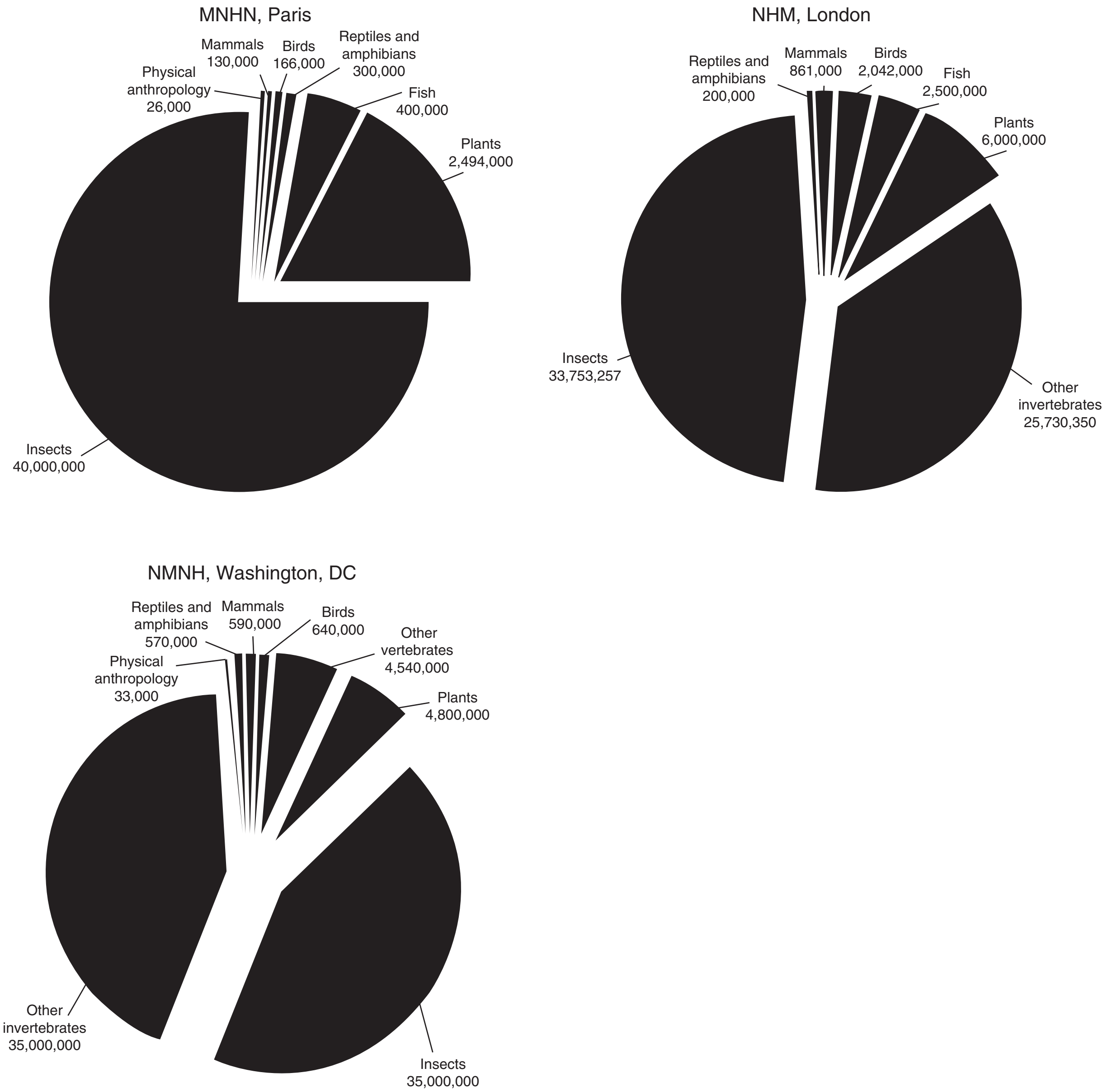


Figure 3 Continued.

cataloguing of older collections is an immense and expensive task, and there is an intimidating backlog of records awaiting digitization. Of the 1.2–2.1 billion units estimated for total collections worldwide, a mere 3% at most are web-accessible through resources like GBIF (Ariño, 2010). Insects represent a particularly monolithic problem as the international community of specialists have traditionally tied records of these huge collections to published literature rather than on a per specimen or per lot basis, and there are as yet no agreed on standards for retrospective data capture. On other fronts there has been some progress. As of 2011, AMNH New York had completed digitization of approximately 86% of its 3.6 million specimen collection of extant vertebrates, but very low percentages for its insects and other invertebrates. This institution as well as others, including the Smithsonian NMNH, are also migrating digital records to a single shared platform (at present the KE EMu system), a move that will enhance content management and data exchange within and among institutions.

The continuing progress toward collections digitization is critical in making these resources more accessible and usable, but it has come with some challenges. Prominent among these is the problem of data storage. Simple text and numerical records are for the most part manageable, but very large amounts of digital images of specimens or parts of specimens, especially the high resolution 3D-images and animations based on computed tomography (CT) scans and related resources, are placing very high demands on server storage (Rowe and Frank, 2011). In fact, the terabyte storage requirements for such image-based data now far outstrip those for

