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FROM MUSEUM CASES TO THE CLASSROOM: EMERGING OPPORTUNITIES FOR SPECIMEN-BASED EDUCATION

Joseph A. Cook[1], Eileen A. Lacey[2], Stefanie M. Ickert-Bond[3], Eric P. Hoberg[4], Kurt E. Galbreath[5], Kayce C. Bell[1], Stephen E. Greiman[1], Bryan S. McLean[1], Scott Edwards[6]

[1]*Museum of Southwestern Biology and Department of Biology, University of New Mexico*

[2]*Museum of Vertebrate Zoology and Department of Integrative Biology, University of California*

[3]*Museum of the North and Department of Biology and Wildlife, University of Alaska*

[4]*United States National Parasite Collection, Agricultural Research Service, USDA*

[5]*Department of Biology, Northern Michigan University*

[6]*Museum of Comparative Zoology, Harvard University*

Corresponding author: Joseph A. Cook, *cookjose@unm.edu*

The value of museum collections to biological research is well established. However, the role and potential of collections in educational activities has been less thoroughly explored, due in part to concerns about making fragile specimens available to large numbers of students. Now, global efforts to digitize museum collections are creating unprecedented opportunities for educators to employ the vast resources contained in such collections and to engage students directly in the process of natural history and biodiversity research. These emerging opportunities have the potential to become prominent elements of biological education because they provide authentic, inquiry-based learning activities that can be tailored to be relevant to local biodiversity studies (i. e., place-based). In sum, the amazing wealth of biological information contained in natural history collections that was previously available to only a few can now be readily incorporated into exciting, important lessons about fundamental biological concepts. To illustrate how museum collections can be used to design activities that encourage active, integrative exploration of biology, we provide several examples drawn from our own efforts to promote the use of natural history collections in undergraduate education. As digital archives improve and awareness of the instructional power of these materials increases, we expect that the greater use of museum specimens in educational programs will generate renewed efforts to build and to maintain these critical resources.

ИЗ МУЗЕЙНЫХ ШКАФОВ В АУДИТОРИЮ: ВОЗМОЖНОСТИ ПРЕПОДАВАНИЯ НА ОСНОВЕ МУЗЕЙНЫХ ОБРАЗЦОВ

Джозеф Кук, Эйлен Лэйси, Стефани Айкерт-Бонд, Эрик Хоберг, Кёрт Гэлбрит, Кейс Белл, Стефен Греймэн, Брайан МакЛин, Скотт Эдвардс

Автор для переписки: Джозеф Кук, *cookjose@unm.edu*

Значение музейных коллекций для биологических исследований хорошо известно. Однако роль и возможности коллекций в образовательной деятельности не столь глубоко исследованы, отчасти вследствие проблемы предоставления хрупких экземпляров в распоряжение большого числа учащихся. В настоящее время глобальные усилия по оцифровке музейных коллекций создают беспрецедентные возможности преподавателям использовать огромные ресурсы, содержащиеся в таких коллекциях, и включать студентов непосредственно в процесс исследований в области естественной истории и биоразнообразия. Эти возрастающие возможности имеют хорошие перспективы сделать коллекции важным элементом биологического образования, поскольку позволяют основывать учебную работу на аутентичной исследовательской деятельности и подключать её к исследованиям по биоразнообразию в данной местности. В целом, потрясающий объём информации, содержащейся в естественнонаучных коллекциях, который ранее был доступен лишь немногим, теперь может быть легко включён в захватывающие и важные уроки, посвящённые фундаментальным биологическим концепциям. Чтобы показать, как музейные коллекции могут использоваться в организации деятельности с целью поощрения активного всеохватного изучения живого, мы приводим несколько примеров, заимствованных из наших собственных подходов, направленных на содействие использованию естественнонаучных коллекций в преддипломном обучении. Мы полагаем, что с ростом цифровых архивов и ознакомлением с обучающей действенностью этих материалов, более широкое использование музейных экземпляров в образовательных программах приведёт к возобновлению усилий по развитию и поддержанию этих важных источников информации.

1. Introduction

Natural history collections are one of the most powerful resources available for documenting the effects of changing environmental conditions on global biodiversity. Worldwide, more than 1.5 billion specimens (Ariño, 2010) are contained in natural history museums. These materials, collected over vast temporal and spatial scales, represent an irreplaceable record of floral and faunal diversity, a substantial proportion of which no longer exists and thus cannot be resampled. Accordingly, the information contained in natural history collections is an invaluable source of information regarding spatial and temporal patterns of organismal diversity.

