Building Natural History Collections for the Twenty-First Century and Beyond

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Natural history collections (NHCs) are important resources for a diverse array of scientific fields. Recent digitization initiatives have broadened the user base of NHCs, and new technological innovations are using materials generated from collections to address novel scientific questions. Simultaneously, NHCs are increasingly imperiled by reductions in funding and resources. Ensuring that NHCs continue to serve as a valuable resource for future generations will require the scientific community to increase their contribution to and acknowledgement of collections. We provide recommendations and guidelines for scientists to support NHCs, focusing particularly on new users that may be unfamiliar with collections. We hope that this perspective will motivate debate on the future of NHCs and the role of the scientific community in maintaining and improving biological collections.

Keywords: natural history collections, herbaria, data archiving, extended specimen, biodiversity, outreach

Natural history collections (NHCs) house data primarily in the form of scientific specimens. NHCs include natural history museums, digital databases of material derived from specimens, and living collections housing invertebrates, vertebrates, fungi, plants, and bacteria (figure 1). Specimens contained within NHCs provide information on multifarious aspects of the natural world, both modern and historical. NHCs are experiencing a renaissance as technological innovations and digitization efforts enable collections to reach new audiences and answer novel scientific questions (Meineke et al. 2018). However, limitations of funding, personnel, and physical space have required tough choices about how to maintain the facilities that care for scientific specimens and how to decide which specimens should be preserved for future research (Lendemer et al. 2019). Many new users of NHCs may be unfamiliar with how to support and contribute to collections, but their informed involvement, and the education and involvement of other scientists, policymakers, and the general public, are critical to address the challenges NHCs currently face, and when planning for the future of NHCs. In the present article, we identify missed opportunities and promising solutions for improving collections while providing general recommendations for scientists to report usage of specimens and data derived from NHCs and to increase their individual contributions to NHCs. We encourage ongoing efforts to increase communication among NHCs, the wider scientific community, and the general public. It is our hope that this perspective will help motivate debate within the scientific community about how to maintain, improve, and grow biological collections to ensure that these invaluable resources are available for future generations of scientists.

Natural history collections today

Historically, natural history specimens have been used to address large-scale evolutionary, ecological, and biogeographic questions, develop robust taxonomies, catalog biodiversity, and investigate the abiotic history and dynamics of ecosystems. Recent advances in technology along with massive efforts to increase access to specimens and their associated data have further broadened the utility of these specimens and their associated data (Meineke et al. 2018). Because these specimens are housed in NHCs, these establishments are fundamental to addressing the biggest research questions and challenges in ecology and evolution, biodiversity loss, public health, agriculture, food security, climate change, and toxicology (e.g., Suarez and Tsutsui 2004, Drew 2011, Lister and Climate Change Research Group 2011, Holmes et al. 2016). The long-term preservation of NHCs is also an integral but generally overlooked component of scientific reproducibility.

Innovations in technology, data collection, and analysis have enabled scientists to glean more data and different types of data from specimens and other materials housed in NHCs. As a result, these NHC materials are being used

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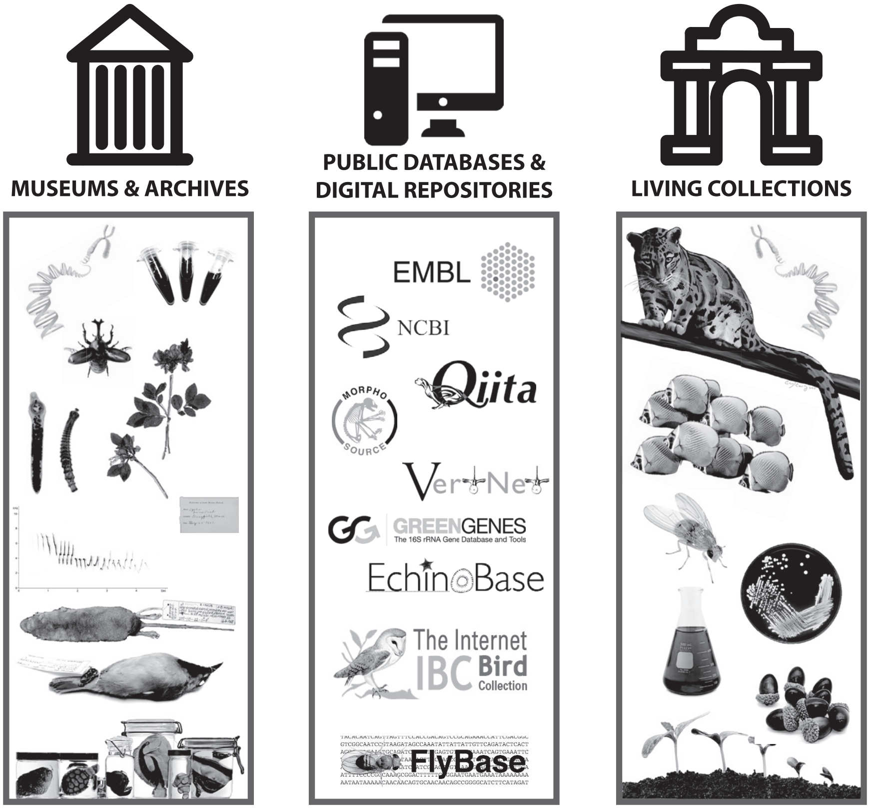