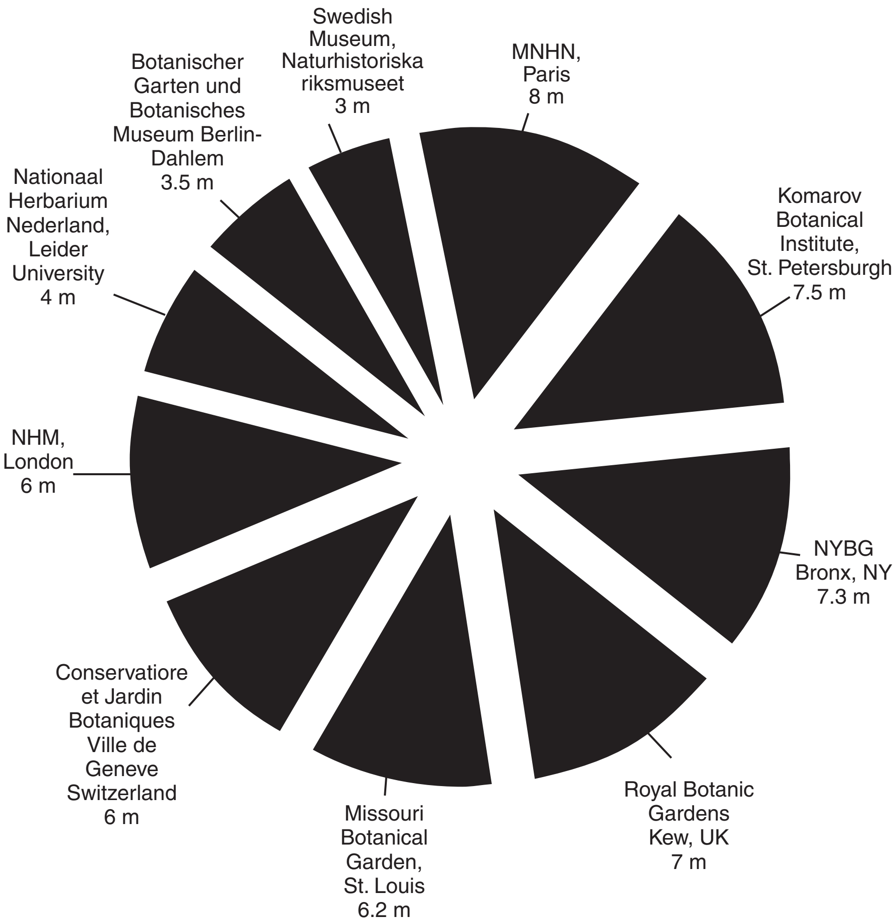


Figure 4 Total size of botanical collections in several major natural history museums and botanical gardens. Abbreviations are: MNHN, Muséum national d'Histoire naturelle; NYBG, New York Botanical Garden. Data are from institutional websites accessed November and December, 2011 updated through direct communications with collections personnel at several institutions.

DNA sequence, amino acid, and other types of molecular data. Digital storage now and going forward is a problem facing the whole museum community and it will require a more concerted effort to find solutions by networked institutions both at national and international levels.

Collections Management and Conservation

Notwithstanding new approaches and technologies, the key factor in ensuring the quality and effectiveness of the natural history collections remains the staff responsible for its management, maintenance, conservation, and use. Here the core positions are the curators and collections managers with expertise relevant to a particular area of the collections. Since collections vary considerably not only in the nature of their taxonomic content but also in the means of their storage preservation and organization, they require a diversity of persons with special expertise and skills. Nonetheless, there is a recent trend toward developing a more hierarchical collections management team within a logically defined area of the collections. For example, there may be one or more curators and one or more collections managers for a particular collection, such as birds or mammals. However, the activities of the collections managers for each of the vertebrate groups can be coordinated by one or more supervising collections managers who report to the various curators responsible for vertebrate collections. Such organization is especially useful where there are shared methodologies and activities, such as the digitization of collections records, the mechanics of loan processing, or the protocol for delivering material for common frozen tissue collections.

Another important function that can be applied across many disciplines and collections is the one involving preparation and conservation of specimens. In recent years, there has been an increase in focus on natural history collections and the special problems they pose for conservation and risk management. This has promoted development of storage facilities that are more temperature- and humidity-controlled and are more effectively sealed from invasion by insect pests. Techniques that call for integrated pest management, involving specimen preservation and optimal cabinetry design are better and safer alternatives to the older and now diminishing use of par-Dichlorobenzine (p-DCBs) and other problematic chemicals to control pests. The First World Congress on the Preservation and Conservation of Natural History Collections held in Madrid in 1993 catalyzed an increase of published studies and activities by such organizations as the Society for the Preservation of Natural History Collections, now in its 27th year.

Museum Research: Its Role in Understanding Biodiversity

Taxonomy and Systematics

Natural history collections of the world, both large and small, comprise the source for the basic science that provides the essential information on present and past biological diversity. Newly discovered species are named and described as part of the discipline of taxonomy, and their evolutionary relationships with other known species are identified in the approach known as systematics. At present, systematic biologists base their studies on genomic data (arrays of genes or whole genomes) and phenomic data (features extrinsic to the genome that include proteins, cell structure, anatomy, and many other characters). Such research leads to the development of phylogenies, tree-like maps that depict the branching relationships of species and higher taxa, and the establishment of biological classifications that array living and fossil species into formally named, more inclusive groups. Natural history museums, botanical gardens, and related institutions represent the greatest concentrations of experts devoted to taxonomy and systematics. Such work and other museum efforts in fields such as biogeography, climate study, paleontology, geology, ecology, molecular biology, and conservation biology provide an important scientific foundation for efforts to conserve and manage biodiversity and contribute to a wide range of applications in animal and human health, agriculture, pharmaceuticals, bioprospecting, resource management, and government policy and practice.

A key practice in taxonomy is the establishment of a type, a particular specimen chosen to be the "name bearer" of a species. The characters that diagnose a given species are to be found in the type. Taxonomy involves a considerable amount of revision, wherein a named species may be found to be indistinguishable from an earlier named species by comparing the types of the two species. Conversely, a new species may be recognized or "split off" from what was once regarded as only a single species because one or more of the specimens referred to the original type show significant differences. The new species will then have its own new type specimen. Such types are extremely important components of any collection. Sometimes even smaller museum collections can be very important resources because they hold a very large number of types relative to the total number of specimens in the collection. Moreover, type collections are often provided special high security locations and are subject to more stringent or even restrictive loan policies.

Another class of specimens important for collections-based research is a vouchered specimen, namely one chosen as the basis for extended study and retained as a reference specimen. A type specimen is a particular vouchered specimen that serves as the basis for taxonomic description and diagnosis of a species. Another example of a vouchered specimen is one retained as a reference source for tissues used in DNA studies. A vouchered specimen may also be one chosen to denote the occurrence of a particular species in a particular geographic locality. Thus, museums provide an important service in housing vouchered specimens for various purposes and are critical to areas such as comparative genetics, biodiversity surveys, and conservation biology.

Genetic, Genomic, and Phenomic Research

Traditionally, specimens and the species they represent have been described and diagnosed on their extrinsic characters – the leaf venation of plants, aspects of internal and external skeletons, hair and feather color, scale number, size and shape measurements, and other features of great variety. For some decades, studies at the molecular level have played an increasing role. Molecular systematics came into play when genetic data could be used to separate groups of individuals or local populations belonging to one species that could not be distinguished by their extrinsic characters. These sibling species, or cryptic species, are thus only distinguishable at the genetic level. A later development is the use of DNA barcoding, wherein slight differences in the order of sequences in a single gene or a few genes are the basis for recognizing different local populations, subspecies, or species (Hebert *et al.*, 2004). DNA barcoding relies on genes with an apparently rapid mutation rate, such as the mitochondrial gene cytochrome *c* oxidase I in animals and chloroplast genes *rbcl* and *matk* in plants. Such genes show high variability even among closely related species. DNA barcoding has been widely adapted and is often applied to the recognition of new species that warrant protection as a conservation priority. Barcoding as well has other conservation uses, such as in identifying the source of illegally transported items such as rhino horn, elephant ivory, or tiger paws, or the true species used as a source for commercial products like lumber, caviar, and tuna. Several museums foster programs that are active in DNA barcoding and its applications.