To harness the full power of natural history collections, it is critical that museum scientists engage teachers and students to understand the value of these resources for addressing scientific questions and societal issues. In addition to improving understand-

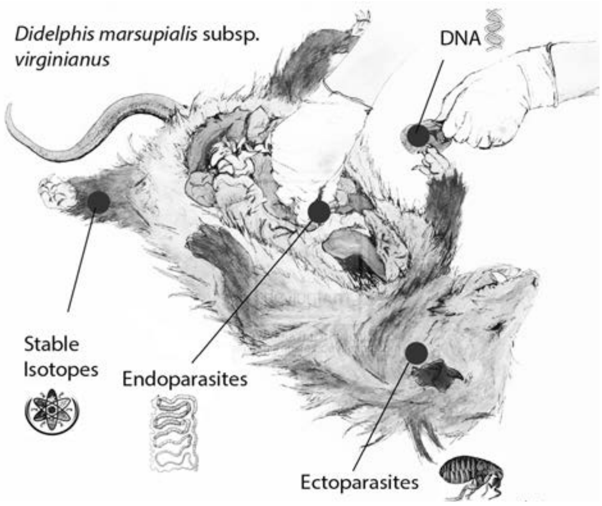

Fig. 1. Holistic specimens are now routinely preserved in ways that allow multiple investigators from diverse subdisciplines in biology to explore important questions, all centered around a single specimen.

Рис. 1. В настоящее время цельные экземпляры стандартно сохраняются в такой форме, которая позволяет многим исследователям разных биологических специальностей выяснять важные вопросы, обращаясь к одному и тому же экземпляру.

ing of the natural world, such efforts are essential to producing scientists, educators, and citizens capable of addressing the many challenges facing humans now and in the future. Specimen collections provide a rich resource in the form of field-collected (original) data, but the specimens themselves further serve as the basis for generating new (derivative) data in critical sample-based studies (Fig. 1). *Original data* (e. g., species identity, date of collection, georeferenced collection locality, standard specimen measurements) can immediately inform biodiversity assessments and models used to project and mitigate the response of organisms to future conditions. *Derivative data*, such as gene sequences, stable isotope ratios, high-dimensional morphometric data and parasite-host associations, are now routinely acquired from specimens in subsequent research projects and available for analysis as long as specimens and materials are preserved. Because many museums are now tracking and linking the web-accessible datasets that host derivative data, a powerful, highly integrative and now freely available resource on biodiversity and related environmental conditions is emerging for investigators and educators alike. The question is: How can we mobilize this rich and ever-expanding data source to address pressing societal issues?

To find solutions for global challenges, such as those relating to changing environmental conditions (e. g., threats to food security, emerging pathogens, loss of biodiversity), and to fully exploit the potential of specimen-based data archives, we need to think strategically about how to develop an informed and creative future work force. Fortunately, natural history collections provide numerous opportunities for educators to engage students in original, data-driven ex-

