The Value of Museum Collections for Research and Society

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Many museums and academic institutions maintain first-rate collections of biological materials, ranging from preserved whole organisms to DNA libraries and cell lines. These biological collections make innumerable contributions to science and society in areas as divergent as homeland security, public health and safety, monitoring of environmental change, and traditional taxonomy and systematics. Moreover, these collections save governments and taxpayers many millions of dollars each year by effectively guiding government spending, preventing catastrophic events in public health and safety, eliminating redundancy, and securing natural and agricultural resources. However, these contributions are widely underappreciated by the public and by policymakers, resulting in insufficient financial support for maintenance and improvement of biological collections.

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Many biological collections, particularly those associated with museums and academic institutions, have recently experienced painful budgetary shortfalls (Dalton 2003, Froelich 2003, Gropp 2003, NSCA 2003, Stokstad 2003). In many cases, these problems have forced staff cuts and reduced financial support for the curatorial work that is necessary for the survival and utility of these collections. Ironically, the importance of these collections and their contributions to society have increased in recent years, particularly following acts of terrorism in the United States and abroad. Not only do biological collections play a critical role in public health and safety as cornerstones in studies of environmental health and epidemiology, they are also central to homeland security as important tools in the prevention, detection, and investigation of various types of biological terrorism (NRC 2003). This disconnect between the importance of biological collections to society and the financial support that is provided to them stems directly from a failure to recognize their contributions.

In this article we provide an overview of some of the many ways in which biological collections have played a vital role for society by contributing to public health and safety, monitoring environmental change, and enhancing national security. Specifically, museum collections contribute unique and invaluable insights to the study of pathogens, vectors of disease, and environmental contaminants. Moreover, these collections have played a crucial role in fields at the forefront of the biological sciences, including the study of biodiversity and its loss, biological invasions, and global climate change. We argue that the storage and maintenance of museum collections is inexpensive compared with the potential costs of their absence. Indeed, these collections confer economic benefits by serving as centralized locations for information processing and storage, saving other institutions, and taxpayers, hundreds of millions of dollars per year.

Public health and safety

The strongest link between museum collections and national security is probably in the realm of public health and safety. Collections are often used to track the history of infectious diseases and identify their sources or reservoirs. The most obvious examples are collections of known viruses and bacteria that are stored for comparison with emerging infections. For example, researchers from the Centers for Disease Control and Prevention (CDC) compared isolates from the 2001 anthrax attack in the United States with stored specimens collected from the 1960s and 1970s to differentiate and identify the strain used (Hoffmaster et al. 2002).

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Museum collections complement those of the CDC by adding a unique source of material for the identification of vectors and reservoirs of diseases. For example, stored tissue specimens from sooty mangabeys *(Cercocebus torquatus)* at the Smithsonian Institution from the late 1800s were used to determine that SIVsm (a simian immunodeficiency virus and a close relative of HIV-2 in humans) was prevalent in Africa at least as early as 1896 (Garrett 1994). Similarly, millions of mosquito specimens have been collected over the past 100 years and stored in collections at the Bishop Museum in Hawaii, the National Museum of Natural History (Smithsonian Institution), the California Academy of Sciences, and the Academy of Natural Sciences in Philadelphia. This material can provide information on the fundamentally important processes of population dynamics and patterns of transmission of many mosquito-borne pathogens, including avian malaria, West Nile virus, and many others. Museums also provide an essential baseline that can be used to detect and monitor the accumulation of contaminants in the environment. Presented below are several specific examples of how museum collections help combat threats to public health and safety.

Influenza. The enormity of the 1918 influenza outbreak is difficult to comprehend by today's standards: 20 million to 40 million people were killed worldwide, including 675,000 people in the United States (Crosby 1989). At its peak, people were dying at a rate of more than 10,000 per week in some American cities (Crosby 1989). How can we protect ourselves from such devastating pandemics in the future? One of the most important steps is to identify the origin and causes of previous pandemics.

Recently, influenza virus from preserved bird specimens in the Smithsonian was compared with that in tissue samples from humans infected in 1918 (Taubenberger et al. 1997, Fanning et al. 2002). These studies showed that the virus responsible for the 1918 pandemic was more similar to strains infecting swine and humans than to avian influenza, suggesting that the pandemic was not caused by the virus jumping from birds to humans, as previously suspected. Other recent studies have used historical samples to reconstruct the evolutionary history of the virus, providing guidance for future vaccine development (e.g., Ferguson et al. 2003). Using museum specimens in this way safeguards society by allowing researchers to define natural reservoirs of disease and focus containment measures on appropriate populations.