Figure 1. Natural history collections (NHCs) encompass a wide range of material types including whole-organism or partial samples of specimens housed in museums or herbaria that have been dried, preserved in alcohol, or frozen. NHCs also contain materials derived from specimens such as associated field notes, tissue samples, parasites, and sound or video recordings. Living collections contained in zoos, aquaria, arboretums, and botanical gardens, as well as seed banks, and fungal or tissue and cell culture banks, are also types of NHCs.

to investigate novel research questions that may have been unimaginable by the original collector. For example, stable isotope analysis of specimens in NHCs has demonstrated changes in trophic ecology of insectivorous, migratory birds spanning 133 years (English et al. 2018). Two areas that have arguably undergone the greatest advances over the last decade are genomics and imaging technologies. Rapid development in next generation sequencing, which can be used successfully with fragmented and degraded DNA that is often characteristic of historical specimens from NHCs, has facilitated genetic analysis of older specimens that would have been impossible using traditional Sanger sequencing methods (Holmes et al. 2016, Meineke et al. 2018). Similarly, imaging technologies such as computed tomography (CT) scans and confocal laser scanning microscopy for three-dimensional reconstruction of specimens have enabled highly detailed morphological analyses while preserving specimen integrity (Mendez et al. 2018, Short et al. 2018).

Technological advances have not only increased the ways in which data are gathered from NHCs, but have also broadened user access to the collections and their associated data (Baird 2010, Hedrick et al. 2020). Digitization efforts continue to increase, and NHCs are increasingly available to scientists, educators, students, and the general public. The digital data include images or CT scans of the specimen, as well as specimen metadata such as age, sex, locality information, ecological descriptions, and links to digitized field notes and audiovisual recordings (Webster 2017). Where once NHC data were only available to those with physical access to the specimens, today an increasing amount of collections data are available to anyone with an Internet connection. The data from NHCs can now be accessed through individual museum databases but are also available more broadly through data aggregators such as VertNet (Constable et al. 2010; vertnet.org), SCAN (Symbiota Collections of Arthropods Network; scan-bugs.org), Tropicos (tropicos.org), and the Biodiversity Heritage Library Field Notes Project (biodiversitylibrary.org/collection/FieldNotesProject), as well as data portals such as GBIF (Global Biodiversity Information Facility; gbif.org) and iDigBio (Integrated Digitized Biocollections; idigbio.org). Finally, the user base of NHCs can garner diverse types of data from each specimen. For example, a single specimen can be linked to nucleotide, genome, or protein data on GenBank (www.ncbi.nlm.nih.gov/genbank), stable isotope data on IsoBank (https://github.com/BrianHayden/IsoBank), and CT scans on MorphoSource (morphosource.org). As a result, diverse data types from specimens collected across geographic and temporal scales are more accessible than ever before (Schindel and Cook 2018).

The current specimens housed in NHCs are and will be vital future resources for understanding the past, present, and future impacts of environmental change on natural systems (Kemp 2015, McLean et al. 2016, Meineke et al. 2018, Schindel and Cook 2018, Cook and Light 2019, Heberling et al. 2019, Lang et al. 2019, Lendemer et al. 2019). The value of NHCs for addressing societal concerns will continue to increase over time as new information streams are unlocked, but these valuable resources will require maintenance and growth to meet these concerns.

Current challenges facing collections

There are several major challenges facing NHCs. Many of these challenges have been discussed within the context of specific taxonomic groups and research fields (e.g., Winker 1996, Middendorf and Pohlad 2014, DiEuliis et al. 2016, Malaney and Cook 2018, Cook and Light 2019). In the present article, we provide a brief summary of some of the challenges across NHCs leading to two main consequences: the loss of collections and taxonomic expertise and missed opportunities for adding specimens to NHCs to provide resources for addressing, among other challenges, the looming consequences of global change. In subsequent sections, we suggest potential solutions to mitigate these challenges.

One of the core challenges for the persistence of NHCs stems from inadequate funding and administrative support (Kemp 2015). Funding is required to employ permanent staff, maintain storage facilities and the collections themselves, enable collection improvement, and sustain collections through times of economic uncertainty. Inadequate funding to sustain collections is highlighted by recent financial hardships caused by the COVID-19 pandemic, leading to actions such as the American Museum of Natural History cutting or furloughing roughly 20% of their full-time staff (Jacobs 2020). The experts working in NHCs represent a combination of permanent and temporary staff who are at risk of not being replaced on retirement or at the end of funded projects. One consequence is a loss of natural history expertise. This expertise is a necessity for NHCs and the breadth of research fields that these collections support in ecology, systematics, conservation biology, parasitology, agriculture, and more (Suarez and Tsutsui 2004, Drew 2011, DiEuliis et al. 2016). For example, although renewed efforts in training taxonomists have been successful, they do not necessarily translate into job opportunities (Agnarsson and Kunter 2007). Staff shortages slow the distribution of specimen loans and provide fewer resources for visitors at a time when more researchers in increasingly diverse fields are using collections (Schindel and Cook 2018).