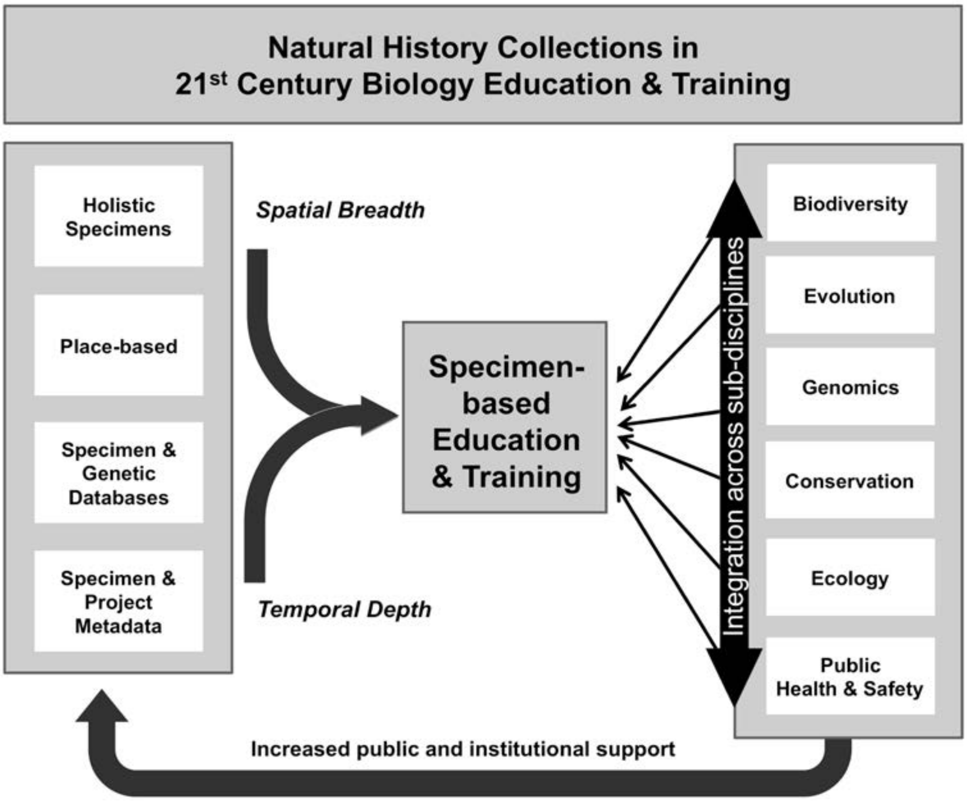

Fig. 2. Each museum specimen can be the basis for significant new or derived datasets to address diverse sets of scientific questions (e. g., stable isotopes ecology, molecular genetics, parasitology). Because these diverse studies are all tied together through a single voucher specimen, educators and students can more easily understand how diverse perspectives can be integrated for a more holistic understanding of biology.

Рис. 2. Каждый музейный экземпляр может служить основой для значимых оригинальных или вторичных данных, позволяющих решать разнообразные исследовательские задачи (например, экология на основе анализа стабильных изотопов, молекулярная генетика, паразитология). Поскольку все эти разнообразные исследования связаны между собой посредством единого удостоверяющего экземпляра, преподаватели и студенты могут легче понять, каким образом разные исследования могут быть объединены для более целостного понимания живого.

ercises that encompass the biological knowledge, analytical abilities, and computational skills required to shape responses to looming real-world problems. The educational potential of natural history collections is particularly powerful given the authenticity of the specimens that form the core of these resources. As tangible, physical records of biodiversity, museum specimens have an unparalleled ability to intrigue and excite students of all backgrounds and programs of study.

To illustrate the value of museum resources to undergraduate education, we outline three themes that provide excellent opportunities for educators to use natural history specimens and data in their lessons. As part of these discussions, we indicate how museum resources provide novel, integrative, and highly collaborative opportunities to develop new strategies for biology education (Fig. 2). We encourage museum scientists, even those without formal classroom responsibilities, to promote the use of natural history collections for educational purposes. These efforts will serve to produce better trained and more integrative scientists, health practitioners, and policy makers; they will also serve to increase general understanding of the importance of natural history collections, thereby helping to ensure that these critical repositories of biodiversity remain vital, active and ever expanding.

2. Digital museum resources

Specimen-based databases, such as GBIF, iDigBio, MorphBank, Map of Life, and GenBank, are profoundly changing how biologists conduct research and share their data (Wen et al., 2015; Buerki, Baker, 2016). Large-scale digitization of museum data andspecimen images (Beaman, Celinese, 2012; Smith, Blagoderov, 2012) increases availability of data worldwide through initiatives such as the Global Biodiversity Informatics Facility (GBIF). Many countries also have national digitization initiatives (e. g., iDigBio in the United States of America) and these provide incredible opportunities to develop new educational modules and let students explore our planet's diversity. New bioinformatics resources (e. g., Map of Life; Jetz et al., 2012) also are making use of specimen data.

Digitized original data provide an accessible gateway for young scientists to learn about the challenges of using big data and the ways in which large and diverse datasets can be integrated into their studies (Cook et al., 2014). As students are exposed to the complexity of the planet's biodiversity, they can develop and pursue their own research questions in evolutionary and environmental biology. An increasing recognition of the value of inquiry-based approaches to education, as opposed to passive-learning models (e. g., Feldman et al., 2012), further motivates efforts to incorporate natural history specimens and the diversity that they document into educational initiatives.

