BioScience Advance Access published March 26, 2014

Natural History's Place in Science and Society

JOSHUA J. TEWKSBURY, JOHN G. T. ANDERSON, JONATHAN D. BAKKER, TIMOTHY J. BILLO, PETER W. DUNWIDDIE, MARTHA J. GROOM, STEPHANIE E. HAMPTON, STEVEN G. HERMAN, DOUGLAS J. LEVEY, NOELLE J. MACHNICKI, CARLOS MARTÍNEZ DEL RIO, MARY E. POWER, KIRSTEN ROWELL, ANNE K. SALOMON, LIAM STACEY, STEPHEN C. TROMBULAK, AND TERRY A. WHEELER

The fundamental properties of organisms—what they are, how and where they live, and the biotic and abiotic interactions that link them to communities and ecosystems—are the domain of natural history. We provide examples illustrating the vital importance of natural history knowledge to many disciplines, from human health and food security to conservation, management, and recreation. We then present several lines of evidence showing that traditional approaches to and support for natural history in developed economies has declined significantly over the past 40 years. Finally, we argue that a revitalization of the practice of natural history—one that is focused on new frontiers in a rapidly changing world and that incorporates new technologies—would provide significant benefits for both science and society.

Keywords: environmental management, ecological knowledge, human health, food security, sustainability

***Natural history* has been defined in many ways** (Bartholomew 1986, Herman 2002, Greene 2005, Schmidly 2005), and no single definition will satisfy all readers. For our purposes, *natural history* is the observation and description of the natural world, with the study of organisms and their linkages to the environment being central. This broad definition is inherently cross-disciplinary and multiscaled, which reflects the span and potential of natural history activity. For most of the history of science, natural history was the natural sciences: "at once the beginning and the end of biological study" (Jordan 1916, p. 3).

A lot has changed since those words were written almost a century ago. The natural sciences now form one of the largest, most diverse collections of disciplines in academia. But across many fields, natural history appears to be in steep decline (Greene and Losos 1988, Noss 1996, Wilcove and Eisner 2000). A number of authors have pointed to a decline in natural history research and education (Suarez and Tsutsui 2004, Schmidly 2005, McCallum and McCallum 2006, but see Arnold 2003); in some countries, this decline may parallel a decline in public participation in nature (Balmford et al. 2009). This decline has troubling implications for science and society.

Direct knowledge of organisms—what they are, where they live, what they eat, why they behave the way they do, how they die—remains vital to science and society. This knowledge may become even more vital as the rate and extent of global change increase (Johnson et al. 2011, Lavoie 2013). Integration of this knowledge is also increasingly important for translating results obtained in cellular, molecular, and genomic studies (Ley et al. 2006); for understanding and optimizing complex human–environment interactions (Pretty et al. 2006); for advancing human health (Colwell et al. 2003); and for expanding technology and design from biomimicry to biology-inspired design (Stafford et al. 2007). The benefits of careful observation of organisms in their environment and the costs of pursuing environmental policies in which this critical component of science is ignored can be seen in human health, food security, conservation, and management. After highlighting these connections, we document the decline in traditional natural history and suggest ways in which the practice of natural history could be revitalized to better connect science and society.

Human health

Human health is dependent on our understanding of the relationships between people and other organisms. An estimated 75% of emerging infectious diseases that afflict humans are associated at some point in their life cycle with other animals (WHO 2011). Many of the strategies currently used to control these diseases rely on an understanding of the distribution and behavior of species and communities that influence their transmission, spread, and prevalence (Garrett 1995). Infectious diseases with animal vectors and reservoirs include

doi:10.1093/biosci/biu032 Advance Access publication XXXX XX, XXXX

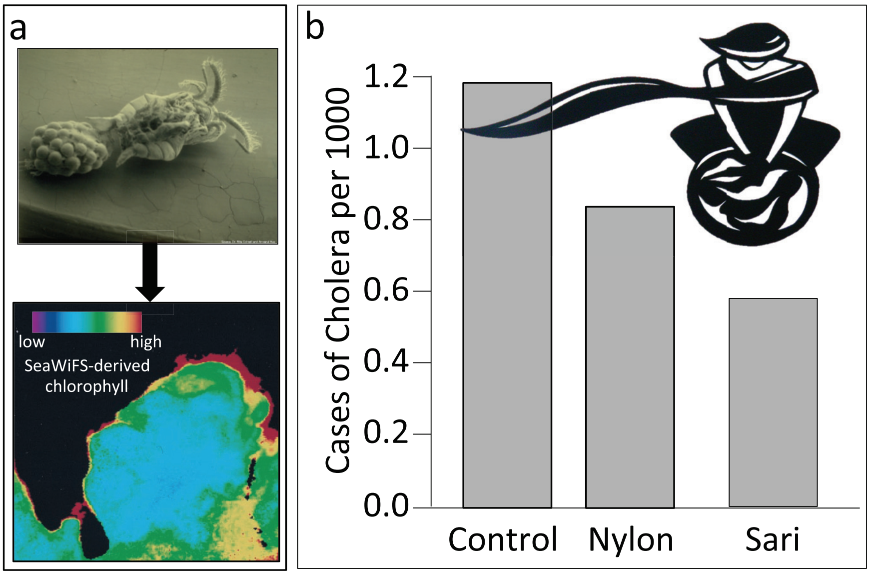

Figure 1. (a) The finding that **Vibrio cholerae** *is carried by copepods (top; micrograph: Rita Colwell and Anwarul Huq, National Science Foundation) explains why scientists and public health experts are able to use satellite sensors to monitor phytoplankton chlorophyll as an early-warning system for cholera outbreaks (Bay of Bengal, bottom; source: Reprinted from Lobitz et al. 2000). (b) It also explains the effectiveness of simple cloth filtering as a means of reducing cholera. The tightly woven cloth of which saris are made does not capture individual* **Vibrio**, *but it filters out the zooplankton to which most* **Vibrio** *in polluted waters are attached and, therefore, prevents cholera even better than nylon filtration, a technique used to filter other copepods (Colwell et al. 2003). Papercut art: Hannah Viano.*

avian influenza, SARS (severe acute respiratory syndrome), Ehrlichiosis, scrub typhus, Lyme disease, hantavirus, West Nile virus, and rabies (WHO 2011). For all of these diseases, knowledge of the hosts' natural history has been critical in predicting and controlling disease dynamics, reducing infection rates, and saving lives (Suarez and Tsutsui 2004, Winker 2004). As human populations expand, this information will play an even more critical role in the control of pathogenic threats, including bioterrorism (Suarez and Tsutsui 2004, Winker 2004).

Cholera (*Vibrio cholerae*) provides a compelling example of how knowledge of natural history is key to disease control (figure 1). The discovery that *V. cholerae* has free-living populations associated with copepods and other zooplankton (Colwell and Huq 1994) forms the foundation of model predictions of temporal and spatial changes in human cholera outbreaks, because these models are based on the dynamics of the zooplankton and phytoplankton on which they feed. With this natural history in hand, public health experts now use satellite sensors to monitor phytoplankton chlorophyll as an early-warning system for cholera outbreaks. The same discovery also explains why filtering polluted water through cloth is surprisingly effective in reducing exposure to cholera: although the cloth does not capture *V. cholerae* individually, it filters out the zooplankton to which most *V. cholerae* are attached (Huq et al. 1996).