Declines in funding have also led to deterioration of facility conditions and security (US Government Accountability Office 2007, Office of the Inspector General 2016). Without proper maintenance, specimens degrade over time from humidity, light, and pest damage. In some cases, the lack of funding and support can lead to the decision to close or discard an NHC or move specimens to a new owner. Recent examples of these threats include the decision to relocate the University of Louisiana–Monroe collection (Bolden 2017), drastic funding cuts endangering the collections at the University of Alaska Fairbanks and the Botanical Garden of Caracas (Hanlon 2019, Torres 2019), and catastrophic fires destroying major collections of the National Museum of Brazil and the zoological collections of the Butantan Institute (De Franco and Kalil 2014, Yong 2018) due in part to a lack of funding for fire suppression systems (Yong 2018). Transferring threatened NHCs can preserve specimens, but more centralized collections limit the number of researchers and students that can access specimens for research and training purposes, and also increase the chance that a single catastrophic event could lead to large-scale losses. Distributing NHCs broadly across local scales reduces the travel time needed to physically access a collection, provides additional opportunities for local collections to serve local interests, and can expand the diversity of regions, institutions, and people that collections serve. In short, although the value of NHCs and responsibilities of the people that manage them have continued to increase, funding and administrative support have not kept pace (Kemp 2015).

A second challenge facing NHCs is ensuring that these collections continue to remain a valuable research resource into the future. With a global population expected to exceed 9 billion by 2050, human activities are affecting every biome on Earth. As archives of historical data, NHCs provide baseline information to facilitate studies of global change on biodiversity (e.g., Moritz et al. 2008). However, the utility of NHCs for addressing global change is limited by several issues related to how samples are, or are not, collected and preserved. For many taxa, specimen acquisition is at an all-time or near-all-time low (Gardner et al. 2014, Daru et al. 2018, Malaney and Cook 2018, Cook and Light 2019). Several potential reasons for these declines were discussed by Malaney and Cook (2018), and include tighter permitting restrictions and limited funding for specimen-based fieldwork. Although negative perceptions persist about the impact that specimen collection has on organismal populations, this concern is not supported by the available evidence (Hope et al. 2018). Furthermore, collectors of botanical and mycological material seldom collect lethal samples whereas other researchers sample entire organisms to obtain data that are inaccessible using only nonlethal sampling techniques (Hope et al. 2018). Many sampling efforts occur without a strategic plan, in narrow regions, or with focus on specific taxa. In addition, when samples are collected for a specific purpose, other useful information is often discarded or becomes dissociated, such as when parasites are not linked to a host specimen (Cook et al. 2016, Galbreath et al. 2019). Finally, when creating strategic plans for the future of NHCs, efforts should be made to engage a broader, more diverse community of scientists, citizen scientists, and the general public in museum-based scientific research. Expanding outreach initiatives aimed at building collections infrastructure and increasing the usability of specimens to diversify the stakeholders using NHCs will benefit both the participants and the collections (Campbell et al. 2013).

Addressing these challenges will require innovative solutions to increase financial and curatorial support for NHCs and continuing and expanding effort from NHCs to effectively engage with their communities. With careful planning and attention to training the next generation of scientists, relatively small changes to the ways in which scientists interact with NHCs moving forward will have a great impact on our future abilities to address societal concerns and scientific questions in a changing world.

Increasing funding and support for collections

The funding for NHCs has been on the decline for the last two decades (Kemp 2015), whereas many NHCs have experienced regular, sustained growth in collection size (Interagency Working Group on Scientific Collections 2009). On average, 41.6% of the funding for large public NHCs comes from earned income (e.g., ticket fees, food sales), 29.5% from private donors, 23.6% from government budgets or grants, and 5.7% from investment income (Manjarrez et al.

2008). Smaller, university funded NHCs have experienced decreased support due in part to a decline in funding of public universities (Newfield 2016), exacerbated in many cases by the lack of an annual operating budget to manage day to day operations (Snow 2005). Maintaining NHCs will require new long-term funding initiatives and an increased recognition of the importance of NHCs in supporting scientific research.