West Nile virus. In 2002, there were 4156 human cases of infection with West Nile virus in the United States, which led to 284 deaths (CDC 2003). In such instances of rapidly emerging, potentially fatal diseases, reconstructing the transmission, evolution, and movement of the pathogen is critical (Lanciotti et al. 1999, Anderson et al. 2001). Doing this requires an understanding of the demography and invasion dynamics of the pathogen's vectors (e.g., mosquitoes for the West Nile virus), and museums are currently playing an indispensable role in this endeavor (e.g., Fonseca et al. 2001). For example, mosquitoes collected as early as 1914 are being studied to examine the timing of introductions of vectors of avian malaria and West Nile virus in the United States (ANS 2003).

Hantavirus. In 1993, a mysterious pulmonary syndrome appeared in the southwestern United States, killing 70 percent of afflicted individuals. The causative agent was quickly identified as a hantavirus, but its origin remained less certain. Although the virus had been found in deer mice in the Southwest before the human outbreak, little was known about its abundance in natural populations or the causes for its sudden jump into human populations (Yates et al. 2002). Some citizens expressed concern that the new human infections might be linked to military weapons testing at nearby Fort Wingate (Horgan 1993).

Fortunately, well-preserved rodent specimens from this area had been maintained at two local museums, the Museum of Texas Tech University and the Museum of Southwestern Biology at the University of New Mexico. Genetic analysis of these specimens conclusively showed that hantavirus had been present in rodent populations before the 1993 outbreak, and the close relationships between different strains of the virus and different rodent hosts suggested an ancient association between virus and host (Yates et al. 2002). Later ecological work showed that rodent populations grew extremely large after the wet El Niño of 1992 and that this greatly increased the probability of the virus infecting human populations in 1993. Studies in subsequent El Niño years confirmed the relationship between increased precipitation, large rodent populations, and higher risk of human hantavirus exposure (Yates et al. 2002).

Environmental contaminants. Environmental contamination is recognized by both scientists and the public as a serious problem. For example, more than 1.6 million Americans are at risk of mercury poisoning, and mercury deposition in fish is the leading cause of governmental advisories against fish consumption in the United States—more than 2200 such advisories were issued in 2000 (EPA 2002, Stoner 2002). By examining museum specimens, researchers can estimate historical levels of contamination and construct a baseline against which current levels can be compared. Analysis of preserved bird specimens from the Swedish Museum of Natural History has shown that concentrations of accumulated mercury increased during the 1940s and 1950s, probably as a result of human industry (Berg et al. 1966). In the 1960s, eggs from museum collections revealed a link between the chlorinated hydrocarbons in DDT and the decline of bird species. Researchers assembled a data set of eggshell thickness through time (from 1880 to 1967), which indicated a marked decrease in shell thickness coincident with the onset of widespread DDT use (Ratcliffe 1967, Hickey and Anderson 1968). More recently, Hayes and colleagues (2002) used museum collections to show that sexual abnormalities in natural populations of frogs were not as common before the herbicide atrazine became widely used. Museum collections not only

Ornithologist Roxie Laybourne amid the bird collection at the National Museum of Natural History (Smithsonian Institution). Photograph: Chip Clark.

warn of impending threats, but they can also be used to allay unwarranted fears. Some studies have demonstrated that the accumulation of toxic compounds, such as mercury, is not occurring in all oceanic fish (Barber et al. 1972, Miller et al. 1972).

Agriculture

The financial impact of agricultural pests is enormous: In the United States, arthropod crop pests cost growers over $14 billion per year, and arthropod pests of lawns, gardens, and golf courses add another $1.5 billion to this figure (Pimentel et al. 2000). Deliberate introductions of highly damaging species could lead to a frightening jump in agricultural damage, agricultural costs, and lost revenue. These potential costs, coupled with the vulnerability of agricultural resources, have led to a recent appreciation of the threat posed by agricultural bioterrorism (Gewin 2003, NRC 2003).