3. Natural history resources and education

There are numerous ways that specimens and associated data can fit into undergraduate and graduate educational initiatives, from mining raw data for student biodiversity lessons, to independent phylogeographic or phylogenetic analyses from associated genetic data derived from specimens, to the possibility of helping to identify specimens online or create new metadata for existing specimens (e. g., Notes From Nature, http://www.notesfromnature.org). However, the use of these new databases by teachers remains limited and needs further encouragement from the museum community. One serious impediment is the lack of intuitive, user-friendly portals or publicly accessible interfaces for museum collections.

There also are relatively few examples of widely distributed and freely accessible lesson plans that successfully incorporate specimens. This presents excellent opportunities to develop educational modules (Cook et al., 2014) and implement approaches that take advantage of the vast new datasets managed by natural history collections. New tools for educators should enhance access, analysis, and visualization of specimen data. The collections resource must engage teachers worldwide and find ways to encourage participation in building and using collections through guided collections-based research by students. This will ultimately contribute to a more informed citizenry.

Examples of ways in which museum resources can be used to create exciting, authentic learning experiences include the following.

3.1. Understanding our changing world: Natural history collections, climate change, and biodiversity

The current, unprecedented rate of change in global climates represents a significant threat to biodiversity. This includes not just the loss of existing taxa, but also the assembly of new communities of organisms, some of which are expected to have negative consequences for humans (e. g., emerging pathogens). Both of these topics are commonly encountered in the popular media; however, many students may not have considered them beyond an abstract level. It is thus important that educators convey the utility of natural history collections and their associated data sets as critical tools for discovering, understanding, and ideally developing well-informed strategies for mitigating negative effects of these changes.

In response to changing climatic conditions, species may move, adapt, or go extinct (Parmesan, 2006). Each of these responses can be explored using natural history collections data. First, specimen locality data from different points in time can be correlated with temperature changes and used to investigate climate-related range shifts. Comparisons of trapping localities for small mammals captured in the Sierra Nevada Mountains of California have revealed sometimes profound changes in the elevational distributions of these animals over the past century (Moritz et al., 2008) coincident with temperature increase, but there are also idiosyncratic shifts among species and localities (Moritz et al. 2008; Rowe et al., 2015). This, in turn, reiterates the importance of broad geographic sampling contained in natural history collections.

Second, characterization of phenotypic, genotypic and/or phenological variation over time can identify potential *in situ* adaptation to changing conditions (Hoffmann, Sgró, 2011). Herbarium specimens, for example, can provide insight into shifts in flowering time, a key character related to individual plant fitness and fitness of associated organisms such as pollinators, herbivores, and parasites. With many (but not all) plant species flowering earlier in response to warming conditions (Primack et al., 2004; Panchen et al., 2012), changes in flowering phenology may have cascading effects on ecosystem function. Museum data highlight these floral resources for pathogens and pollinators, as well as information on insect emergence, bird, bat, and insect migration, seed dispersal, and timing of reproduction. Understanding phenological changes has particular significance for agriculture and is directly related to food security.

Finally, integration of specimen locality data with ecological niche modeling can provide insight into potential fates of species at specific localities in the face of changing environmental conditions; application of this analytical strategy to locality records for birds (Thomas et al., 2004) suggests the potential for climate-driven extinction of up to 37% of the species examined. Using museum records, Hope et al. (2013) also used predictive modeling to assess future distribution of tundra plant communities and associated shrews (*Sorex* spp.) in Alaska. In sum, the multifaceted data contained in natural history collections are central to efforts to describe and predict the diverse impacts of changing global climates. Given the scale and anticipated catastrophic outcomes of the climatic changes now underway, it is imperative that we prepare students to investigate and to develop solutions to these challenges. Natural history collections provide a logical and compelling foundation for inquiry-driven learning experiences designed to provide that training. Examples of such activities are provided by Lacey et al. (in review), who have developed a series of web-based educational exercises that harness the power of digital museum resources to examine responses of Sierra Nevadan small mammals to a century of environmental change. These exercises are only a starting point; although a complete series of activities in their own right, they can be easily modified to fit the specific needs of different instructional settings. Learning how to investigate the temporally deep educational resource held in museum collections provides students with perspectives on how organisms and ecosystems will respond to changing climate.