Genetic approaches, such as DNA barcoding, have been criticized as overly reliant on such a small unit of the entire genome for drawing important taxonomic decisions (Tautz *et al.*, 2003). Earlier phylogenetic studies that relied on DNA sequencing also faced similar criticisms because they accounted for only a few genes out of the tens of thousands of genes in any given genome. The dramatic technological improvements in high throughput DNA sequencing have, however, obviated some of these issues. The cost and time necessary for sequencing large portions of the genome and even whole genomes has decreased dramatically in only the 10 years since the publication of the first sequence of the human genome in 2001 accomplished at costs greater than $100 million (Metzker, 2010). As of June 2011, it was possible to sequence the human genome comprising 25,000 protein-coding genes and 3 billion nucleotide bases for $10,000 in direct costs (Wetterstrand, 2011 National Human Genome Research Institute (NHGRI) website). It is conceivable that in the near future whole genome sequencing will become so automated, efficient, and inexpensive that many museum specimens will be routinely sequenced in this way. In the meantime, most of the current phylogenetic studies on more complex organisms, such as animals and plants, with larger genomes (10–100 billion base pairs) are being carried out at subgenomic levels. For example, a recent study of mammalian phylogeny compared sequences of 26 gene fragments in 164 living mammal species and five vertebrate species outside mammals (out-groups) using newly generated sequence data and the gene libraries available in the international repository GenBank (Meredith *et al.*, 2011).

Another molecular approach allows the sampling of a far greater number of genes by sequencing the RNA that transcribes the sequences of genes that code for proteins (Wang *et al.*, 2009). This transcriptome method can yield patterns that represent thousands of genes, but it does not provide precise maps of the actual base pair sequences of particular genes that one can identify when sequencing whole genomes. Moreover, sampling and sequencing RNA require very fresh, high quality material that exceeds the preservation standards usually found in museum collections and even earlier collected specimens in frozen tissue facilities. This requirement places a premium on careful collecting, rapid freezing and preservation, and a well-curated tissue repository. However, one great advantage of whole genome sequencing, when it becomes even more readily accomplished at lower cost, is that it can also be used on material that has been preserved in collections for decades, such as feathers, hair, skins, and even fossils (Green *et al.*, 2010). Many collections-based institutions, such as NYBG and AMNH, New York: The Field, Chicago; NHM, London; CAS, San Francisco; NMNH, Washington, DC; and MNHN, Paris now have laboratory facilities and active programs in comparative genetics, and some of these (e.g., AMNH) are even sequencing whole genomes of less complex organisms, such as bacteria.

The increase of genetic and genomic research in museums has not diminished the importance of phenomic research at these institutions. Indeed, the museum expertise that combines a deep knowledge of natural history, basic taxonomy, comparative anatomy, and histology with genetic approaches offers powerful insights to major questions that deal with the organization and evolution of biodiversity. A much clearer understanding of the relationship of the genome to the phenome remains a central goal of all biology, and museum scientists have and will continue to play a key role in this quest. Modern comparative phenomics, such as the study of very detailed aspects of anatomy and tissue structure, is greatly aided by powerful imaging and software tools, such as CT-scanners, confocal microscopes, and 3D-digital reconstruction and animation. Such new technology is now readily being used to study fossils, the overwhelming majority of which are inaccessible to DNA sampling. Some museums now support state-of-the-art imaging laboratories to carry on such important research.

Technology and research activity has produced a huge influx of both genomic and phenomic information – a data deluge – which places an enormous burden on the effort to clarify, code, organize, and analyze these data. Thus, museums are committing major resources to the development of on-site and collaborative bioinformatics. Such programs generally comprise three components: (1) computing hardware infrastructure, such as facilities for cluster computing; (2) software tools and web applications for organizing databases, developing data pipelines for processing information, and providing visualizations; and (3) theoretical and computational research reliant on high-end computing, discrete math, and algorithmics. Examples of projects that rely heavily on advanced bioinformatics and involve museum and botanical garden science include a comprehensive study by the New York Plant Genomics Consortium (NYBG, AMNH, Cold Spring Harbor, and New York University) of 150 different species of plants based on 23,000 sets of genes that code for certain proteins. Using powerful databasing and computation tools, these gene data were grouped, ordered, and organized into a phylogenetic tree representing the evolutionary relationships of the plant species (Lee *et al.*, 2011).

On the phenomics side, diverse and complex character information can now be interactively and simultaneously loaded into very large matrices incorporating images, labels, comments, and literature citations through powerful cloud-computing web applications. One such application, MorphoBank, (O'Leary and Kaufman, 2011) is currently the home site for more than 100 published and 383 ongoing projects. MorphoBank is being used for one of the largest phenomics projects ever launched, an investigation supported by the National Science Foundation-sponsored Assembling the Tree of Life project for living and fossil mammals, which has produced a matrix with 4500 characters from the skeleton, dentition, and soft anatomy in a large number of species (Novacek and The Mammal ATOL Team, 2008). The resultant matrix, which incorporates nearly 450,000 labeled images, was developed by 22 international investigators from nine institutions, including four museums.

The development of such bioinformatics capacity will be vital to collections-based institutions going forward. Comparative biological data relating to museum research are among the most complex in any science. The supersized data matrices like those noted above, require sophisticated computational programs for tree construction and other operations. Such complex data require a heuristic approach to achieving resolution among an astronomical number of possible trees (more than 2 million for a data set with only 10 taxa and 4.5×10^{190} for 100 taxa). For this reason some museums have developed research areas that encompass theoretical computational biology in addition to other areas in bioinformatics.

Biogeographic and Environmental Studies

In addition to taxonomy, systematics, genomics, and phenomics, museum research extends into other areas that rely on complex data to address questions important to understanding biodiversity. One of the most notable of these endeavors is the application of Geographic Information Systems, using satellite-based imagery and other means to assess the distribution of species in relation to various environmental parameters, such as climate conditions, topography, vegetation cover, and proximity to cities or other sites of human occupation. Some of these studies incorporate sophisticated computational tools that allow investigators to predict the occurrence of particular species in areas yet unexplored for them by analyzing the multidimensional parameters that are consistently present at localities where these species are known to occur. These analyses then can be applied to assessments of conservation priorities in regions, such as Madagascar, experiencing widespread habitat destruction (Kremen *et al.*, 2008). Other approaches model changes in the range, density, and diversity for groups of species under different likely scenarios for climate change in a given region, such as the critical studies of vulnerable FynBos flora of southern Africa (Midgley and Miller, 2005). The application of such approaches to informing conservation strategies and policies has and will continue to be critical.