In a similar vein, understanding how organisms compete and defend themselves against predators and pathogens can reveal new pathways for pharmaceutical prospecting and can perhaps spur the development of new drugs (Coley et al. 2003). Although the importance of natural products in drug discovery is undisputed (e.g., drugs from natural products are used to treat more than 85% of current diseases; Newman et al. 2003), the screening process for bioactive compounds is often automated and largely blind to natural history. Instead of using natural history knowledge to reveal especially likely sources of such compounds, many pharmaceutical prospectors adopt a brute-force approach, sampling at random or, less often, targeting a subsample of organisms identified by ethnobotanists and anthropologists as historically and culturally important to local people (Coley et al. 2003). The empirically demonstrated success of ecological theories in which natural history is used to target potentially rich sources of bioactive compounds is typically ignored in these approaches (Albuquerque et al. 2012). For example, the presence of herbivores with warning color patterns feeding on tropical plants has been used to indicate plants with bioactivity against cancer cells and protistan parasites (Helson et al. 2009). In addition, young leaves in tropical forests tend to be rich in chemical defenses, because their relatively high protein content and lack of physical defenses make them a favorite food for many herbivores; these leaves also tend to have more biologically active compounds than do older leaves (Coley et al. 2003).

Food security

Sustainable agriculture requires a detailed understanding of crop species' local requirements and their long-standing interactions with co-occurring species (Pretty et al. 2006). Knowledge of growing conditions, phenology, pollinators, herbivores, weeds, and pathogens comes from natural history observations. Agricultural practices, such as companion planting, crop rotation, and pest control, are based on knowledge of local natural history. Much of this knowledge was discarded or lost with the advent of the Green Revolution, which relied heavily on the extensive use of chemicals, irrigation, and high-yield crop varieties. The initial success of the Green Revolution in Mexico and India led to the widespread adoption of a one-size-fits-all approach to agriculture. In many parts of Africa, agricultural modernization was focused on the import of new crop varieties developed for other regions in an effort to shortcut the difficult task of local crop development (Evenson and Gollin 2003). This approach,

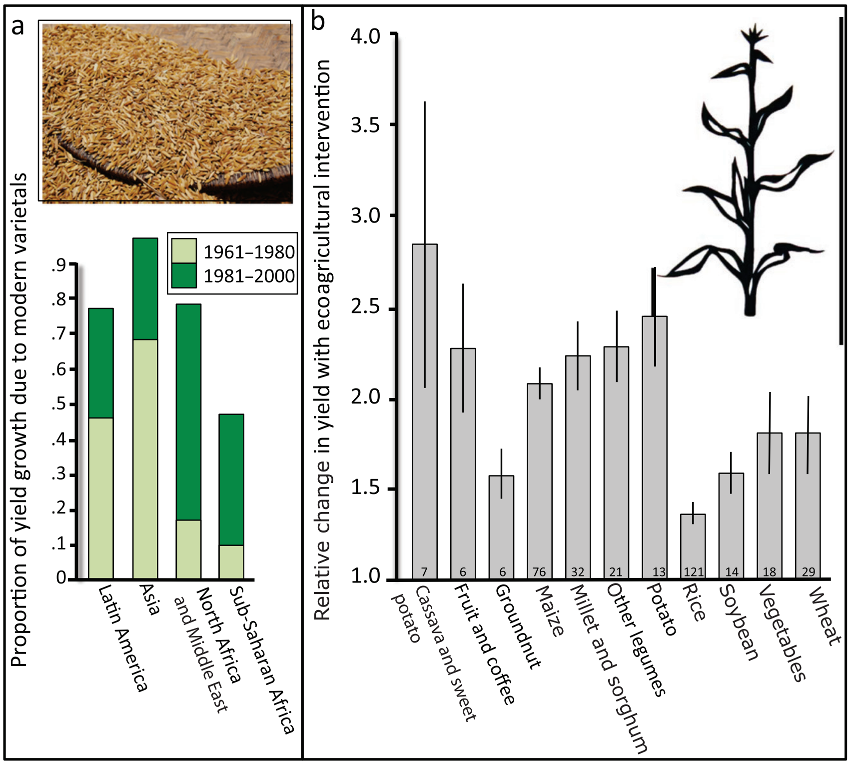

Figure 2. (a) Yield increases due to modern varietals were slow to take place in much of Africa and the Middle East because the varietals that were used were developed in Asia and moved to these regions (compare the light green bars across regions). After investments in local varietals were made, beginning in the 1980s, the yield increased rapidly throughout Africa and the Middle East (the dark green bars). Source: The data are from Evenson and Gollin (2003). Photograph: Sandra Mbanefo Obiago, courtesy of the World Wildlife Fund–Canon Photogalleries. (b) Increases in yield for various crops during or after the implementation of projects that incorporate sustainable agriculture principles and techniques based on natural history knowledge of the crop species. The number in each bar indicates the number of studies using each crop. The error bars represent the standard error of the mean. Source: The data are from Pretty and colleagues (2006). Papercut art: Hannah Viano.

in which local knowledge of the environment and locally adapted crops was ignored, resulted in severe setbacks in regional agricultural production that were not ameliorated until agronomists began to evaluate how and why particular varieties thrive under local conditions (figure 2). There are many subsequent examples of the successful integration of natural history observations that have led to agricultural improvements, including the use of integrated pest management practices and successful biological control.

In the oceans, natural history knowledge has been a double-edged sword. Successful fishermen have always depended on natural history knowledge to find fish, and this knowledge, combined with improvements in fish tracking technology, has resulted in extensive pressures on marine fisheries. However, much of the same natural history—age at maturity, longevity, fecundity, spawning and recruitment habitat, nursery grounds—has also been critical for setting catch limits, safeguarding spawning and nursery habitat, and protecting species from overharvesting. The difficulty for rapidly developing fisheries lies in the rate of knowledge accumulation. Because less effort is typically made to understand the biology of harvested species than to harvest them, the detailed information needed to set catch limits at sustainable levels is sometimes revealed only after a fishery has collapsed. The spectacular collapse of the Bering Sea fishery for walleye pollock (*Theragra chalcogramma*) serves as an important example (Bailey 2011). This fishery was the most abundant and lucrative natural fishery in North America until unregulated harvest focused on prespawning females (for their roe), combined with rapid advances in technology and the buildup of international fleets, led to its complete collapse: The catch in 2007 was only 3% of what it was during the 1980s. This collapse might have been prevented, but the natural history surveys needed to assess the pressure and structure of the population were stymied by a lack of funds and began in earnest only as the population crashed (Bailey 2011).