3.2. Learning about emerging parasites and pathogens through museum collections

Parasites in the broad sense, including viruses, bacteria, protozoans, fungi, helminths, and arthropods, are often obscure to students and certainly are among the most underappreciated components of biological systems. Incongruously, however, these organisms collectively represent in excess of 40–50% of species on Earth, play a role in at least 75% of trophic junctions within food webs (Dobson et al., 2008), and are significant mediators of health and well-being for people and animals. Their influence bears on food sustainability, food security and safety, socioeconomic development, and the integrity of ecological structure and ecosystem services that contribute to continuity and connectivity in the biosphere (Brooks et al., 2014).

The myriad ways in which parasites interact with their environment create compelling pathways for students to learn about fundamental biological phenomena. For example, patterns of geographic distribution and host association among parasites offer unique insights into both natural and anthropogenic processes that have structured biodiversity over deep history (e. g., Hoberg, 1997, 2010). These observations open windows into changing patterns of distribution and emergence of pathogens in contemporary time (e.g., Huberg, Brooks, 2008, 2015), providing access points for students to learn about rapidly emerging and interacting crises linking global climate, burgeoning human populations, environment, ecological disruption, species loss, and emergent diseases (Brooks, Hoberg, 2013). For example, as in the ecological niche modeling above, disease vectors (e. g. ticks) are predicted to have range shifts corresponding to changing climate (Brownstein et al., 2005; Gray et al., 2009), which can be modeled using museum specimen data.

Specimen-derived parasite data provide opportunities for students to make novel discoveries. Parasites often interact with other parasites or harbor their own endosymbionts that may not harm their parasite host, but may harm the vertebrate host of the parasite. Key examples include the endosymbiotic bacteria *Wolbachia* and *Neorickettsia*. *Wolbachia* are endosymbionts of filarial nematodes that are essential to the normal development and fertility of the nematodes. However, when the filarial nematodes are targeted by anti-filarial drugs, the bacteria are released from the nematode host and cause the pathology seen in diseases such as river blindness (Onchocerciasis; see Taylor et al., 2005). *Neorickettsia* are obligate intracellular endosymbionts of parasitic flukes (*Digenea*) and pass through the entire complex life cycle of the parasite

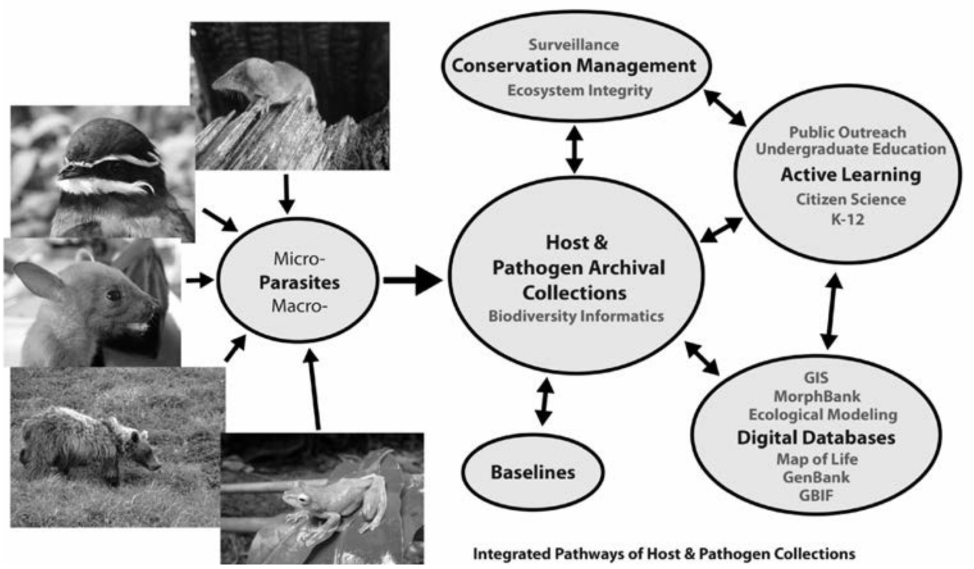

Fig. 3. Parasite specimens, when combined with their hosts, provide integrated pathways for students to learn about the relationships between research, public health and mitigation.