Biodiversity: The Need for a Better Census of Life

The aforementioned research areas underscore the importance of museums and like institutions in our effort to understand the vast array of species that occupy the planet. Museum scientists represent a large proportion of working systematists who deal with the description of the basic units of biodiversity, namely species, and place them in an evolutionary context by mapping the relationships of those species and their higher groups within phylogenies. Other aspects of museum research in biodiversity concern the geographic distribution of species as a function of various environmental factors, as well as the study of life cycles and ecological relationships.

Yet we are still confronted with the challenge to more fully account for such diversity, and demonstrate how it is impacted by the global scale environmental changes in play. As noted above, the 1.8 million species named do not, within orders of magnitude, capture the true number, which may be in the order of 10 million or more species yet to be identified (Wilson, 2003). Insects alone represent a staggering amount of known and unknown diversity with 800,000 species named, and doubtless millions more to discover. Approximately 100,000 fungi have been described and named, but this group is thought to number more than 1.5 million species. In terms of sheer biomass, the various worm groups, including segmented annelids and unsegmented nematodes, may represent four out of every five animals on Earth. Approximately 15,000 nematodes species have been named and the existence of millions more is suspected. An even more profound void in the census of life concerns bacteria and related microbial species, the oldest, most ubiquitous, most rapidly evolving, most physiologically diverse, and most poorly known of all organisms. Only approximately 6000 species of bacteria are recognized, but estimates of true diversity in the soil and the water columns using DNA probes and other methods indicate the presence of many millions of species (Gans *et al.*, 2005).

It is clear that the great collections and active research programs in museums and botanical gardens, and other collections-based institutions underrepresent the true diversity of such important groups as terrestrial arthropods, marine invertebrates, fungi, and microbial bacteria and protists. Indeed, specialists on certain of these groups are either nonexistent or a very few of the already insufficient number of some 6000 taxonomists worldwide (Wilson, 2003). There has been a welcome and recent introduction of microbial programs in a few museums, but this area is due much more emphasis as museums consider options and opportunities for future expansion of their collections and research. In addition, there is further need to integrate basic information of species diversity with other biological phenomena, such as population patterns, nutrient cycling, and resource partitioning, in order to demonstrate the important ecological roles of species within biological communities. Such more integrative research requires a scale-up in multidisciplinary approaches involving numbers of museum investigators and colleagues at other institutions.

Biodiversity Science and Conservation

Museums and other collections-based institutions have taken a number of different approaches in responding to the urgency and magnitude of the biodiversity and other environmental crises. Recruitment of curators to leadership scientific positions in some cases has emphasized the need for coverage of poorly known biological groups, or for expertise that relates basic biodiversity knowledge to experience in bioprospecting, surveys, environmental trend analysis, and related approaches. Many institutions have also developed special centers devoted to biodiversity science and conservation biology and programs. These units are meant to initiate programs more connective to the needs of local communities and governments by providing current, accurate, and relevant information on biodiversity and other impacts on the habitats in question. They also help in organizing large scale interdisciplinary projects, such as surveys that enlist teams of experts on diverse taxa and produce results that are of use in setting policy for the management of natural areas and habitats under threat.

It is clear that such scaled-up efforts in surveys and inventories are much needed. Many species now known to science have yet to be sufficiently sampled for their genetic composition. Large areas of the planet, such as the mid ocean, deep sea, and polar regions have barely been explored. There are hundreds of sites and regions throughout the world now considered under high threat or endangerment that contain a large diversity of endemic species, namely, species that are found nowhere else outside of the region in question (Sala *et al.*, 2000). Such highly vulnerable regions include most of Madagascar, the floral communities of southern Africa, Mediterranean coastal habitats, many coral reefs, high-latitude deserts, and montane forests of the Andes, Himalayas, and other ranges (Sala *et al.*, 2005). The identification of such regions and their endemics is the direct result of taxonomic and biogeographic research, much of it museum based. These areas, sometimes referred to as biodiversity hotspots (Myers *et al.*, 2000), help to define the ongoing and future agenda for biodiversity science and conservation.

Museum Advisory Roles and Applications in Biodiversity Conservation

Basic information stemming from surveys and collections is important in informing much broader constituencies about biodiversity loss and thus underscoring the need for mitigation and more effective conservation management. Vouchered specimens from collections serve as keys and references to field experts and parataxonomists in identifying the specimens or in assessing the impact of environmental degradation on animal and plant populations. Web-based publications such as the International Union for the Conservation of Nature's (IUCN's) Red Lists of Threatened Species are to a large part reliant on information from museum-sponsored field surveys and collections (see also Henderson and Chalmers, 2001). The ongoing digitization effort for large collections is an important advance that provides more ready access of information to conservation practitioners and land managers.

Such programs may also link to private or government agencies that manage biodiversity (Henderson and Chalmers, 2001). The latter include the Environmental Resources Information Network in Australia, the National Commission for the Knowledge and Use of Biodiversity (La Comision Nacional Para El Conocimiento Y Uso de la Biodiversidad) in Mexico, and the National Biodiversity Institute (Instituto Nacional de Biodiversidad; INBio) in Costa Rica. INBio was established as an initiative with a particular emphasis on biodiversity science and conservation across a broad range of activities, from maintaining collections, conducting bioprospecting, and training parataxonomists, to educating the public on the importance of biodiversity resources. Collections- and field-based institutions also serve many other needs relating to biodiversity conservation (Henderson and Chalmers, 2001). They deliver scientific information bearing on the regulation of import and export of biological species, many of which present both environmental and health hazards in areas where they are artificially introduced. They also provide data vital to the development of international treaties and conventions meant to protect species, such as The Convention on International Trade in Endangered Species (CITES). And they play a prominent role in resource management. Accurate identification of species is necessary in developing effective pest management and programs for management of such commercial activities as agriculture, fishing, and domestic breeding. The increased trend toward local farming, green markets, and farmland that embraces a combination of cultivated and natural habitats (Foley *et al.*, 2005) relies on information of local and highly beneficial biodiversity, such as wild species of pollinating bees. Surveys by taxonomic experts disclose biodiversity and population changes before and after high impact industrial projects, such as mining or oil exploration or industrial-induced environmental disasters.

A more formal extension of such activities is the Museum service as a source for recommendations and advice on policy and practice relating to biodiversity loss and other environmental issues. Here the institutions must distinguish their mission as the providers of recommendations based on sound scientific results from that of various advocacy groups that may use such information for various purposes. In this way, the reputation of museums as trusted guides and the impact of the scientific work they foster are assured. Museums and like institutions provide the fundamental data on the realities of habitat degradation and its biological affects due to urban sprawl, deforestation, mining, war, and other human activities. Some countries, such as Australia, require biodiversity surveys and impact studies before any development is approved, and both impact studies and remediation programs are required by many local authorities in many countries.