The slow pace of accumulation of essential natural history knowledge for many economically important species, from fisheries to crop pests, has repeatedly hindered the development of robust, predictive policies that would benefit humanity. In many industries, this has resulted in repeated failures of sustainable management, even though these extractive systems are the very ones for which natural history knowledge should be most complete. However, where natural history approaches have been integrated into management agendas, the results have been strongly positive. For example, the successful control of the California citrus cottony cushion scale was accomplished through careful study of two biocontrol organisms, the vedalia beetle (*Rodolia cardinalis*) and the fly *Cryptochetum iceryae*, before their introductions—a model for successful biological control (Caltagirone and Doutt 1989). Such research has helped farmers in developing countries increase yields, save money, and reduce environmental harm by replacing pesticides with natural enemies and ecoagricultural approaches to pest management (figure 2; Pretty et al. 2006).

Conservation and management

Forest conservation and landscape restoration owe much of their success to the inclusion of detailed natural history information. For example, knowledge of the importance of plant–fungal symbioses to the health of forest systems has led to the common restoration and forestry practice of inoculating trees and native plants with mycorrhizae (Horton and van der Heijden 2008). However, failing to incorporate natural history information has sometimes led to large-scale, costly reversals in policy. The most iconic of these reversals may be the decision to suppress forest fires in the western United States during much of the twentieth century. This decision reflected the application of silvicultural principles developed in Germany and eastern North America, whereas the critical importance of fire—well known to Native Americans—in the life history of many dominant tree species in western forests was ignored (Donovan and Brown 2007). As a result, the US fire management program now costs more than $1 billion annually (Abt et al. 2009) and requires intensive management of endangered species threatened by altered fire regimes (Wilcove and Chen 1998).

Water management in the United States has also suffered from a lack of natural history knowledge. In salmon-bearing rivers of the northwestern United States, large stumps and logs were intentionally removed to increase navigability and to assist salmon migration. Only after hundreds of streams were cleared did the managers recognize that accumulations of large woody debris are essential for maintaining suitable salmon habitat (Fausch and Northcote 1992). Millions of dollars are now spent on restoration efforts, which often require helicopters in order for logs to be put back into the streams (Watanabe et al. 2005).

A case in which natural history knowledge has facilitated positive management outcomes is the restoration of tropical forest on degraded, abandoned cattle pastures. Multiple processes may create barriers to forest regeneration, including nutrient depletion, competition with pasture grasses, and a lack of seed input by animal dispersers. Restoration efforts can fail if they do not account for the relative importance of these obstacles at different stages of regeneration and in specific locations (Nepstad et al. 1990). "Legacy" trees within pastures often serve as recruitment foci for forest species (Griscom and Ashton 2011), in part because seed-dispersing birds and bats void seeds more often while perched than while in flight and also because shade from trees suppresses aggressive pasture grasses. In addition, regeneration is greater around fallen logs, which ameliorate harsh environmental conditions within pastures (Slocum 2000). These observations have led to management practices that facilitate forest regeneration, and, combined with falling cattle prices, they facilitated rapid restoration efforts in many areas of the Neotropics. Forest cover in Guanacaste Province, Costa Rica, for example, increased from 24% to 47% of the total land area between 1979 and 2005 (Calvo-Alvarado et al. 2009).

Natural history has proven vital in many efforts to conserve and responsibly manage iconic species and places—organisms and landscapes that symbolize the heritage of well-loved social–ecological systems. Shared concern over preserving these well-known species spurs social action. Reversing declines in species such as eagles, whales, redwoods, and songbirds has repeatedly relied on an understanding of the organisms themselves. Long-term monitoring of breeding success in bald eagles (*Haliaeetus leucocephalus*) was critical in linking the pesticide DDT (dichlorodiphenyltrichloroethane) with population declines and in determining subsequent recovery efforts (Grier 1982). The establishment of a sustainable quota for bowhead whale (*Balaena mysticetus*) hunting by the Alaskan Iñupiat was possible only because the Iñupiat people possessed detailed knowledge of whale migration routes and behavior. This information, later confirmed by acoustic and aerial surveys and stable isotope analyses (Huntington 2000), was instrumental in estimating whale abundance and spatial dynamics and provided support for a hunting quota that allows a traditional harvest to be sustained and that satisfies conservation policies.

Recreation

Hunting and fishing activities provide direct connections between natural history and rural economies around the world. When they are well managed, activities from safari hunting to fly fishing combine low-impact recreation with income for guides, licensing agencies, and supporting industries in areas that often struggle to balance the protection of natural resources and economic growth (Balmford et al. 2009).

It is often the collective focus on natural history by hunters, fishers, wildlife watchers, and conservationists that allows consensus-based management of fish and game species. The waterfowl conservation movement in the United States serves as an example. This partnership was set in motion in the early twentieth century by observations of large-scale duck mortality caused by botulism brought on by invertebrate die-offs in wetlands and by lead poisoning in high-intensity hunting locations. In both cases, observations by hunters and bird watchers alerted managers to the issue. The initial focus on disease was fortunate, because it provided a common enemy, and, at least for botulism, the most effective management centered on the designation of federal and state bird refuge areas in wetlands (Bolen 2000). More generally, the many groups that came together to change state and federal policies around these issues led to the creation of powerful hunting and conservation groups. These collaborations also led to a hunting license fee structure that supports the more-than-500-unit federal wildlife refuge system in the United States. The success of waterfowl conservation efforts, and the hundreds of other species that they support, comes in large part from the diverse interest groups that recognized the importance of basic natural history in setting management and policy objectives and that created a stable funding stream to support the collection of that information.

These interest groups do not always act with a clear understanding of natural history. When they fail to include natural history, the results can lead to the collapse of the system that supports the industry. For example, sport fishing for salmonids in western North American lakes is a quintessential wilderness experience with considerable economic importance to local communities dependent on tourism.