Initiatives aimed at bridging the funding gap. The National Science Foundation (NSF) is the primary agency funding initiatives aimed at supporting and developing nonfederal collections. NSF's Collections in Support of Biological Research (CSBR) program provides funds for enhancements and improvements to collections and accessibility of collection-related data; however, the CSBR program was placed on hiatus in 2017 (Rogers 2016), then offered on a biennial basis. This program has also experienced a decline in funding, further limiting support for basic care and maintenance of NHCs. Another program funded by NSF, the National Ecological Observatory Network (NEON), provided funding for the NEON Biorepository at Arizona State University, which curates new collections as well as some legacy samples originally cataloged at other facilities. However, this collection is limited to samples obtained at NEON field sites. The Advancing Digitization of Biodiversity Collections program through NSF has provided substantial resources for digitization of specimens in NHCs in the United States. A special track of the NSF Postdoctoral Research Fellowships in Biology program, called Research Using Biological Collections, was initiated in 2015 that supported early career scientists, with the aims of broadening the core set of investigators using collections and applying new technologies and questions to specimen-based research (e.g., Pauli et al. 2017, Greiman et al. 2018). Over the past few decades, a series of NSF Research Coordination Networks have addressed topics related to NHCs, including Advancing the Integration of Museums into Undergraduate Programs (AIM-UP!; https://aimup.unm.edu), Biodiversity Literacy in Undergraduate Education (BLUE; www.biodiversityliteracy.com), and the Biodiversity Collections Network (BCoN; https://bcon.aibs.org), all of which were established to build a community of practice related to research, education, and digitization of collections (Lendemer et al. 2019).

Although they are crucial for a baseline of support, the NSF funds available for care and digitization of collections are still insufficient for the gargantuan task, especially when combined with NHC staff shortages (Vollmar et al. 2010). Although some private funding is available to NHCs, these resources often come with restrictions that limit the use of funds to exciting or novel opportunities such as genomics research or new exhibits; rarely are these resources used for basic collections management and infrastructure maintenance. This means that we, as scientists and citizens, must advocate for financial support of NHCs.

Scientific community support for funding NHCs. To support and encourage greater funding for NHCs, the scientific community needs to improve acknowledgement of the role of NHCs in research so that NHCs may more effectively demonstrate their impact. Of particular importance is acknowledging NHC infrastructure. One challenge associated with attribution for NHCs has been the lack of a standardized method of citation for tracking publications. Museum staff rely on authors to inform the museum of papers using NHC data or conduct time-consuming online searches of keywords or catalog prefixes in new publications (Lendemer et al. 2019). However, the advent of online databases such as GBIF has allowed for digital object identifiers (DOIs) to be attached to particular collections. Several NHCs now maintain Google Scholar profiles, and each collection could also be assigned an ORCID identifier (https://orcid.org; Cook and Light 2019, Hobern et al. 2019). One option for acknowledgement of an NHC along with its specimens is citation of the institutions (or their individual departments) by DOI (found in GBIF) in concert with complete voucher lists containing sample accession numbers (Funk et al. 2005). In fact, data sets from iNaturalist are automatically assigned citable DOIs; a similar approach could be taken with NHCs. This will facilitate tracking of publications that result from collections-based work and represents an excellent opportunity for scientists to support NHCs. Researchers should work with the curators of the collections to identify the most appropriate way to acknowledge that particular NHC in publications but working toward a standardized method for acknowledging NHCs will aid in tracking the global contributions of NHCs.

The contribution of NHCs to scientific research through data derived from collections material must also be recognized and cited. For example, DNA sequences generated from an NHC specimen can be deposited on GenBank. Users of DNA sequences may not realize the importance of NHCs for generating this data. By associating data on GenBank with vouchered specimens, the role of NHCs can be acknowledged and tracked (Federhen et al. 2009). Similar considerations can be made for digital or physical output created from direct specimen use (e.g., isotopic signatures, images, morphosource specimens, CT scans; Pauli et al. 2017), and the use of data downloads from data aggregators (Lendemer et al. 2019). To properly acknowledge NHCs in research, databases such as GenBank need to enlist consistent formatting of specimen acknowledgement, which will help integrate data sets generated by independent researchers. Increasing acknowledgement of specimens (and associated catalog numbers) will allow NHCs to efficiently track the scientific output from collections use and, therefore, better position them to demonstrate the impact of those collections on science and society to funding sources and administrators.

Beyond simply acknowledging NHCs, the scientific community must also provide stronger investment in programs that seek to maintain and connect NHCs across the globe, such as BCoN (https://bcon.aibs.org), the Natural Sciences Collections Alliance (www.nscalliance.org), the Society for the Preservation of Natural History Collections (SPNHC;

https://spnhc.org), and Distributed System of Scientific Collections (DISSCO, www.dissco.eu; Addink et al. 2019), as well as data portals that provide significant access (e.g., GBIF and iDigBio). Service and social investment (e.g., participation in relevant working groups, social media support) in particular are critical for these programs to promote NHCs and their benefits. Such engagement provides these programs and organizations with better opportunities to develop strong policy goals and strategies for building public support (and, in turn, funding) for NHCs.