At the government level, Museums have and will continue to play a critical role in both the development and implementation of policy. The effectiveness of the CITES treaty, for example, requires the continued contributions of accurate identifications and assessments supported by museums and like institutions. Museums are also important participants in developing initiatives prescribed by the Convention on Biological Diversity (CBD), and official delegations of the CBD, the IUCN, and many other international organizations and conventions include museum scientists and staff (Henderson and Chalmers, 2001). Implementation here is aided again by museum-based programs that offer training of in-country expertise in biodiversity sciences.

Applications in Human Health and Other Areas

Museum-based research on biodiversity also has applications that extend to other areas such as health and commerce. Studies by museum scientists and collaborators on the evolution of *Plasmodium*, the microbial parasite responsible for malaria in humans and other species, is contributing to our effort to understand better the nature and effects of the world's deadliest infectious disease (Perkins, 2008). Other insights by comparative biologists are important for forecasting the spread of viral epidemics, managing conditions for the prevention of diseases like cholera and typhus, and finding relationships between environmental degradation and likelihood of disease outbreak promoted by opportunistic species. Importantly, the comparative approach used by most museum scientists to investigate problems in biomedicine and health moves beyond a focus on standard model organisms – such as the fruit fly, mouse, or the bacterium *Escherichia coli* – and instead relies on the 3.6 billion-year-old experiment that is integral to the evolution of all life. Such a comparative approach may lead to insights that allow the mapping of convergent evolution of certain diseases, such as human papillomavirus (Chen *et al.*, 2009) or the variations evolved in blood anticoagulants (Phillips and Siddall, 2005). A classic study by Pershing *et al.* (1990) disclosed the potential for the spirochete *Borrelia burgdorferi* infection before the recognition of Lyme disease as a clinical entity by sampling museum specimens of the deer tick *Ixodes dammini* for the presence of spirochete-specific DNA sequences. The latter sequences were detected in 1940s specimens from Montauk Point and Hither Hills, Long Island, New York. These results suggested that the Lyme disease spirochete was already active in arthropod vectors for at least a generation before the formal recognition of this disease in the USA. Bioprospecting continues to produce discoveries important to pointing the way to new pharmaceuticals or food sources. In fact, the recent burgeoning interest in wild species of plants, fungi, insects, marine invertebrates, and other organisms as sources for healthy, and in some cases gourmet foods, reflects an appreciation for the potential bounty of biodiversity and the scientific information required for utilizing it.

Biodiversity and Culture

Noteworthy also is the knowledge of biodiversity as an inroad to understand the relationship among different cultures and societal traditions. The common formal taxonomy for species names and their classification, which is currently used in virtually all scientific literature, is actually an European development attributed to the work of the great eighteenth century Swedish naturalist Carolus Linnaeus, but some form of ''folk'' taxonomy has emerged from virtually every region and culture. We know that many people have developed traditional skills and languages for identifying species, and their success at this practice is impressive. Certain tribes in the Amazon are familiar with thousands of species, many of them important as sources for foods and medicines; outsiders have learned much from these great native naturalists. A study by a research team including museum scientists (Fleck *et al.*, 2002) examined the folk taxonomy of bat species used by the Matses Indians in

Amazonian Peru and found it surprisingly comprehensive. Although Matses have only one name for all bats, cuesban, they use descriptive terms to distinguish 43 different bats. Of the 57 species collected by scientists in the area over the years, 34 species had also been hunted by Matses, whose notebooks provided previously unknown information on the roosting habits of several of them. Moreover, at least 14 Matses names closely correspond to standard Linnaean taxonomic names.

This is only one of numerous examples where knowledge of local cultures demonstrates a shared interest and understanding of nature, a common attitude extremely important in developing practices for the sustainability of local species and habitats. Accordingly, staffs at some museums include anthropology curators with specific interests in the ways in which different cultures recognize and use biodiversity as integral to their traditional practices and everyday lives. Biodiversity training programs that take into account local traditions and perspectives are also offered by museum-based biodiversity and conservation centers.

Current Challenges

Despite the clear linkage among collections-based biodiversity science and conservation, human health, and other areas of societal need, there are many challenges to the effort to strengthen this connection. As noted, there is still a deficit in the number of experts, particularly for some of the groups least known and potentially most important for ecosystem services such as microbial organisms, fungi, and pollinating insects. The possible training programs for developing such expertise at universities, museums, and other institutions are limited in number. Even at the broadest levels, the uneven distribution of expertise and collections resources impedes efforts to account for biodiversity on a global scale. Much of the world's biodiversity is located in economically depressed countries very poorly endowed with relevant expertise and scientific infrastructure (Argawal and Redford, 2006). Thus, international programs for in-country training of local people are among some of the most needed and effective programs sponsored by museum-based biodiversity centers and similar organizations.

Results of biological surveys and prescriptions for the implementation of locally- or nationally- directed conservation management are often insensitive to local concerns relating to particular levels of education, economic background, cultural affiliations, and religious beliefs. People in developing countries are, for instance, faced with difficult choices because of their very poor standard of living (Argawal and Redford, 2006). Development of recommendations and programs more sensitive to these factors yields a more effective and feasible strategy for sustaining local natural resources, and is also key to identifying some of the overarching concerns shared by many different communities and cultures.

In the end, the reliable data and results of biodiversity surveys and research may have a less than desired impact in some instances simply because decision-makers and their constituencies fail to recognize biodiversity sustainability and management as a priority need. In many cases, this lack of attention seems rooted in a poor understanding of the fact that biodiversity loss is not a completely isolated issue, but one that bears on the economic, health, and quality of life issues that demand so much attention (Novacek, 2008). Hence, biodiversity research, surveys, and recommendations for conservation must be closely linked with educational efforts at many levels, a point expanded further below.

Training, Education, and Outreach

Graduate and Postdoctoral Training

Museums and the like are in reality major centers not only for research but also for training in the sciences concerned with biodiversity, such as taxonomy, systematics, evolutionary biology, biogeography, and conservation biology. Their increasing role in this respect relates to particular trends in higher education, where much of the training in these fields was displaced at universities by other areas, such as biomedical research, experimental neurobiology, and genomics centered on model organisms. In more recent years, the evolution of these disciplines has come full circle – the flood of technology offered by genomics and computational biology has been readily adopted and expanded on by researchers devoted to field work, collections, and the natural sciences. At the same time, there has been a rebirth at some universities of programs in evolutionary and organismic biology that draw more emphatically on the kind of expertise normally found in museums. A continuing trend in this convergent effort in research and training among universities, museums, and other collections-based institutions offers increased opportunity for the cultivation of biodiversity expertise.