When biological agents threaten an agricultural resource, how can scientists determine whether they arose naturally, accidentally, or deliberately? Again, collections can provide the clues necessary for biological detectives to identify the sources of agriculturally harmful organisms. Specifically, museums are a forensic resource for determining when and from where a pest, pathogen, or vector was introduced. For example, Davies and colleagues (1999) used preserved specimens from the US Department of Agriculture's Animal and Plant Health Inspection Service to reconstruct the invasion history of one of the world's most damaging agricultural pests, the Mediterranean fruit fly *(Ceratitis capitata)*. Using molecular markers, Davies and colleagues were able to show that individuals captured in the introduced range in different years represent separate introduction events, rather than captures from an infestation that persisted at low levels. Without carefully stored and cataloged insect collections, the source of new infestations would not have been identified, and the effectiveness of control strategies for this damaging and costly species would have been reduced. In fact, a recent National Research Council report states that one priority of a defense plan aimed at combating bioterrorism should be to "develop reference specimens and other taxonomic information for pests or pathogens likely to be used in bioterrorist attacks against US agriculture so that rapid and accurate identification can be made after a pest or pathogen is discovered" (NRC 2003, pp. 91–92).

Habitat loss, biological invasions, and global climate change

Natural history collections have long been indispensable resources for studies of Earth's biodiversity, and the need to maintain them has recently taken on greater urgency (Davis 1996, Ponder et al. 2001). Museums offer a unique perspective, providing data over a vast time span ranging from millions of years ago (paleontological collections) to the present. Three broad areas of study related to species decline and the loss of biodiversity have become crisis disciplines and depend heavily on the baseline information that museum collections offer: species' response to habitat loss and fragmentation, biological invasions, and the consequences of global climate change.

Habitat loss. Habitat loss (including fragmentation and degradation) is widely considered to be the greatest threat to biodiversity, and museum collections allow researchers to document the pace of these changes and their ecological consequences (McCarthy 1998, Shaffer et al. 1998). In the midwestern United States, for example, collections from 18 museums were used to show that the loss of prairie habitat has led to the decline or local extinction of small mammals that require this habitat to survive (Pergams and Nyberg 2001). Similarly, measurements of bird specimens from the Department of Ornithology of the National Museums of Kenya have been used to show that phenotypic traits of individual birds can be important predictors of species persistence in fragmented landscapes (Lens et al. 2002).

Recent advances in molecular techniques have also permitted the genetic analysis of ancient specimens. For example, the loss of genetic diversity in the greater prairie chicken *(Tympanuchus cupido)* has been precisely estimated by genetic studies comparing current populations with prairie chickens that were collected and stored 65 years ago at the Illinois Natural History Survey (Bouzat et al. 1998). This loss of genetic diversity has been tied to reduced fitness in these populations (Westemeier et al. 1998). With these data, managers can effectively plan the recovery of prairie chickens in Illinois. Similarly, Miller and Waits (2003) used museum specimens collected up to 90 years ago to show that grizzly bears *(Ursus arctos)* isolated in Yellowstone National Park are characterized by reduced levels of genetic diversity, although those levels are not as low as previously hypothesized.

Egg collections such as these from the National Museum of Natural History (Smithsonian Institution) have provided insight into the effects of toxin accumulation in the environment (Ratcliffe 1967, Hickey and Anderson 1968). Photograph: Chip Clark.

Biological invasions. Biological invasions are also recognized as an increasingly serious form of global change (Lovei 1997, Vitousek et al. 1997). Estimates of the costs of control and

Museum collections of small mammals have been used to identify reservoirs of hantavirus (Yates et al. 2002), reconstruct community structure in relation to habitat modification (Pergams and Nyberg 2001), and even build a predictive framework for crop pests (Sanchez-Cordero and Martinez-Meyer 2000). Photograph: Chip Clark.

damage caused by invaders run in the billions of dollars (Pimentel et al. 2000). Museum collections have been used to determine the current distributions of invaders, identify the source of introduced populations, reconstruct rates of spread, and gauge the ecological impact of invaders (e.g., Mills et al. 1996, Davies et al. 1999, Fonseca et al. 2001, Suarez et al. 2001). In a recent study, Suarez and colleagues (2001) used museum collections to reconstruct the spread of the invasive Argentine ant *(Linepithema humile)* throughout the United States during the past 100 years. This work quantified the relative contributions of natural, local dispersal and human-mediated dispersal, two distinct processes in the Argentine ant's pattern of invasion.

Museum collections have even been used to measure evolution in invasive species. Berenbaum and Zangerl (1998) studied specimens collected as early as 1873 to examine the chemical coevolution of two introduced species in the United States, the wild parsnip and the parsnip webworm, demonstrating a coevolutionary chemical arms race between this plant and its herbivore. This work illustrates the potential for rapid evolutionary response of species in new environments, essential information for understanding both the potential for the spread of invasive species and the effectiveness of control strategies.