Finally, the curation of small NHCs requires significant investments of time and money, and many institutions do not provide dedicated employees or an operating budget for NHC facilities. This is due in large part to a decline in the value attributed to the natural history and systematics work that has long been the focus of many who work with collections (Schmidly 2005, Tewksbury et al. 2014). As such, researchers interested in positions that include curation responsibilities should ask questions upfront related to the current quality of care and funding available for the NHC and negotiate for resources and formal acknowledgement of time commitment (Snow 2005). That said, responsibility for these collections should not be placed solely on new hires. Current faculty at institutions with NHCs can contribute significantly to their long-term care by acknowledging the value of the collections for their work and educational endeavors and by advocating for funding and dedicated staff for collection administration. Similarly, researchers using scientific collections should work with curators when writing grant proposals to budget for necessary supplies, space, and salary for processing and storing specimens. Furthermore, when researchers do attempt to include funding for NHC support activities, it is critical that these line items are viewed as necessary by the funding agencies that support such research. Small contributions from even a subset of researchers, faculty, and educators working with or using NHCs could have dramatic and positive effects on long-term development of these collections and ensure their continued quality for future research and teaching.

Incorporating NHCs into public data management and archiving policies. In the last decade, federal funding agencies and academic journals have adopted data archiving policies to make published data publicly available (Whitlock et al. 2010). These policies have been effective at increasing the availability and longevity of research data (Renaut et al. 2018) and can reduce the cost of research by avoiding duplication of data collection (e.g., Piwowar et al. 2011). However, these data archiving policies rarely, if ever, include provisions for linking data to physical specimens stored in NHCs. The reusability of specimens can be enhanced by ensuring specimen data is findable, accessible, interoperable, and reusable, following the FAIR principles of scientific data management (Wilkinson et al. 2016). Data derived from specimens (including whole organisms or parts such as tissues or symbionts) should be assigned a globally unique identifier (GUID) that is easily searchable and connected back to the catalog numbers of the original archived specimens as standard practice. GUIDs are automatically assigned to specimens by iDigBio; therefore, we suggest archiving digitized specimen metadata with iDigBio or a similar data aggregator prior to publication. Linking data with the original specimen has the added benefit of facilitating comparisons across data sets, extending previous work, and aiding in data reproducibility. Following the model of online data repositories such as Dryad (https://datadryad.org), archiving physical specimens into NHCs could require a small fee to offset the costs of long-term storage. The scientific community can encourage journal editors and granting agencies to update data archiving policies to require proper attribution of data derived from NHCs and where appropriate, the deposition of new specimens into NHCs and associated metadata to digital repositories. Reviewers of manuscripts and grants can assist in this aim by helping to enforce these policies during the review process.

Scientific community support for curation of NHCs. Collections-based research and digitization efforts depend on accurate organization, identification, and labeling of specimens. However, the loss of museum staff, particularly taxonomic specialists, has limited the effort and hours that curators can devote to improving the curation of material currently housed in collections (Agnarsson and Kuntner 2007). Research scientists that do not typically work in museum collections are a vast but underused resource for improving the curation of NHCs. Within their study systems, scientists are experts on organismal characteristics and are the group most likely to benefit from a well-curated collection of their organisms of interest. Deputizing these scientists as associate curators to help curate the specimens relevant to their field of study can free museum staff to address other sections of the collection. We encourage scientists at all career stages to consider contributing to curation of biological collections as part of both research and scientific outreach.

There are a number of other ways for scientists to contribute to curating biological collections: (a) Start local but think global. Assist with specimen identification in collections at your home institution and contact in-country collections to offer your expertise when visiting collaborators or traveling for fieldwork. Scientists working in developing countries should consider contributing curation assistance to help grow and maintain in-country collections. (b) Advertise your taxonomic expertise and willingness to participate in NHC outreach as part of your online profile on ResearchGate, Academia.edu, and ORCID to allow museum personnel to easily identify people to contact to assist with undercurated parts of their collections. (c) Make the most out of your contribution by ensuring that when you add new specimens to collections or update sample information that these data are simultaneously added to digital databases. (d) Consider budgeting for costs associated with data archiving (e.g., hard drive space or cloud-based backups to store data in perpetuity) when writing grant proposals. (e) Leverage your society affiliations for the good of biological collections. Professional societies can help support curation efforts by connecting local NHCs with visiting experts as part of specimen identification blitzes associated with annual meetings or other BioBlitz events. (f) Even people who are not specialists in a particular taxonomic group can provide valuable assistance with specimen identification and curation. For example, reclassifying an insect specimen from the Order Hymenoptera to the subfamily *Polistinae* narrows the task of identification from 150,000 species to 300 species. This requires less specific knowledge than identifying that specimen to the genus or species level but significantly improves the metadata resolution for that specimen, and allows specialists to focus on fewer specimens that require their particular expertise. Collections also need assistance with tasks outside of specimen identification, including specimen digitization and database management, which can be performed by trained nonexperts including students or citizen scientist volunteers. In summary, these outreach opportunities can require only a few additional hours of work per person per year; when aggregated across the biological community, these small contributions can have a huge impact on the quality of collections.