Many museums and botanical gardens for example participate in joint programs with universities in the graduate training of new generations of scientists. Prominent among these are AMNH and NYBG (with Columbia, Cornell, New York University, and the City University of New York), the Smithsonian's NMNH (with George Washington University), the Field Museum (with the University of Chicago), and San Francisco's CAS (with University of California at Berkeley and Stanford University). Many of these arrangements involve a cost share for the graduate program, the advisory role of curators who are also adjunct faculty at the partnering university, and the eventual bestowal on the successful candidate of a PhD degree by the university involved. A more independent role for museums in graduate training is represented by the establishment in 2008 of a PhD program in comparative biology in the Gilder Graduate School at the AMNH. Thus the AMNH joins the Paris MNHN as the only independent museums in the world that offer a PhD degree.

At more advanced training levels, there are numerous postdoctoral programs that support scientists at museums concerned with biodiversity. Some of these incorporate international postdoctoral and graduate level training in order to develop the level of in-country expertise necessary for the global effort. Still, the number of programs and opportunities available in museums and in joint museum-university programs are limited and are far outstripped by the current demand for them by talented, well-educated students.

Student and Teacher Training

Museums of course have a much broader educational agenda than that concerned with graduate and postdoctoral training. These and related institutions intersect daily with vast audiences – families, school children, senior citizens, and other individuals from diverse cultural and economic backgrounds. Much of the investment by museums and related institutions in education involves better ways to serve the millions of students in classes from primary and secondary schools that visit museums each year. Many museums are now tied to school curricula and are timed to intersect with course work in general biology and related fields. After-school programs offer opportunities for field trips and laboratory activities not readily available in classrooms. Much educational learning is greatly aided by digital offerings on the web and software applications that allow students to prepare for museum visits and assemble information after they return to the classroom. Several cities have also developed cooperative educational programs in biodiversity and other subjects that link museums, gardens, zoos, and related institutions in the region as an educational resource for both teachers and students. For example, the Urban Advantage program in New York City is a standards-based partnership designed to improve students' understanding of scientific inquiry through collaborations between urban public schools and science cultural institutions with AMNH as the lead institution, and including, NYBG, the Bronx Zoo, the Brooklyn Botanical Garden, and others. Urban Advantage has now been adapted in other cities, including Boston, Miami, and Denver.

Eliciting Public Understanding and Engagement

Beyond advanced academic training and school programs, museums, botanical gardens, and related institutions have a unique connection with a vast public audience. Even in more economically and technologically advanced countries, there are limited opportunities for the lay public to stay abreast of the rapid rate of scientific discovery (Falk *et al.*, 2007). Outside popular science books, periodicals, films, television specials, and web offerings, the responsibility for providing a lifelong exposure to science falls to museums, botanical gardens, zoos, aquaria, science centers, and similar venues devoted to the public education of science.

These institutions are thus critically important in educating people on biodiversity issues and other environmental problems. However, in doing so they confront some major challenges. A consistent result in surveys of public attitudes, such as the Biodiversity Roadmap Report of 1998, is that the basic message – that the biodiversity enormously important to the sustainability of the environment and the quality of our own lives is at serious risk – is not getting across to many of the target audiences. The most penetrating messages are those that clearly relate scientific insights concerning biodiversity and biodiversity loss to more general environmental problems and in turn to problems rooted in common experience – poor water quality, depletion of fisheries, zebra mussels and other invasive species, forest clearing, open pit mining, urban sprawl, and many others. Basic biodiversity science of course provides the important database for all these arguments. But the public recognition of the importance of this work is elusive without the themes that address more familiar issues (Novacek, 2008).

One bridge that must be crossed in connecting biodiversity science with a diverse public is in inspiring a closer interest in and affinity with nature. The fact that museums and like institutions can offer an encounter with nature that is both vivid and authentic defines their cultural impact (Novacek, 2001). Many people, especially in urban areas, will rarely, if ever, see a relatively unspoiled tract of woodland in their region, let alone a tropical rainforest. For these individuals, an encounter with nature means a visit to a museum or the like. The enthusiastic response of visitors to this opportunity can be appreciated in terms of the huge audiences such institutions attract. Attendance figures for 2010 provided on the websites of just 18 museums, botanical gardens, zoos, and aquaria, including some of those shown in **Figures 1** and **2**, numbered more than 44 million visitors. Another survey claimed that more than 865 million people visited museums, gardens, zoos, nature centers, science centers, and related venues in 1999 in the USA alone (Lake and Perry and Associates, 2001). An additional attribute of museums and institutions as venues for communicating science is the feeling of trust they invoke in the public. Surveys show that natural history and science museums have extremely high credibility ratings (Lake and Perry and Associates, 2001).

The Impact of Exhibits

Notwithstanding the many educational programs offered by museums and like institutions, the primary "flagship" vehicle for connecting with the public has always been and continues to be exhibitions. The accuracy, currency, and inspirational qualities of such exhibits of course reaffirm the museum's role as a powerful source of public education and enlightenment. Yet, on the biodiversity front, there was a period of educational stasis; such institutions had not fully capitalized on their reputation as trusted guides. During the early 1990s, when dimensions of the biodiversity crisis became more evident, very little of the scientific concern was reflected in public exhibits. Many permanent exhibits that included environmental topics had not been revised since the time they first opened decades before, or were not complemented by new halls or temporary exhibits that addressed current themes (Novacek, 2001).

Part of the reason for such arrested development was doubtless financial. Renovating exhibit halls or building new ones are massive and extremely expensive endeavors, and there are often major economic constraints to progress. Despite the challenge, there are more recent notable improvements on this front, and exhibits dealing with current environmental issues, including biodiversity, have been developed by many museums and related institutions. The AMNH in New York was one of the first, if not the first, to open in 1998 a major permanent Hall of Biodiversity. The exhibit is meant not only to inform the public on the stark realities of global species loss and the biodiversity crisis but also to show the beauty, wonder, and diversity of what is at risk. Its features include an electronic "BioBulletin" presenting regularly updated accounts of events that impact biodiversity and scientific and conservation efforts to mitigate these impacts, in places like Madagascar, Bolivia, the Congo, and Mongolia. The exhibit also has a walkthrough diorama of a section of rain forest of the Central African Republic that shows the impact of human activity on even a relatively pristine environment. The diversity of life in the hall is covered by the "wall of life," that displays more than 1500 specimens and models complemented by videos of organisms in action and interactive touch screens. The wall of life has proven to be one of the museum's most popular attractions. A completely renovated Milstein Hall of Ocean Life incorporating many environmental themes and adjoining the Hall of Biodiversity reopened in 2003.