Рис. 3. Экземпляры паразитов, рассматриваемые совместно с их хозяевами, позволяют студентам получить целостное представление о связях между наукой, здравоохранением и профилактикой.

by vertical transmission. In some cases, neorickettsiae are transmitted horizontally from digeneans to their definitive vertebrate hosts where the bacteria can infect leucocytes and cause debilitating disease in horses, dogs, and humans (Vaughan et al., 2012). With the advent of next generation sequencing, it is possible to sensitively and conclusively detect such endosymbionts. Publishing these large sequence datasets in databases like GenBank enables students to conduct their own research to discover pathogenic endosymbionts, potentially known or unknown but often in as yet undetected hosts.

Finally, burgeoning amounts of host genetic data can also be integrated with parasite occurrence records to educate students on emerging infectious diseases. For example, the spread of white-nose syndrome, a fungal disease affecting North American cave-dwelling bats, was partially predicted by the degree of interconnection of certain bat populations to other species in their respective ecological communities (Wilder et al., 2015). Where host genetic data are properly linked to spatially-defined museum specimens, similar investigations using other organisms and infection scenarios are possible. Parasite collections with online databases linking host and parasite data offer an extraordinary resource for educators to introduce students to biological complexity (Fig. 3). For example, georeferenced specimens can be used to generate ecological niche models to examine possible scenarios for environmental change and the distribution of disease (Waltari, Perkins, 2010). Records with host association data can validate predictions about biological outcomes of ongoing geographic colonization and host switching (e. g., Hoberg et al., 2013; Kutz et al., 2013; Laaksonen et al., 2015).

To date, few parasite collections meet their full potential as resources for student training. This result may be driven by problems with data quality (e. g., incomplete host or geographic data associated with parasite records), but is more often a consequence of database limitations that create barriers to creative manipulation of the information housed within. Issues of data quality can be partially addressed with more widespread implementation of standardized field collection protocols that effectively record and track host and parasite data. One such strategy for investigating complex host-parasite systems (Hoberg et al., 2015) codifies approaches for biodiversity informatics, linking field collections, archived specimens, and derivative data acquired from museum resources. Moreover, involving students directly in specimen-based biological surveys creates powerful hands-on learning opportunities that can foster a lifelong fascination with diversity and the complexity of biological interactions.

3.3. Using museum collections to engage educators in rural and indigenous communities

Museum collections are especially valuable for developing so-called “place-based” lessons in which educators can use locally and culturally relevant examples to teach new skills and essential biological principles. Advancing the Integration of Museums into Undergraduate Programs (AIM-UP!) was a network of museum scientists and educators that examined ways to increase the use of natural history collections in undergraduate education. One set of modules (aimup.unm.edu) developed for the rural communities of the Alexander Archipelago of Southeast Alaska uses fundamental concepts from island biogeography to explore patterns and processes of diversity across this vast set of islands that differ in size, distance to mainland and geologic history. Because young people in these small communities already know many of the local organisms, these lessons have readily engaged students in authentic exploration of their surroundings and their research projects emerging from these lessons have been recognized in Alaska statewide science competitions.

Rural populations can contribute to building significant collections and monitor changes due to their subsistence lifestyles in difficult to access areas. By building broad networks across these communities through meaningful educational engagement, museums can gain access to large-scale geographic sampling. A number of efforts are now underway to engage rural communities in monitoring change (Sigman, 2015); however, most of these efforts are observational and do not result in permanent archives of specimens. In the 1990’s we (Cook et al., 1999) established long-term collaborations between Native-organized subsistence commissions and the University of Alaska Museum to help build a temporally deep and spatially broad archive of marine mammal specimens. We also partnered with local high schools to explore changes in small mammal communities over time. These efforts had strong community and student engagement and over time resulted in significant series of mammals for scientific study. Both the original and subsequent derivative data are now available on-line (arctos.database.museum) so that rural students can explore how local specimens have fostered new scientific insights.

Students from rural communities have potential to make meaningful scientific contributions with far-reaching impacts, and the experience of participating in such work can have equally profound consequences for student life trajectories. For example, high-latitude communities are experiencing accelerating environmental change in some of the most sensitive environments on the planet. Ongoing survey and inventory of complex northern ecosystems has already demonstrated substantial ecological perturbation in marine and terrestrial habitats (e. g., Hoberg et al., 2013; Kutz et al., 2013; Meltofte et al., 2013; Dudley et al., 2015; Hoberg, Brooks 2015). Collaborative efforts among educators and researchers can maintain research continuity in these remote environments while providing authentic, potentially transformative educational experiences for students (e. g., Hoberg et al., 2015). Concurrently, communication among stakeholders can offer opportunities for bidirectional exchange of critical information, including both recent scientific discoveries and ecological knowledge about animal pathogens and disease (e. g., Hoberg et al., 2013; Dudley et al., 2015).