Developing collections for the twenty-first century and beyond

NHCs are invaluable resources that provide the means for better understanding the past, present, and future impacts of environmental change on natural systems (Kemp 2015, McLean et al. 2016, Schindel and Cook 2018). In the present article, we outline considerations for specimen collection to maximize the usability of NHCs by future scientists and its impact on their work, although we emphasize that developing collection priorities is the responsibility of the entire scientific community. We focus on the utility of collections for addressing global concerns such as rapid loss of natural habitats, populations, and species, as well as ensuring that future collections are compatible with rapidly advancing technologies.

The role of NHCs in developing collections for the future. Specific interests of collections-based researchers largely drive current specimen acquisition, whereas growth of NHCs through broad, holistic sampling is less common. Increasing the breadth of specimen acquisition will help fill gaps in biodiversity data and increase the future utility of NHCs (Lendemer et al. 2019). To broaden the scope of collections, NHCs should develop strategic priorities for collection development and specimen acquisition including designating the species, diversity and number of samples and preparations, sampling frequency, and storage medium for specimens. Priorities should be developed using feedback from collections managers, curators, researchers that use the collection, and users of digital databases. Explicit efforts should be made to broaden the inclusion of diverse researchers, including those that have not traditionally been a part of the museum community (McLean et al. 2016). Development of strategic priorities should not be done in isolation; instead, NHCs of the future should ideally integrate across the broader biodiversity collections network in prioritizing what to collect. Specimens should be digitized at the time of accession and made broadly available to public users and researchers (Watanabe 2019, Lendemer et al. 2019). Strategically, this means that museums may need to evaluate their specific role in both serving their local community and the broader scientific community. The operations and aims of large publicly funded institutions complement smaller, regionally focused collections; as such, the diverse missions among NHCs collectively provide a breadth of natural history specimen information for diverse research questions. Strategic planning can help guide institution-specific decisions such as identifying taxonomic or spatial gaps the collections hope to fill, retrospective resampling to develop time series, and planning how the collections should grow over time. All of these strategies can influence an NHC's activities, from collection procedures to hiring. However, strategic priorities and collections policies also need to be flexible and capable of evolving over time to allow researchers to collect new types of data (e.g., allowing destructive sampling for DNA sequencing).

Guided by the utility of past collections, we can make some generalized predictions about which taxa to target for preservation in NHCs. Given that many ecosystems are changing at a rapid pace in response to human-induced environmental change, there is an urgent need to preserve and store biological samples that archive current biodiversity and allow for future understanding of biotic responses to environmental change. Such biological collections should document historical species ranges and host–symbiont associations, represent the degree of phenotypic, demographic, and genetic variability of populations through time, and provide a time series of phenotypes in response to environmental change (e.g., Weeks et al. 2020). High-resolution time series of samples collected at sites that span heavily affected (e.g., urban and agricultural) to more pristine landscapes will be particularly valuable. When possible, efforts should be made to collect samples from regions where environmental change is imminent (e.g., sites designated for future development, mining, or damming; Fitzgerald et al. 2018) or where environmental change is projected to be most rapid (e.g., NEON field sites, neonscience.org; and polar regions).

Developing collections for future generations of scientists will only be possible with increased internal and external support of NHCs. Therefore, once strategic priorities have been developed, these priorities should be clearly communicated and made easily accessible to administrators and researchers. For example, providing clear policies for specimen collection and preservation can streamline the process of adding to collections while reducing the barriers to working with NHCs, thereby increasing involvement of scientists that would otherwise interact infrequently with these facilities. Below we discuss opportunities for scientists to contribute to NHCs of the future.

The extended specimen. It is often the case that researchers, who are focused on a particular question, collect data relevant