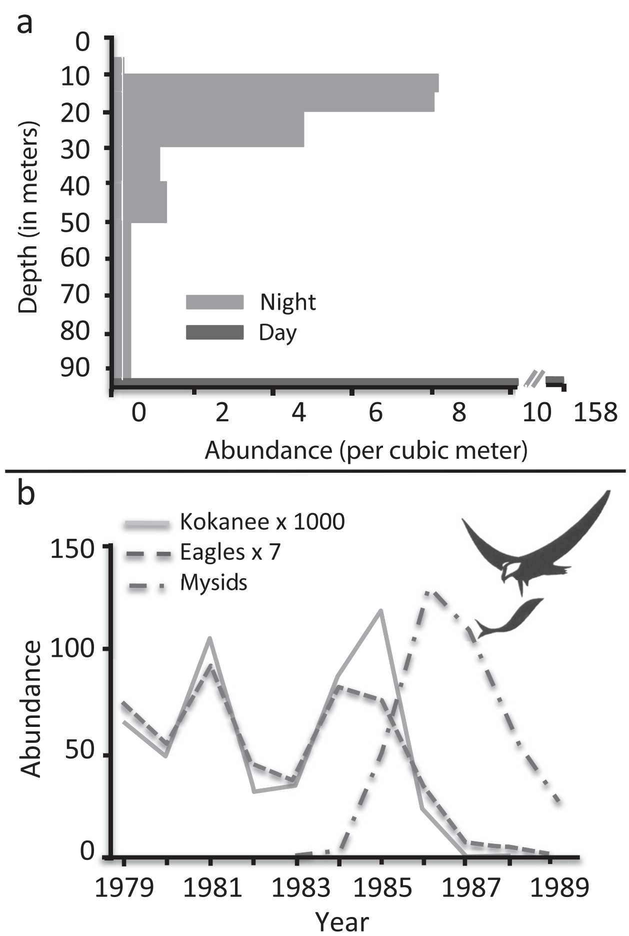

Figure 3. Opossum shrimp (*Mysis relicta*) were introduced into lakes in western North America as forage to increase salmonid production (Spencer et al. 1991). (a) In deep lakes, such as Lake Tahoe and Flathead Lake, the mysids migrated to deep water to avoid predation by fish during the day (note the break in horizontal axis) and returned to the surface to feed at night. Source: The data are for Flathead Lake, from Spencer and colleagues (1991). (b) Mysids (the dashed and dotted line, expressed in number per cubic meter) were introduced to lakes above Flathead Lake between 1978 and 1986 and became established in Flathead Lake in the early 1980s. Once they had become established, they outcompeted kokanee trout (the solid line, reflecting the estimated annual peak of absolute population estimated from biweekly counts) and reduced spawning runs in the lake's tributaries. The rapid drop in salmonid numbers led to a corresponding drop in bald eagles (dashed line, annual peak estimates from weekly counts; Spencer et al. 1991). Papercut art: Hannah Viano.

To support the industry, opossum shrimp (*Mysis relicta*) were introduced into Lake Tahoe in 1963 and into Kootenay Lake in 1968, specifically as forage to increase salmonid production (Spencer et al. 1991). These intentional introductions were followed by many accidental introductions into other lakes, such as Flathead Lake in Montana. Although it was credited for a short-term boom in Kootenay Lake's salmon populations, the shrimp's impacts in deeper lakes (Flathead Lake and Lake Tahoe) were very different. Mysids in Flathead Lake and Lake Tahoe migrated to deep water to avoid predation by fish during the day and returned to the surface to feed at night (figure 3). Rather than serving as prey for salmonids, mysids were highly effective competitors, consuming the smaller zooplankton on which juvenile fish depend. As a result, they are widely blamed for the decline in salmonid production in both of these lakes. In Flathead Lake, the loss of the salmon led to large declines in bald eagles and in tourists (figure 3). Because diel vertical migrations were already well known for mysids at the time (e.g., Beeton 1960), this outcome could have been predicted had the details of the shrimp's natural history been recognized.

A similar story unfolded at approximately the same time in Lake Atitlán, in Guatemala, where largemouth bass (*Micropterus salmoides*) were introduced to promote sport-fishing tourism. The bass thrived but did so at the expense of freshwater crabs and small fish, which were the dietary mainstays of the flightless Atitlán grebe (*Podilymbus gigas*; LaBastille 1983). The grebe's population plummeted in the 1960s; by 1988, the species was considered extinct (Hunter 1988). Although other factors, such as harvesting of reed beds and interbreeding with pied-billed grebes, may have contributed to the extinction, there is little doubt that competition with bass triggered the initial population decline and that even a cursory consideration of natural history would have cautioned against the introduction of an apex predator into a large, high-altitude, *endorheic* (i.e., isolated from the sea) lake.

Decline of natural history

Despite the importance of detailed natural history information to many sectors of society, exposure and training in traditional forms of natural history have not kept pace with growth in the natural sciences over the past 50 years. One way to track the exposure and training in natural history is through changes in the gathering and curation of the natural history material contained in these collections. The general trend in natural history collections has been toward consolidation, not expansion, in spite of the increased use of specimens in global climate change research and ecoinformatics (Ward 2012, Lavoie 2013). In Europe and North America, for example, the number of active *herbaria* (i.e., collections of preserved plants and their associated natural history information) peaked in 1990; the last 20 years have seen a steady consolidation of collections (figure 4a). In other parts of the world, the number of herbaria is still growing slowly, but the rate of growth has slowed everywhere (supplemental figure S1). In the 1980s, the number of active herbaria around the world increased by more than 30 per year; today, we add fewer than 2 herbaria per year (figure 4a). This trend is not limited to herbaria (supplemental figure S2); although the consolidation of collections can often increase the ease of access by professional taxonomists and can focus curatorial talent (which is, itself, unfortunately scarce), the same

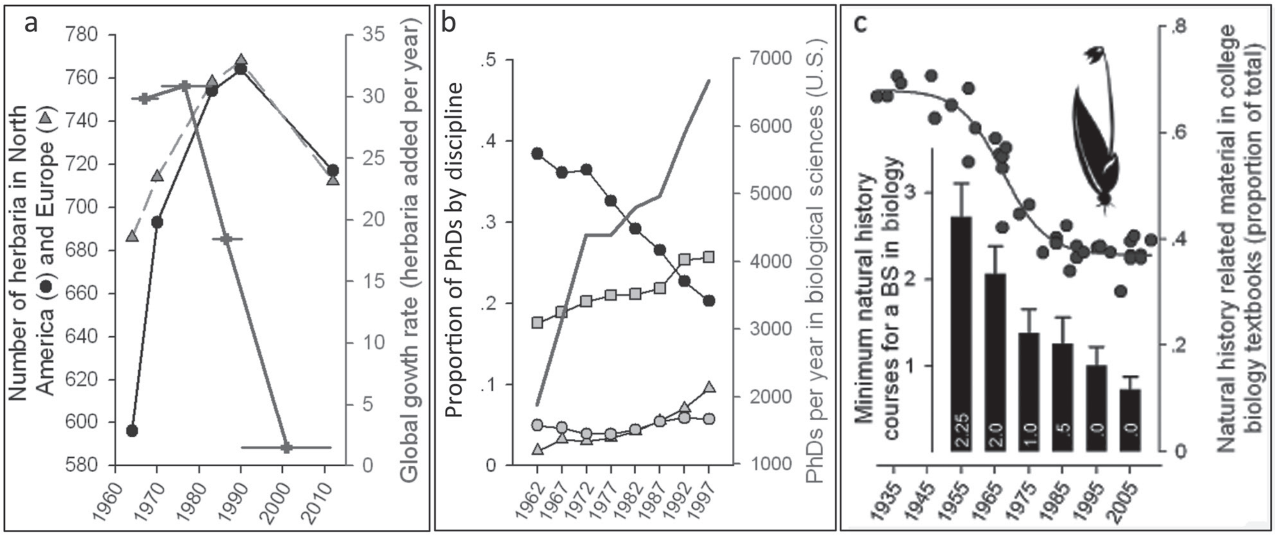

Figure 4. Declines in both access to and emphasis on natural history as illustrated through changes in (a) research collections, (b) graduate education, and (c) undergraduate education. (a) The number of registered herbaria in North America (the circles) and Europe (the triangles) and the global growth rate of herbaria (the solid line with barred circles, right axis) from the Index Herbariorum (Thiers 2014). The horizontal bars indicate the years over which each herbaria growth rate estimate was calculated. The consolidation of collections is also seen in vertebrate research collections (see the supplemental material). (b) The total number of PhDs in biology issued by US institutions from 1960 to 1995 (the line with no marked points) and the proportion of those PhDs granted in natural history–related disciplines (the solid circles), microbiology and molecular biology (the squares), biophysics and neurology (the triangles), and genetics (the gray circles). Source: The data are from Thurgood and colleagues (2006; see the supplemental material). (c) The minimum number of natural history–related courses required for a BS degree in biology in US institutions (the bars; the median is indicated within each bar) and the proportion of introductory biology texts devoted to natural history–related material (the circles, right axis; see the supplemental material). The error bars represent the (positive) standard error of the mean. Papercut art: Hannah Viano.

process limits local exposure and reduces opportunities to engage and educate local communities.