Elsewhere, exhibitions devoted to more current environmental issues have been developed at various scales. At the ambitious end of the spectrum, the CAS reopened in 2008 in an entirely new structure devoted to collections, research, and exhibition halls, including many exhibits with a strong environmental emphasis. The new museum is itself one of the largest high grade, green buildings in the USA (Barinaga, 2004). London Natural History Museum's new Darwin Center is a bold statement that reveals its massive collections and its laboratories to visitors within an evocative seven-story, concrete "cocoon" encased in a huge glass-walled "cube." The Darwin Center thus brings the public more in contact with the kind of biodiversity- and collections-based research that is usually "behind the walls." Complementing the magnificent Grande Galerie de l'Evolution at the Museum National d'Histoire Naturelle in Paris are a series of temporary exhibits that explore the wonders of biodiversity and the mysteries of oceanic life, such as its recent exhibit "The Deep," which subsequently traveled to other venues. There are other similar installations at the Smithsonian's NMNH, the Field Museum, the Denver Museum of Nature and Science, and others too numerous to describe here. Also, new partnerships among institutions have allowed the sponsorship and nuanced development of timely exhibits on such themes as endangered species, climate change, the importance of evolution in understanding biodiversity, and issues regarding the present and future availability of fresh, clean water. These and other exhibits with similar themes offer clear and consistent messages as they travel to various international destinations.

Public Educational Programs and Citizen Science

Although exhibition remains the principal educational portal and indeed the prime visitor attraction in museums, there has been an increasing emphasis on educational programming either connected to or independent of exhibits. Much of this relates to the programs noted above that link to school programs for teacher and student training and are designed to complement approved curricula. In addition, museums and like institutions are demonstrably very effective locations for major conferences on subjects of high public interest. Several aforementioned institutions sponsor annual symposia on biodiversity issues that include public lectures and panel discussions and the proceedings are now very often webcast in order to reach very large online audiences. Museum scientists are heavily featured in many media offerings including television specials, newspaper articles, and online blogs. For example, a recent feature of the New York Times, "Notes from the Field" provides daily journals from field scientists conducting biodiversity surveys and similar studies in remote regions. Another increasingly common feature of museums, are "Science Cafes," regular evening informal gatherings aimed at young adult audiences, wherein scientists share their adventures, results, and thoughts over cocktails.

These programs and many others are largely built on a strategy of engagement that allows educators to share information and perspectives, and elicit reactions in terms of questions and discussion. What about more active roles on the part of public audiences? A relatively new educational effort aimed at eliciting broader public engagement – dubbed citizen science – involves public–professional partnerships that allow people of all ages an opportunity to participate in real scientific research and to interact with scientists in the process (Cohen, 1997; Brossard *et al.*, 2005). This kind of proactive participation is intended to not only contribute new data on species and habitats but will also increase the participants' understanding of the process and results of the relevant science (Tuss, 1996). Such enlightenment is further hoped to strengthen participants' connections with both science and the environment in ways that cultivate a sense of stewardship.

Citizen science programs require intensive investment of professional time and energy, and, to date, the number of people that actually have the opportunity to become citizen scientists is limited. The problem seems surmountable as more efficient programs, including the use of social networking and web-based technology for linking scientists with science educators and their students, become available. The *Bioblitz* (2007) biodiversity surveys that have been carried out in New York's Central Park, Washington, DC, and many other sites yielded new scientific results that not only further enthused participants and galvanized their activities but also attracted media interest. It seems that programs in citizen science have much potential if they allow more people to participate, their impacts are more thoroughly analyzed, and participants are given a more explicit presentation of the environmental issues that relate to their contribution (Brossard *et al.*, 2005).

Conclusions: Museums and the Biodiversity Challenge

Many major museums and related institutions of the present day have histories extending back well nearly two centuries. Yet these institutions are arguably more important than ever, as we contend with the dramatic environmental transformation of this planet in this century. There is an exciting and unprecedented opportunity for museum researchers to participate in and even lead the great quest to account much better for the great scope of biodiversity and the organization and evolution of life.

There are of course many challenges to the enterprise. On the science front, the lack of taxonomic expertise in many areas, the uneven distribution of scientific personnel and resources globally, and the huge expenses and investment in time necessary for collecting, organizing, and digitizing collections information are all impediments. On the educational front, the low level of science literacy coupled with public indifference or even resistance are also major obstacles. A very large and diverse public demonstrates a sense of concern about environmental problems (Biodiversity Project, 1998). However, people also often do not recognize the implications of the biodiversity loss in exacerbating many problems more familiar and more important to them, such as health and economics. Thus museums and like institutions devoted to the study of nature are still challenged with the goal defined for the biodiversity agenda more than 20 years ago. They must provide enhanced understanding of biodiversity and its degradation that empowers people to make choices based on sound science and reliable recommendations.

To this end, the momentum in both museum research and education in relation to biodiversity is encouraging. Museums and their kinship institutions support their expeditions, collections, research, exhibitions, and educational programs because they are enlisted in a human quest of paramount importance – to understand biodiversity, the evolution of life, and the critical roles of species in ecosystems, and to share this information with a broad public in ways that elicit enlightenment and engagement with issues important for sustaining the quality of life. The degree to which such institutions are successful in this quest in the coming years will be pivotal in determining how effectively societies will deal with the greatest environmental crisis in the history of the human species.

References

Argawal A and Redford J (2006) Poverty, development and biodiversity: Shooting in the dark? *Wild Life Conservation Society Working Paper 26*, i–iv, 1–58.

Ariño AH (2010) Approaches to estimating the universe of natural history collections data. *Biodiversity Informatics* 7: 81–92.

Barinaga M (2004) California Academy starts on the museum of its dreams. *Science* 304: 669–670.

Bioblitz (2007) National geographic in the field. *National Geographic Society*. http://www.nationalgeographic.com/field/projects/bioblitz-dc-2007.html.

Biodiversity Project (1998) Engaging the public on biodiversity: A roadmap for education and communication strategies. *The Biodiversity Project*, pp. vii + 118. Wisconsin: Madison.

Brossard D, Lewenstein B, and Bonney R (2005) Scientific knowledge and attitude change: The impact of a citizen science project. *International Journal of Science Education* 27(9): 1099–1121.

Chapman A (2005) *Uses of Primary Species Occurrence Data, Version 1.0*, pp. 106. Copenhagen: Global Biodiversity Information Facility.