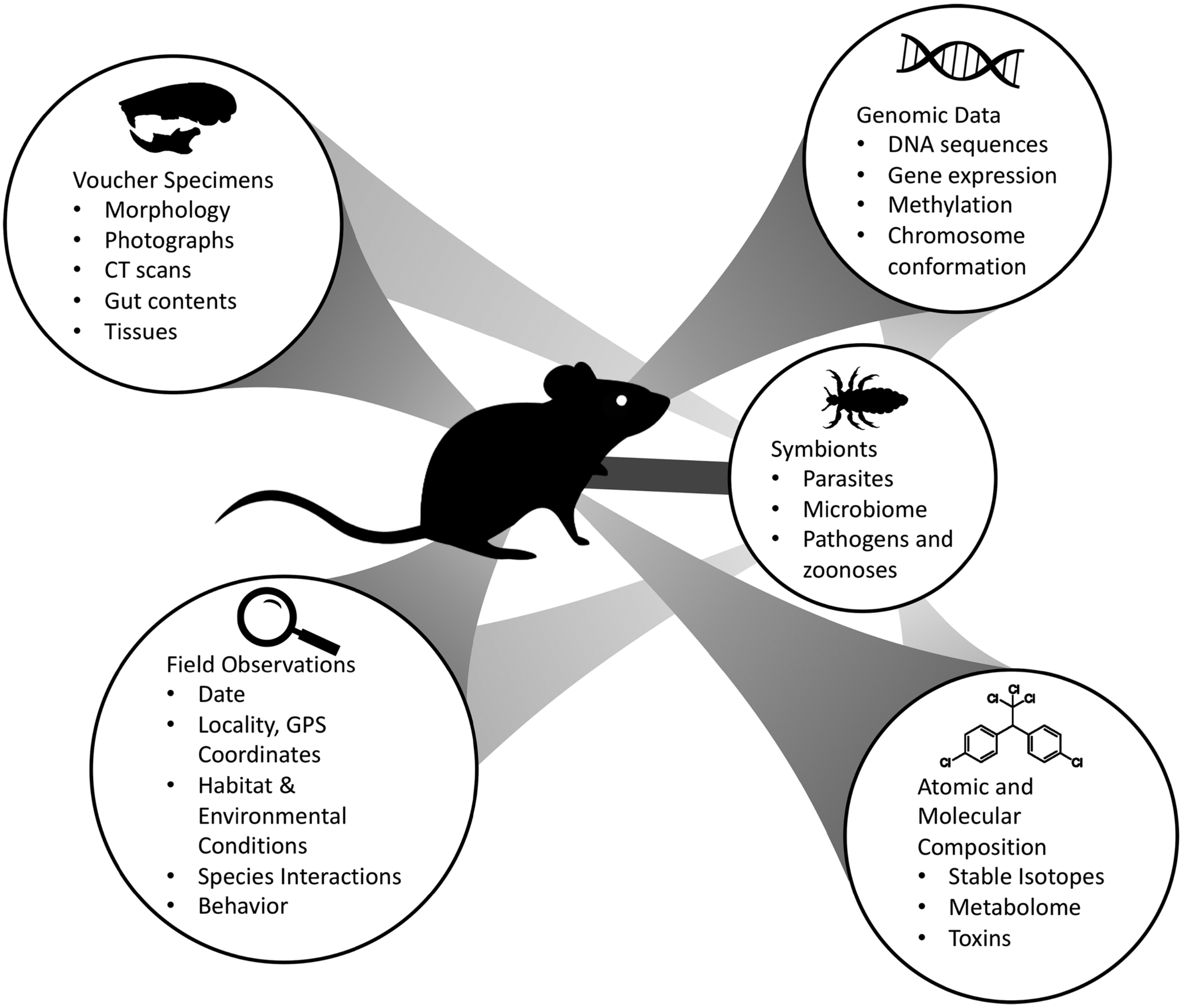

Figure 2. The extended specimen concept. Multiple data types are recorded and preserved during the collection event to maximize the value of a specimen in future research, including data on symbionts that themselves have vouchers and associated data, and the context in which the specimen was collected.

specifically to their work rather than a broad spectrum of data types. However, data obtained during the collection event itself can be maximized by expanding the scope of the data and materials that are collected with each specimen. Audio and visual recordings, descriptions of the habitat or community, parasite and microbial symbiont samples, and tissue sampling for cryogenic preservation are just a few examples of additional data types that are increasingly represented among scientific collections. Data describing the context of the specimen are crucial for reporting biodiversity change; can include abundance, behavior, phenology, reproductive status, or other essential biodiversity variables; and should be reported for each specimen and not aggregated (Kissling et al. 2018). In combination with more traditional or common data types, these auxiliary sources of data represent an extended or holistic specimen (Webster 2017, Schindel and Cook 2018, Galbreath et al. 2019) that attempts to best represent the spatiotemporal and biological contexts in which a specimen existed (figure 2). When these additional types of data are collected with a specimen, they are often dispersed to specialists and experts located across a number of institutions. Therefore, care must be taken to maintain links between host voucher specimens and ancillary data. The recent Extended Specimen Network initiative aims to promote methods of tracking and integrating these diverse types of data (Lendemer et al. 2019). This extended specimen concept has become common in vertebrate research and could be successfully applied to other disciplines. However, not every researcher has the expertise or resources to collect and preserve all types of samples; therefore, achieving the collection of extended specimens