Other trends suggest more general declines in exposure to natural history at the graduate and undergraduate levels. In the United States, the proportion of PhDs with degrees in natural history–related fields of biology has declined steadily over the past 50 years (figure 4b; see the supplemental material for methods). Exposure to and emphasis on natural history have also declined in undergraduate education (figure 4c). We used two metrics to measure this decline: the minimum number of natural history–related courses for a bachelor's degree in biology in US universities and colleges and the coverage of natural history in introductory biology textbooks. In the 1950s, all of the schools that we surveyed required some natural history courses for a biology degree (median = 2.25 courses), and introductory biology texts were dominated by natural history (figure 3c). Today, the majority of universities and colleges in the United States have no natural history requirements for a degree in biology, and the emphasis on natural history in introductory biology texts has dropped by 40% over the past 50 years (figure 4c). This decline in traditional natural history training has largely coincided with the rise of molecular biology, theoretical and experimental biology, and ecological modeling (figure 4b, 4c, and the supplemental material), and there is some evidence that these shifts in education have coincided with a parallel decline in the rate of natural history publications in some disciplines (McCallum and McCallum 2006) and funding for natural history in some countries (Suarez and Tsutsui 2004, CCA 2010).

These trends in research and education, most of which come from the United States, may reflect the more general decline in public engagement with nature that is found in the United States and Japan but not in many other parts of the world (Pergams and Zaradic 2008, Balmford et al. 2009). Shifts in science and society are difficult to measure and are rarely attributable to a single cause, and diminishing attention to nature and natural history is no different (Balmford et al. 2009). Urbanization and a lack of exposure to nature, changes in affluence, a reduction of unstructured time for children, and increased television and computer use have all been implicated in the reduced public awareness of nature (Louv 2008, Pergams and Zaradic 2008, Balmford et al. 2009). Evaluating the causal pathways between these factors is beyond the reach of this article, but the declines in natural history literacy are clearly embedded in a larger social context with large implications for science and society.

Natural history in academia: Connecting science and society

The stature of natural history within many academic institutions will depend on its capacity to generate revenue and

Box 1. Revitalizing natural history within institutions: Claim the title.

The vitality of natural history will depend on the willingness of professionals in the natural sciences to self-identify as natural historians, to teach natural history, and to articulate the importance of their expertise across a wide range of disciplines, through lectures, conferences, professional societies, and public talks. Those professionals who embrace the revitalization of natural history within and beyond their institutions will lead and define the field for the twenty-first century. This is not an easy path for early-career academics, but it is an essential shift for established academics because they can use their tenure to validate and promote the importance of natural history within and beyond their programs. A big part of this work is the establishment of a strong platform or support structure, which would allow professional naturalists at all levels to claim credit for their work using traditional institutional metrics. Such a platform must include awards, conferences, organizations, and society sections that support and recognize naturalists throughout their career and integrate natural history with other disciplines; sections within high-impact journals devoted to excellent natural history; and increased recognition of data sets, themselves, as legitimate products of research and scholarship.

For example, natural history societies and institutions around the world have been promoting the work of professional naturalists for more than a century, and many of these groups have formed consortia that support a broader community of naturalists and allow greater integration across disciplines (box 5). In the United States, a number of recent initiatives (e.g., the Natural History Initiative, the Natural Histories Project, the Natural History Network, the Natural History Section of the Ecological Society of America) have joined more-established museum- and society-based efforts to explicitly focus attention on the importance of connections between natural history and other disciplines. In addition, journals within established societies have also made changes. The reinstatement of the Natural History Miscellany section within the *American Naturalist* is an excellent example of ways in which high-impact-factor journals can provide legitimacy to the work of naturalists, and journals focused on pedagogy, such as the *Journal of Natural History Education and Experience*, provide a platform for sharing natural history teaching techniques and curricula.

Box 2. Revitalizing natural history within institutions: Avoid exclusivity, enhance connectivity, and embrace technology.

The practice of natural history needs to be inclusive and adaptive to survive the twenty-first century. Its relevance will depend on the willingness of its practitioners to embrace new modes of observing the world and their capacity to recruit naturalists who use a much wider set of tools and skills than were historically associated with the study of natural history. The twenty-first century naturalist is as likely to work with a smartphone and a social network or with a scanning electron microscope and a mass spectrometer as with binoculars and a hand lens. Taking advantage of tools and techniques from other disciplines and the rapid expansion in the capacity for the digital collaboration, curation, and sharing of natural history knowledge, naturalists can blend disciplines and modes of observation, thereby building a broader constituency. This is as important in the development of new course curricula as it is in the development of research collaborations and citizen science programs. One of the fundamental roadblocks to a vibrant and contemporary natural history movement is the broad perception that natural history consists only of walks in the woods and lifeless collections and that it is the domain of a small set of people generally out of touch with society.

A wide range of programs are using technology to collect and share natural history data and to make these data available across disciplines (see box 5).

contribute to the academic currencies used to measure the success of individuals and programs. In research-oriented universities, these currencies are typically large grants, publications in high-impact-factor journals, and public recognition for the institution. Disciplines that cannot compete in these currencies will typically be given little attention in critical decisions surrounding hiring, promotion, course offerings, degree programs, buildings and infrastructure, and institutional direction. Even in institutions at which the focus on teaching is more prevalent, disciplines such as natural history can be marginalized because of the relatively high per-student cost of field- and collection-based courses and because of these courses' low enrollments relative to those in higher-profile disciplines. Maintaining a strong natural history curriculum within higher education will require a clear articulation of the importance of the discipline, backed up by collaborative work to design and sell a twenty-first century natural history research and educational agenda to funding agencies, foundations, and the public (Winker 2004). Such an agenda must cross a series of high bars: It must recognize its connections with a wide range of other disciplines and promote new ways of doing natural history, it must embrace rapid shifts in demography and technology to engage a larger and more diverse array of participants, and it must promote an open-source community of collaboration that generates and distributes data at scales relevant to other disciplines and to society as a whole. Below, we articulate some of what we see as the major frontiers for natural history in the twenty-first century. In boxes 1–4, we offer recommendations to individuals and institutions interested in

Box 3. Revitalizing natural history within institutions: Work collectively.

Individual naturalists with isolated knowledge have little capacity to demonstrate the importance of their work, but groups that integrate and share knowledge across disciplines will flourish. Naturalists of all types need to contribute to common resources, work toward standardized formats, and move their work into the public sphere. In these open data warehouses, objects and empirical observations can be shared, used, and repurposed to meet the rapidly changing needs of society (Winker 2004, Hampton et al. 2013). Investment in naturalist partnerships can add value to a larger effort to provide common access to natural history knowledge and applications. Most institutions have begun to see the value in collaboration across these boundaries. For example, all of the major environmental nongovernmental organizations now have research and curation partnerships with multiple universities and museums, and many museums are shifting toward porous boundaries, with as much happening outside of the museum walls as inside (Sunderland et al. 2012). This practice, as long as it does not distract these institutions from their core object-based focus, will make them better able to collaborate with other institutions with similar missions but different perspectives.