Global climate change. There is widespread agreement that global climate change threatens the survival of ecological communities and individual species, including humans (Hughes 2000, IPCC 2001, McCarty 2001, Walther et al. 2002). By examining museum specimens, researchers have documented the effects of climate change on a variety of organisms and furnished a glimpse of future impacts. The contributions of these studies fall primarily into two categories: ones that document changes in the distribution of species through time (including their extinction) and ones that document changes in the biology of particular species in response to climate changes.

Some of the most convincing evidence for species range shifts in response to climate change comes from studies of butterflies. In the 1990s, Parmesan (1996) censused Edith's checkerspot butterfly *(Euphydryas editha)* at 115 sites in North America. She compared these data with historical records from museum collections (as well as private collections and researchers' field notes) and showed that southern populations (in Mexico) were four times more likely than northern populations (in Canada) to have gone extinct, resulting in a significant northward range shift. Similarly, when the histories of 35 European butterfly species were examined, 63 percent had ranges that had shifted to the north, whereas only 3 percent had advanced to the south (Parmesan et al. 1999).

Museum collections have also shown that the effects of global warming have altered the biology of some species.

A section of the fish collection at the National Museum of Natural History (Smithsonian Institution). Stored specimens such as these have allowed scientists to reconstruct the history of contaminants (such as mercury) in our food supply (e.g., Barber et al. 1972, Miller et al. 1972). Photograph: Chip Clark.

For example, Dunn and Winkler (1999) examined 3450 nest records of tree swallows *(Tachycineta bicolor)* in North America (from a survey of over 21,000 nest record cards in museums, universities, and ornithological societies) and found that the egg-laying date advanced by about 9 days between 1959 and 1991, most likely as a result of higher air temperatures during the spring breeding season.

For some species, museum specimens have provided evidence for both range shifts and morphological evolution in response to climate change. Hellberg and colleagues (2001) utilized paleontological and genetic data to demonstrate a Pleistocene range expansion in a marine gastropod *(Acanthinucella spirata)*. This expansion was coupled with changes in shell morphology, suggesting rapid evolution in response to climate change.

Are museums being used?

The use of museum collections is so widespread, and the scope of research they benefit is so varied, that it would be impossible to review even a small fraction of individual cases. Only by considering the frequency with which museums are used can their vast contributions to the biological sciences be properly appreciated (tables 1, 2).

Scientists often travel to museums to use their collections, and museums loan many specimens to interested researchers (table 1). For example, in 2002, the entomology department of the Smithsonian Institution's National Museum of Natural History hosted 266 visitors, for a total of 3663 visitor days (Scott Miller, Smithsonian Institution, Washington, DC, personal communication, 10 February 2003). Between 1976 and 1986, the Smithsonian's entomological collection loaned, on average, over 100,000 specimens each year (Miller 1991). The California Academy of Sciences' entomological collection currently has about 750,000 specimens on loan to over 40 countries (Norman Penny, California Academy of Sciences, San Francisco, personal communication, 4 April 2003).

The knowledge disseminated by the curators of these museums is immense and often stems from the reference collections themselves. For example, one curator (Philip S. Ward) from one museum (Bohart Museum, University of California–Davis) studying one family of insects (Formicidae—ants) typically identifies 3000 to 4000 specimens each year for other institutions (Philip S. Ward, University of California–Davis, personal communication, 9 January 2003). When extrapolated across curators of all museums in the United States, how many hundreds of thousands of such identifications are made each year?

The prominence of references to museums in peer-reviewed publications is a testimony to the contribution that they make to scientific knowledge. While it is obvious that scientific collections are essential for taxonomic work, museums also make significant contributions to basic and applied science by providing raw data and logistical and

Table 1. Examples of some of the largest entomological collections in the United States, including approximate collection size (number of processed specimens) and a yearly estimate of loaned material.

Institution	Size[a]	Loan activity[b]
National Museum of Natural History	25,000,000	103,722
American Museum of Natural History	16,204,000	50,563
Bishop Museum	13,500,000	37,640
Field Museum of Natural History	10,300,000	53,724
California Academy of Sciences	7,601,000	75,167
Museum of Comparative Zoology	7,300,000	25,549
Los Angeles County Museum	5,500,000	18,115
Carnegie Museum of Natural History	6,900,000	13,782
Illinois Natural History Survey	6,500,000	23,379
Bohart Museum (University of California–Davis)	6,800,000	19,441
Essig Museum (University of California–Berkeley)	4,500,000	25,797

a. All estimates are from 2002, except those for the National Museum of Natural History and the American Museum of Natural History (Miller 1991).

b. Figures are the yearly average of the years 1976, 1981, and 1986 (Miller 1991), except for the Illinois Natural History Survey, for which the period 1993 to 2002 was used to calculate the yearly average (Colin Favret, Illinois Natural History Survey, Champaign, IL, personal communication, 27 June 2003).

financial support. Many publications in the most prestigious and frequently cited journals in the fields of ecology and evolutionary biology rely on museums for data, funding, and reference material (table 2). Nonetheless, there is room for improvement. Because a cornerstone of the scientific process is repeatability, specimens used in scientific investigations should be cataloged and vouchered in museums to ensure that species identifications can be confirmed and the results interpreted correctly (Ruedas et al. 2000).