Chen Z, van Doorslaer K, DeSalle R, *et al.* (2009) Genomic diversity and interspecies host infection of α*12 Macaca fascicularis* papillomaviruses (MfPVs). *Virology* 393: 304–310.

Cohen KC (ed.) (1997) *Internet Links for Science Education: Student–Science Partnerships*. New York: Plenum Press.

Duckworth WD, Genoways HH, and Rose CL (1993) *Preserving Natural Science Collections: Chronicle of Our Environmental Heritage*. Washington, DC: National Institute for the Conservation of Cultural Property.

Falk JH, Storksdieck M, and Dierking LD (2007) Investigating public science interest and understanding: Evidence for the importance of free-choice learning. *Public Understanding of Science* 16: 455–469.

Fleck DW, Voss RS, and Simmons NB (2002) Undifferentiated taxa and sublexical categorization: An example from Matses classification of bats. *Journal of Ethnobiology* 22: 61–102.

Foley JA, DeFries R, Asner GP, *et al.* (2005) Global consequences of land use. *Science* 309: 570–574.

Gans J, Wolinsky M, and Dunbar J (2005) Computational improvements reveal great bacterial diversity and high metal toxicity in soil. *Science* 309: 1387–1390.

Global Biodiversity Information Facility (GBIF) (2003) Global Biodiversity Information Facility Annual Report 2001–2002. Copenhagen.

Green RE, Krause J, Briggs AW, *et al.* (2010) A draft sequence of the Neandertal genome. *Science* 328: 710–722.

Hebert PDN, Penton EH, Burns JM, Janzen DH, and Hallwachs W (2004) Ten species in one: DNA barcoding reveals cryptic species in the neotropical skipper butterfly *Astraptes fulgerator. Proceedings of the National Academy of Sciences USA* 101: 14812–14817.

Henderson P and Chalmers N (2001) Museums, and institutions, role of. In: Levin SA (ed.) *Encyclopedia of Biodiversity*, pp. 271–280. San Diego: Academic Press.

Kohlstadt SG and Brinkman P (2004) Framing nature: The formative years of natural history museum development in the United States. *Proceedings of the California Academy of Sciences* No. 2(supplement 1): 7–33.

Kremen C, Cameron A, Moilanen A, *et al.* (2008) Aligning conservation priorities across taxa in Madagascar with high-resolution planning tools. *Science* 320: 222–225.

Lake Snell and Perry and Associates (2001) *Americans Identify a Source of Information they can Really Trust*. Washington, DC: American Association of Museums.

Leakey RE and Lewin R (1996) *The Sixth Extinction: Patterns of Life and the Future of Humankind*. New York: Knopf/Doubleday.

Lee EK, Cibrian-Jaramillo A, Kolokotronis S-O, *et al.* (2011) A functional phylogenomic view of the seed plants. *PLoS Genetics* 7(12): e1002411.

May RM (1988) How many species inhabit the earth? *Science* 241: 1441–1449.

Meredith RW, Janečka JE, Gatesy J, *et al.* (2011) Impacts of the Cretaceous terrestrial revolution and KPg extinction on mammal diversification. *Science* 334: 521–524.

Metzker M (2010) Sequencing technologies – the next generation. *Nature Genetics* 11: 31–46.

Midgley GF and Miller D (2005) Modeling species range shifts in two biodiversity hotspots. In: Lovejoy TE and Hannah L (eds.) *Climate Change and Biodiversity*, pp. 229–231. New Haven: Yale University Press.

Myers N, Mittermeir RA, Mittermeir CG, da Fonseca GAB, and Kent J (2000) Biodiversity hotspots for conservation priorities. *Nature* 403: 853–858.

Novacek MJ (2001) The role of natural history museums in the stewardship of biodiversity. In: Mares M (ed.) *A University Natural History Museum for the New Millennium*, pp. 47–55. Norman, Oklahoma: Sam Noble Oklahoma Museum of Natural History.

Novacek MJ (2008) Engaging the public on biodiversity issues. *Proceedings of the National Academy of Sciences, USA* 105: 11562–11578.

Novacek MJ and The Mammal ATOL Team (2008) A team-based approach yields a new matrix of 4500 morphological characters for mammalian phylogeny. *Journal of Vertebrate Paleontology* 28(supplement 3): 121A.

Organization for economic co-operation and development (OECD) (1999) *Final Report of the OECD Megascience Forum Working Group on Biological Informatics*. Paris: OECD Publications.

O'Leary MA and Kaufman S (2011) MorphoBank: Phylophenomics in the cloud. *Cladistics: the International Journal of the Willi Hennig Society* 27: 1–9.

Perkins SL (2008) Molecular systematics of the three mitochondrial protein coding genes of malaria parasites: Corroborative and new evidence for the origins of human malaria. *Mitochondrial DNA* 19: 471–478.

Pershing DH, Telford 3rd SR, Rys PN, *et al.* (1990) Detection of *Borrelia burgdorferi* DNA in museum specimens of *Ixodes dammini* ticks. *Science* 249: 1420–1423.

Phillips AJ and Siddall ME (2005) Phylogeny of the new world medicinal leech family macrobdellidae (Oligochaeta: Hirudinida: Arhynchobdellida). *Zoologica Scripta* 34: 559–564.

Pimm SL, Russell GJ, Gittleman JL, and Brooks TM (1995) The future of biodiversity. *Science* 269: 347–350.

Raven PH (1987) The scope of the plant conservation problem world-wide. In: Bramwell D, Hamann O, Heywood V, and Synge H (eds.) *Botanic Gardens and the World Conservation Strategy*, pp. 19–29. London: Academic Press.

Ross D (1995) *Aristotle*, 6th edn. London: Rutledge.

Rowe TR and Frank LR (2011) The disappearing third dimension. *Science* 11: 712–714.

Sala OE, Chapin III FS, Armesto JJ, *et al.* (2000) Global biodiversity scenarios for the year 2100. *Science* 287: 1770–1774.

Tautz D, Acrtander P, Minelli A, Thomas RH, and Vogler AP (2003) A plea for DNA taxonomy. *Trends in Ecology and Evolution* 18: 70–74.
Tuss P (1996) From student to scientist, an experiential approach to science education. *Science Communication* 17: 25–44.
Wang Z, Gerstein M, and Snyder M (2009) RNA-Seq: A revolutionary tool for transcriptomics. *Nature Reviews Genetics* 10(1): 57–63.
Wetterstrand KA (2011) DNA Sequencing Costs: Data from the NHGRI Large-Scale Genome Sequencing Program Available at: www.genome.gov/sequencingcosts. (Accessed December 30, 2011).
Wilson EO (2003) The encyclopedia of life. *Trends in Ecology and Evolution* 18: 77–80.