In Europe, organizations and programs such as the Consortium of European Taxonomic Facilities, Natural Europe, and SYNTHESYS are providing strong models for collaboration, and, in the United States, the USA National Phenology Network (box 5) and the US Virtual Herbarium Project are engaged in parallel activities. At even broader scales, projects such as the Global Biodiversity Information Facility provide international coordination and support (see box 5).

Box 4. Revitalizing natural history within institutions: Go where the people are.

Many naturalists of the twentieth century were inspired by sustained contact with nature at an early age, but the pace of urbanization is fundamentally changing the way in which the next generation will interact with the natural world. Finding exciting ways to build natural history into the fabric of modern urban life is a key challenge for natural history, and there are a number of programs that are focused directly on urban natural history.

Your Wild Life develops and hosts citizen science projects focused on life on and around people. Its projects range from assessment of the microbial biodiversity of belly buttons to the crowd-sourced collection and identification of urban ants. The Children and Nature Network is a growing US movement that offers resources and tools, practical advice, and a catalog of local events for families and educators to connect with nature. They recently helped pass a resolution titled "The child's right to connect with nature and to a healthy environment" at the World Congress of the International Union for the Conservation of Nature.

the revitalization of natural history. Our objective is to start a conversation about the future of natural history, and we invite you to join the conversation (please see the details at the end of this article).

Frontiers for twenty-first century natural history

Technology is expanding the reach of the naturalist, uncovering a new world of opportunities at the microbial scale. Microbial cells outnumber human cells 10:1 in the human body and contribute to defense, metabolism, and nutrition (HMPC 2012). The amount that is unknown in this field is truly vast. The rapidly growing understanding of the wide range of microbial impacts on human health comes in large part from linking knowledge of microbial natural history with details observable at the macroscopic scale (Ley et al. 2006). As ecologists catalog the diversity of microbes in various habitats and disease states within the body, clinical researchers will use this knowledge, along with information on the natural history of the microbes—their behaviors and defenses against their natural enemies—to design new therapies. Equally important is the growing understanding of the powerful role that microbes play in mediating plant traits. Endophytic fungi, in particular, are now known to form mutualistic symbioses with an enormous number of plants, which mediate interactions with herbivores, pathogens, and the abiotic environment (Strobel and Daisy 2003). Bringing a natural history, organism-centered ethos to the study of microbial life will provide context-specific knowledge of which microbes are present in particular environments and how they interact with their surroundings both within and outside the human body.

The capacity to build networks of natural history collections on a global scale has never been greater, and this capacity is only just beginning to be realized. There is now a wide range of efforts to collect and curate natural history information in a standardized manner at global scales (box 5). These programs, coupled with the widespread availability of remote-sensing technologies, allow observers to study large-scale phenomena across ecosystems in ways that were previously unimaginable. Indeed, current technologies provide huge opportunities to build a united understanding of complex processes that interact over a wide range of scales. A key challenge moving forward will be the intelligent integration of field-collected natural history information to facilitate studies across disciplines. Global natural history will require collective efforts by professional societies, museums, universities,

Box 5. Natural history and the digital revolution.

Technology influences how we observe, organize, and share information about the natural world. Here, we highlight programs that use technology to change the way we see the world and programs that organize and standardize the collection and curation of natural history information.

The democratization of natural history information

An increasing number of digital platforms are focused on dramatically expanding participation in the collection, curation, and exchange of natural history information. These platforms represent a fundamental shift away from private records and individual papers and toward a more collaborative approach to observing and understanding our world. Many sites are now dedicated to organizing citizen science projects within and across disciplines, and the number of natural history projects is growing rapidly and includes camera-trap photo identification, online transcription of museum records, and the identification of whale and bat sounds. The growth in citizen science can be seen in platforms such as iNaturalist and iSpot and in taxonomy-focused efforts, such as eBird. These platforms combine a social-media interface with crowd-sourced identification. The iNaturalist platform alone currently hosts over 850 projects.

Going big and getting organized

Big-data efforts to standardize the collection, curation, and dissemination of natural history information are beginning to shift the focus of natural history toward collaborative projects and platforms.

Global Biodiversity Information Facility. The Global Biodiversity Information Facility (GBIF) is a global repository for natural history information, focused on providing open-access data on biodiversity, particularly the vast holdings of specimens and data distributed across natural history museums worldwide. Through a global network of countries and organizations, the GBIF promotes and facilitates the mobilization, access, discovery, and use of information about the occurrence of organisms over time and across the planet.

Encyclopedia of Life. The Encyclopedia of Life is an easy-to-search and freely available compendium of natural history information on thousands of species from around the world. Its content is contributed by members, including the lay public, and reviewed by curators. The total number of pages with content is currently more than 1.3 million.

Map of Life. The Map of Life is a global collection of species-distribution data, currently housing over 365 million records from almost 800,000 species and providing mapping tools and area-specific species lists for anywhere on the globe. The Map of Life is designed to provide a platform and tool set for the development and analysis of species-distribution maps across all taxa.

Vital Signs. Integrating ecosystem service and biodiversity monitoring from an agricultural perspective at local to continental scales, Vital Signs uses standardized, targeted collection of natural history information to build explicit links between biodiversity and human well-being.

USA National Phenology Network. The USA National Phenology Network is a national clearinghouse for data sets focused on the timing of events in nature, from blooming times in plants to migration timing in animals. The platform hosts citizen science projects, curates global data on phenology, and organizes phenological research for a wide range of applications.

FishBase. FishBase is an international online database of the world's fishes. This collaborative effort bridges ecological, genetic, zoological, biogeographical, conservation, and commercial information. It is commonly cited in peer-reviewed literature and used as a management tool.

nongovernmental organizations, and international bodies. Particular attention will need to be given to issues of collaborative structures and to incentives for participation and for the maintenance, quality, and provenance of data.

The current capacity of humanity to alter the planet's natural systems has created an unprecedented need for ecological forecasting (Luo et al. 2011). Empirical information about complex natural systems is fundamental to accuracy in forecasting (Hastings and Wysham 2010), and natural history provides this essential baseline information against which to measure the reality and scope of change (Winker 2004). Although the capacity of scientists to model complex systems is now greater than during any period in history, the collection and organization of basic information needed to parameterize these increasingly complex models have not kept pace (Botkin et al. 2007). As a result, a lack of basic natural history knowledge is often the limiting factor in the development of predictive ecological theory. The behavior of complex environmental systems cannot be predicted with simple models, and complex models cannot be built without empirical knowledge of organisms under realistic conditions. Meeting this challenge requires a greater investment in the organization, integration, and dissemination of current natural history knowledge within and outside of traditional collections (Suarez and Tsutsui 2004, Winker 2004, Hampton et al. 2013). Identifying and filling critical gaps in that knowledge will likely be a multiscaled effort involving both historical and contemporary natural history.