Monetary value

Museums save time and money. First, as centralized storehouses of reference material, museums act as "biological libraries"—sites of accumulated knowledge and resources that eliminate the need for costly, time-consuming (and sometimes dangerous) fieldwork. Given the costs of traveling to remote locales to collect specimens, it is easy to believe that museum collections save the scientific community many millions of dollars, a savings that is passed on to citizens whose tax dollars often support scientific research.

Second, as with literary libraries, museums eliminate the wastefulness of duplication and redundancy. Just as a library liberates borrowers from the expense of purchasing every book they wish to read, museums free researchers from the time and expense of curating all the specimens necessary for a functional reference collection. Although a fiscal analysis of the savings achieved by the nation's biological collections is not available, a comparison with other collections provides an insightful approximation. The US Library of Congress, which curates a large collection of reading material, saves the nation's libraries $268 million a year by cataloging more than 250,000 books and serials annually and supplying the bibliographic record (Librarian of Congress 2000).

By reducing the costs of studying vectors of human disease, biological invasions, and global climate change, biological collections provide direct financial and social benefits to society. Our own research on biological invasions offers evidence of the savings that museums provide. During the past few years, we have used specimens that we collected in the field (Argentina) as well as specimens that we borrowed from museum collections for our research. A typical research trip to Argentina lasts about a month and costs at least $5000 for airfare, car rental, food and lodging, and collecting supplies and other materials. In contrast, our visits to various museums during the past year have cost us a fraction of that amount, between $100 (the cost of driving to the University of California–Davis Bohart collection) to about $1000 (the cost of traveling to the National Museum of Natural History for one week). If similar savings were enjoyed by the other 265 visitors to the National Museum's entomological collection last year, we can estimate that this one department saved academic and other scientific institutions over $1 million in 2002 alone. In the future, these savings will grow as more collections are put into databases and made available online.

Table 2. The number of articles from some leading journals that relied on museums for support and data.

Journal	Years	Number (%) of articles using museums for support[a]	Number (%) of articles using museums for data
Ecology	1990–1996	266 (17.4)	17 (1.1)
Ecological Monographs	1990–1996	42 (31.3)	6 (4.5)
The American Naturalist	1990–1998	216 (19.0)	26 (2.3)
Systematic Biology	1992–1998	140 (45.6)	41 (13.4)

a. Articles utilized collections for species identification, referenced museum publications, or relied on museums for space or financial support (through grants or salary).

Conclusions

During the last two centuries, scientific collections were considered essential components of research, particularly for taxonomists and systematists. Biology was in an age of exploration and discovery, and in these early stages, the role of collections was paramount and instrumental in the thinking of visionaries such as Darwin and Wallace. We are still in this stage of discovery, and a majority of the species that exist on our planet—and their roles and potential value—have not yet been described (Wilson 2003). But the continued existence of many contemporary collections and the services that they provide are threatened by state and federal budget cuts (Dalton 2003, Froelich 2003, Gropp 2003, NSCA 2003, Stokstad 2003). Nothing will ever replace the taxonomic knowledge and training that museums provide; funding in this area should become a national priority. Otherwise, knowledge of this planet's biodiversity, and of all the potential benefits therein, will be lost.

How can the survival of these assets and the untapped knowledge they contain be guaranteed? First, these collections must be well curated and maintained, which will require a commitment to support and train taxonomists and to maintain modern facilities. Second, the benefit of these collections to society must be maximized by stepping up the rate at which this information is entered in databases and made accessible.

Ultimately, maintaining and developing the infrastructure of museums will most likely produce unforeseen benefits. Consider, for example, the revolutions in computer science and molecular biology over the past three decades, which can trace their origins to government support of basic science. If 40 years ago someone had pronounced that someday computers would process billions of bits of information per second and be the size of a notebook, the reply would have been "What's a computer?" If the time and energy it takes to support museum collections is expended now, who can guess what dividends this investment will pay to future generations? Although the future payoffs of wise investments are impossible to predict precisely, failure to support museum collections is the most certain way to eliminate any benefits.

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