4. A pressing need to develop easier-to-access specimen-based electronic resources for education

As is evident from the ideas presented above, digitized museum data are a common factor facilitating a variety of new educational experiences for students of many ages. We have discussed only a few ways in which they can link major ecological and societal issues such as climate change, biodiversity loss, and emerging pathogens to the fundamental scientific concepts that are typical of many modern classrooms. Because specimens span the spectrum of biological units from genomes to organismal biology to studies of complex ecosystems, specimen-based lessons can reveal the process of scientific discovery and how scientists investigate the impact of abiotic systems on the structure of biotic diversity. Specimens can be a relatively simple point of entry for beginning students to learn about such basic concepts as variation, scaling across time and space, ecological complexity, and sustainability (Cook et al., 2014). As a vast amount of original natural history museum data becomes available online, as well as more intuitively linked to derivative specimen data, an unparalleled platform is emerging for inquiry-based science learning that is increasingly accessible across student socioeconomic status or physical access to biodiversity objects.

Museum databases were originally created to manage specimens, but now there is a growing trend to make these data available via the internet through international initiatives such as the Global Biodiversity Information Facility (GBIF.org). The result is that museum data are used not only by collection managers, but a spectrum of scientists and educators have been incorporating this incomparable resource on the planet's diversity into their activities. Indeed, museum specimens now fill an important pivot point between significant clusters of other big data available on the web. This unique pivot or connection is because specimens represent temporally-anchored and georeferenced records on individual organisms from across the globe, hence providing a critical layer for spatial analyses using Geographic Information Systems (GIS) approaches. Therefore, in the future, there is a critical need for museum staff to continue collaborating with information scientists to implement protocols ensuring that their database structures and levels of accessibility will stimulate even greater use by both researchers and educators. In particular, user-friendly, searchable databases should provide unimpeded access to specimens and associated original and derivative data.

Traditionally, natural history museums engaged a limited number of students in biodiversity studies through specimen-based laboratories in university courses, field projects, or training in specimen preparation and curation. They have also, of course, provided the scientific foundation and detailed information for numerous field and nature guides used by millions of students, teachers and recreationalists worldwide. New educational directions are now possible with teaching modules that take advantage of the growing cyberinfrastructure that has been developed through museum digitization efforts (e. g., DryadLab 2016, AIM-UP! 2016, iDigBio 2016). Museum specimens can now reach and be used by educators, students, and even citizen scientists. Educational modules provide unique opportunities for teachers to incorporate inquiry-based exercises and lesson plan development in the sciences (e. g. Cook et al., 2014). Finally, there is potential to draw on increasing access to remote computing and online implementation of some advanced software programs in developing new lessons along the lines of those we describe above (e. g., phylogenetic, phylogeographic, ecological modeling).

Natural history museums connect students to our natural world in a variety of ways. We must bear this in mind, even while continuing to develop new and innovative educational initiatives that employ digital specimen data. First, when students participate in natural history field studies, they may learn how to record basic environmental and specimen data as they press plants, pin insects, or prepare a variety of other museum specimens. Later, as specimens become curated and available for study, there are often opportunities for students to conduct cutting-edge, sample-based science in fields as diverse as molecular evolution, stable-isotope ecology, and developmental biology. Many universities now provide opportunities for direct student involvement in research projects as educators recognize that active participation in science is the most effective means of instruction (e. g., Museum Research Apprenticeship Program at the University of Alaska, Fairbanks). Because specimens can serve as the basis for so many different kinds of questions, collections naturally bridge perceived gaps between various disciplines in biology. By pointing out how a single specimen might have been used in multiple studies to address different hypotheses (see Fig. 1), students more easily grasp how science integrates and transforms perspectives on diversity (Dunnum, Cook 2012).The instructional power of all of these approaches can lead not only to greater use of museum specimens in educational programs, but also bolster renewed efforts to build and to maintain these critical resources for the benefit of biodiversity and society in an era of profound global change.

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