The rapid spread of consumer technologies—most notably, the rise of smartphones—is expanding opportunities for participation in biodiversity science, allowing broad partnerships through social networks, collective species discovery, and the real-time mapping of species and communities (see box 5 for examples). The vitality of natural history will depend on its capacity to build broad collaborative efforts using technological advances to lower the barriers associated with collecting, analyzing, and sharing natural history knowledge. The rapid growth in citizen science has the potential to yield a large increase in the number of people helping to build natural history knowledge, and this ethos of collaboration and public participation needs to permeate natural history research, outreach, and education. An outstanding example of the potential for this approach is provided by eBird, a Web-based program developed by the Cornell Lab of Ornithology that has capitalized on the widespread interest in and appeal of birds. The program has witnessed a rapid, global increase in data contributors and users, which has enabled both researchers and the general public to benefit in diverse ways from technologies for the collection, organization, and dissemination of vast numbers of bird observations. Successful programs on other taxa, such as eButterfly and the Lost Ladybug Project, illustrate that birds are not unique in their ability to engage the public in documenting and compiling natural history data.

Conclusions

A renewed focus on the natural history of organisms is central to the growth of basic and use-inspired research and is also a critical step toward sustainable management and toward providing increased predictive capacities and improved outcomes across disciplines as diverse as health, agriculture, and conservation. However, natural history in the twenty-first century will look different from that of the nineteenth as this fundamental knowledge is applied to new frontiers and as new technologies are used in the practice of natural history. Despite these differences, however, the importance of natural history to science and society remains timeless.

Acknowledgments

This work was supported by National Science Foundation grant no. DEB 1025591 to JJT, KR, and Thomas L Fleischner; a matching grant from the College of the Environment at the University of Washington to JJT and KR; and further support from Prescott College, The Doug and Maggie Walker Chair in Natural History, and the National Center for Ecological Analysis and Synthesis to JJT. The manuscript was initiated as a part of the Natural History Initiative (*http://naturalhistoryinitiative.net*) and was improved by discussions with and reviews by Nancy Baron, Harry Greene, Jonathon Losos, Scott Sampson, Ruth Ley, and Kevin Winker. Artwork was generously provided by Hannah Viano (*http://devilspursediary.com*). Thanks to Barbara Thiers and the New York Botanical Garden for data on global herbaria.

Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/biu032/-/DC1*. AIBS has also made available for a limited time a moderated discussion forum at *www.access.aibs.org/group/overview*.

References cited

Abt KL, Prestemon JP, Gebert KM. 2009. Wildfire suppression cost forecasts for the US Forest Service. Journal of Forestry 107: 173–178.

Albuquerque UP, Ramos MA, Melo JG. 2012. New strategies for drug discovery in tropical forests based on ethnobotanical and chemical ecological studies. Journal of Ethnopharmacology 140: 197–201.

Arnold SJ. 2003. Too much natural history, or too little? Animal Behaviour 65: 1065–1068.

Bailey KM. 2011. An empty donut hole: The great collapse of a North American fishery. Ecology and Society 16 (art. 28).

Balmford A, Beresford J, Green J, Naidoo R, Walpole M, Manica A. 2009. A global perspective on trends in nature-based tourism. PLOS Biology 7 (art. e1000144).

Bartholomew GA. 1986. The role of natural history in contemporary biology. BioScience 36: 324–329.

Beeton AM. 1960. The vertical migration of *Mysis relicta* in Lakes Huron and Michigan. Journal of the Fisheries Research Board of Canada 17: 517–539.

Bolen EG. 2000. Waterfowl management: Yesterday and tomorrow. Journal of Wildlife Management 64: 323–335.

Botkin DB, et al. 2007. Forecasting the effects of global warming on biodiversity. BioScience 57: 227–236.

Caltagirone LE, Doutt RL. 1989. The history of the vedalia beetle importation to California and its impact on the development of biological control. Annual Review of Entomology 34: 1–16.

Calvo-Alvarado J, McLennan B, Sánchez-Azofeifa A, Garvin T. 2009. Deforestation and forest restoration in Guanacaste, Costa Rica: Putting conservation policies in context. Forest Ecology and Management 258: 931–940.

[CCA] Council of Canadian Academies, Expert Panel on Biodiversity Science. 2010. Canadian Taxonomy: Exploring Biodiversity, Creating Opportunity. CCA.

Coley PD, et al. 2003. Using ecological criteria to design plant collection strategies for drug discovery. Frontiers in Ecology and the Environment 1: 421–428.

Colwell RR, Huq A. 1994. Vibrios in the environment: Viable but nonculturable *Vibrio cholerae*. Pages 117–133 in Wachsmuth IK, Blake PA, Olsvik O, eds. *Vibrio cholerae* and Cholera: Molecular to Global Perspectives. American Society for Microbiology.

Colwell RR, et al. 2003. Reduction of cholera in Bangladeshi villages by simple filtration. Proceedings of the National Academy of Sciences 100: 1051–1055.

Donovan GH, Brown TC. 2007. Be careful what you wish for: The legacy of Smokey Bear. Frontiers in Ecology and the Environment 5: 73–79.

Evenson RE, Gollin D. 2003. Assessing the impact of the Green Revolution, 1960 to 2000. Science 300: 758–762.

Fausch, KD, Northcote TG. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49: 682–693.

Garrett L. 1995. The Coming Plague: New Emerging Diseases in a World Out of Balance. Penguin.

Greene HW. 2005. Organisms in nature as a central focus for biology. Trends in Ecology and Evolution 20: 23–27.

Greene HW, Losos JB. 1988. Systematics, natural history, and conservation: Field biologists must fight a public-image problem. BioScience 38: 458–462.

Grier JW. 1982. Ban of DDT and subsequent recovery of reproduction in bald eagles. Science 218: 1232–1235.

Griscom HP, Ashton MS. 2011. Restoration of dry tropical forests in Central America: A review of pattern and process. Forest Ecology and Management 261: 1564–1579.

Hampton SE, Strasser CA, Tewksbury JJ, Gram WK, Budden AE, Batcheller AL, Duke CS, Porter JH. 2013. Big data and the future of ecology. Frontiers in Ecology and the Environment 11: 156–162.

Hastings A, Wysham DB. 2010. Regime shifts in ecological systems can occur with no warning. Ecology Letters 13: 464–472.

Helson JE, Capson TL, Johns T, Aiello A, Windsor DM. 2009. Ecological and evolutionary bioprospecting: Using aposematic insects as guides to rainforest plants active against disease. Frontiers in Ecology and the Environment 7: 130–134.

Herman SG. 2002. Wildlife biology and natural history: Time for a reunion. Journal of Wildlife Management 66: 933–946.

[HMPC] Human Microbiome Project Consortium. 2012. Structure, function and diversity of the healthy human microbiome. Nature 486: 207–214.

Horton TR, van der Heijden MGA. 2008. The role of symbioses in seedling establishment and survival. Pages 189–214 in Leck MA, Parker VT, Simpson RL, eds. Seedling Ecology and Evolution. Cambridge University Press.

Hunter LA. 1988. Status of the endemic Atitlan grebe of Guatemala: Is it extinct? Condor 90: 906–912.

Huntington HP. 2000. Using traditional ecological knowledge in science: Methods and applications. Ecological Applications 10: 1270–1274.

Huq A, Xu B, Chowdhury MAR, Islam MS, Montilla R, Colwell RR. 1996. A simple filtration method to remove plankton-associated *Vibrio cholerae* in raw water supplies in developing countries. Applied and Environmental Microbiology 62: 2508–2512.

Johnson KG, et al. 2011. Climate change and biosphere response: Unlocking the collections vault. BioScience 61: 147–153.

Jordan DS. 1916. Plea for old-fashioned natural history. Bulletin of the Scripps Institution for Biological Research 1: 3–6.

LaBastille A. 1983. Drastic decline in Guatemala's giant pied-billed grebe population. Environmental Conservation 10: 346–348.

Lavoie C. 2013. Biological collections in an ever changing world: Herbaria as tools for biogeographical and environmental studies. Perspectives in Plant Ecology Evolution and Systematics 15: 68–76.

Ley RE, Peterson DA, Gordon JI. 2006. Ecological and evolutionary forces shaping microbial diversity in the human intestine. Cell 124: 837–848.

Lobitz B, Beck L, Huq A, Wood B, Fuchs G, Faruque ASG, Colwell R. 2000. Climate and infectious disease: Use of remote sensing for detection of *Vibrio cholerae* by indirect measurement. Proceedings of the National Academy of Sciences 97: 1438–1443.

Louv R. 2008. Last Child in the Woods: Saving Our Children from Nature-Deficit Disorder. Algonquin Books.

Luo YQ, Ogle K, Tucker C, Fei SF, Gao C, LaDeau S, Clark JS, Schimel DS. 2011. Ecological forecasting and data assimilation in a data-rich era. Ecological Applications 21: 1429–1442.

McCallum ML, McCallum JL. 2006. Publication trends of natural history and field studies in herpetology. Herpetological Conservation and Biology 1: 62–67.

Nepstad DC, Uhl C, Serrao EAS. 1990. Surmounting barriers to forest regeneration in abandoned, highly degraded pastures: A case study from Paragominas, Para, Brazil. Pages 215–229 in Anderson AB, ed. Alternatives to Deforestation: Steps toward Sustainable Use of the Amazon Rain Forest. Columbia University Press.

Newman DJ, Cragg GM, Snader KM. 2003. Natural products as sources of new drugs over the period 1981–2002. Journal of Natural Products 66: 1022–1037.

Noss RF. 1996. The naturalists are dying off. Conservation Biology 10: 1–3.

Pergams ORW, Zaradic PA. 2008. Evidence for a fundamental and pervasive shift away from nature-based recreation. Proceedings of the National Academy of Sciences 105: 2295–2300.

Pretty JN, Noble AD, Bossio D, Dixon J, Hine RE, de Vries FWT, Morison JIL. 2006. Resource-conserving agriculture increases yields in developing countries. Environmental Science and Technology 40: 1114–1119.

Schmidly DJ. 2005. What it means to be a naturalist and the future of natural history at American universities. Journal of Mammalogy 86: 449–456.

Slocum MG. 2000. Logs and fern patches as recruitment sites in a tropical pasture. Restoration Ecology 8: 408–413.

Spencer CN, McClelland BR, Stanford JA. 1991. Shrimp stocking, salmon collapse, and eagle displacement. BioScience 41: 14–21.

Stafford R, Santer RD, Rind FC. 2007. The role of behavioural ecology in the design of bio-inspired technology. Animal Behaviour 74: 1813–1819.

Strobel G, Daisy B. 2003. Bioprospecting for microbial endophytes and their natural products. Microbiology and Molecular Biology Reviews 67: 491–502.

Suarez AV, Tsutsui ND. 2004. The value of museum collections for research and society. BioScience 54: 66–74.

Sunderland ME, Klitz K, Yoshihara K. 2012. Doing natural history. BioScience 62: 824–829.

Thiers B, ed. 2014. Index Herbariorum: A Global Directory of Public Herbaria and Associated Staff. New York Botanical Garden. (28 January 2014; *http://sciweb.nybg.org/science2/IndexHerbariorum.asp*)

Thurgood L, Golladay MJ, Hill ST. 2006. U.S. Doctorates in the 20th Century. National Science Foundation. Report no. NSF 06-319.

Ward DF. 2012. More than just records: Analysing natural history collections for biodiversity planning. PLOS ONE 7 (art. e50346).

Watanabe M, Adams RM, Wu J, Bolte JP, Cox MM, Johnson SL, Liss WJ, Boggess WG, Ebersole JL. 2005. Toward efficient riparian restoration: Integrating economic, physical, and biological models. Journal of Environmental Management 75: 93–104.

[WHO] World Health Organization. 2011. The control of neglected zoonotic diseases. WHO. (28 January 2014; *www.who.int/zoonoses/control_neglected_zoonoses/en/index.html*)

Wilcove DS, Chen LY. 1998. Management costs for endangered species. Conservation Biology 12: 1405–1407.

Wilcove DS, Eisner T. 2000. The impending extinction of natural history. Chronicle of Higher Education 47: B24.

Winker K. 2004. Natural history museums in a postbiodiversity era. BioScience 54: 455–459.

Joshua J. Tewksbury (jtewksbury@wwfint.org) is affiliated with the Department of Biology and the College of the Environment at the University of Washington, in Seattle, and with the Luc Hoffmann Institute at World Wide Fund for Nature International, in Gland, Switzerland. John G. T. Anderson is affiliated with the College of the Atlantic, in Bar Harbor, Maine. Jonathan D. Bakker, Peter W. Dunwiddie, and Liam Stacey are affiliated with the School of Environmental and Forest Sciences, and PWD, Timothy J. Billo, Noelle J. Machnicki, and Kirsten Rowell are affiliated with the Department of Biology at the University of Washington. KR is also affiliated with the Burke Museum of Natural History and Culture at the University of Washington. Martha J. Groom is affiliated with the School of Interdisciplinary Arts and Sciences at the University of Washington Bothell and with the Department of Biology and the College of the Environment at the University of Washington. Stephanie E. Hampton is affiliated with the National Center for Ecological Analysis and Synthesis, at the University of California, Santa Barbara. Steven G. Herman is affiliated with The Evergreen State College, in Olympia, Washington. Douglas J. Levey is affiliated with the National Science Foundation, in Arlington, Virginia. Carlos Martínez del Rio is affiliated with the Biodiversity Institute and the Berry Biodiversity Conservation Center, at the University of Wyoming, in Laramie. Mary E. Power is affiliated with the Department of Integrative Biology at the University of California, Berkeley. Anne K. Salomon is affiliated with the School for Resource and Environmental Management at Simon Fraser University, in Burnaby, British Columbia, Canada. Terry A. Wheeler is affiliated with the Department of Natural Resource Sciences at McGill University, in Ste-Anne-de-Bellevue, Québec, Canada. Stephen C. Trombulak is affiliated with the Department of Biology at Middlebury College, in Middlebury, Vermont.