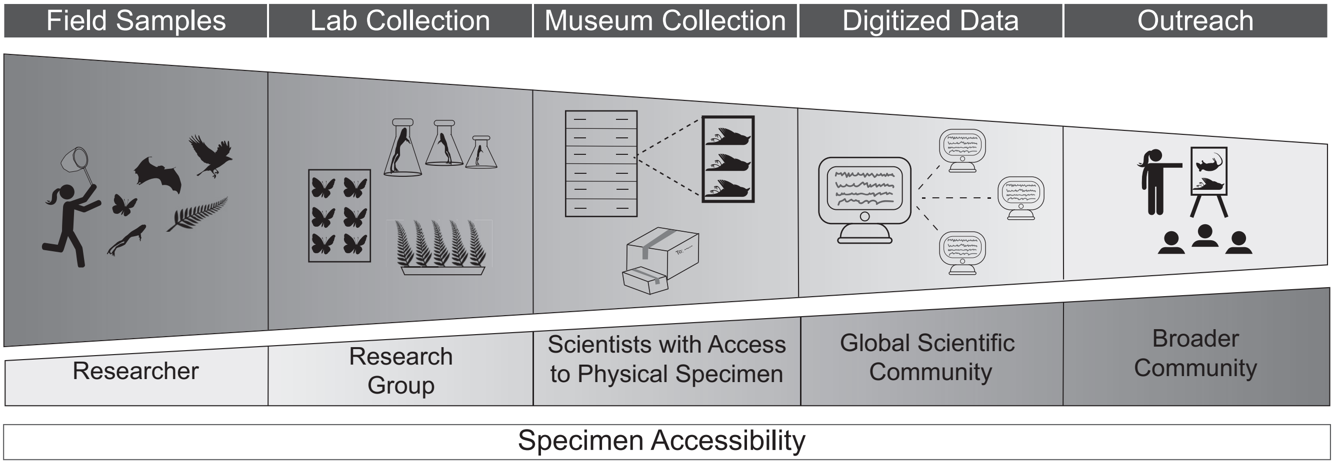

Figure 3. The accessibility of specimens increases when specimens are collected, properly labeled and preserved, stored in NHCs, added to digital databases, and incorporated into outreach programs. The inverse triangles show that a leaky pipeline of specimens is occurring at the same time as the potential user base is increasing across categories.

may require increased training initiatives and collaborations between researchers and NHCs (see below).

Expanding opportunities for specimen acquisition. There are many opportunities for researchers to support NHCs by helping expand specimen acquisition. In many cases, specimens are already being collected as part of research projects or coursework but are temporarily housed by individual researchers rather than being archived in a collection. For example, college courses with labs that involve specimen collection (e.g., pitfall traps or seine nets to sample insect communities) could consider working with NHCs to add those specimens and data to collections. In some cases, teaching labs happen in the same place year after year, providing a great opportunity to preserve a record of community change through time and teach students about the importance of NHCs, their uses, preservation techniques, and public databases. Incorporating these specimens into NHCs increases the breadth of the user base of specimens and extends the impact of individual specimens for future generations (figure 3). Samples that are not currently archived at NHCs should be stored with sufficient identification information to allow them to be incorporated into collections at a later date. At a minimum, this information should include a voucher accession or unique identification number, collection date, location, species if known, preservative (if any), and permit information. Furthermore, information including, but not limited to, study design, behavioral state, habitat or community information, and the extended specimen (see figure 2) can further increase the utility of each specimen (Kissling et al. 2018).

Establishing relationships with local natural resource managers and federal agencies can also lead to opportunities to acquire specimens or tissues that might otherwise be discarded, including those from hunting stations, removal trapping of pests, bycatch from surveys, or other salvage efforts, which can yield important insights (McLean et al. 2016, Cook and Light 2019, Weeks et al. 2020). In concert, these efforts can help reduce the number of specimens collected, while allowing these specimens to be used for future research, supporting established ethical principles for minimizing the use of animals in research (Russell and Burch 1959). NHCs can also grow by accepting personal and orphan collections, provided that these collections have been properly labeled and preserved. Considering the uses of samples beyond the immediate goals of a project and identifying opportunities that are feasible to integrate into standard practices will lead to the growth of resources for the scientific community. These opportunities will require concerted efforts and strengthened relationships between NHCs, researchers, and natural resource managers (Morrison et al. 2017).

Specimen preservation methods. Past methods of sample preservation and data accession have reduced the utility of existing collections to address certain questions. For example, specimens preserved in formalin can be used in genetic studies with only limited success (e.g., Ruane and Austin 2017). Attempting to predict future researchers' needs, especially in terms of the best sample fixation or preparation methods required for new technologies, is a near impossible endeavor. Therefore, we should apply the current best-known practices for proper fixation and long-term storage of each particular sample type and when possible, specimens should be preserved using multiple methods as a bet-hedging strategy. Many reviews of best practices and protocols for varying specimen types have been published in recent years (e.g., Lutz et al. 2017, Galbreath et al. 2019, Phillips et al. 2019). The SPNHC maintains a best practices wiki that currently covers many topics related to specimen and sample preservation for various taxa (https://spnhc.biowikifarm.net/wiki/Category:Best_Practices), and many NHCs post sample preparation protocols on their websites. Researchers can contribute to online training resources by documenting practices specific to their areas of expertise and making them available to the scientific community by submitting protocols through resources such as https://protocols.scienceexchange.com or www.protocols.io. Fixation procedures will not only vary according to specimen type, but should also take into consideration the accessibility, feasibility, and cost of storing particular types of samples at NHC facilities. Decisions on sample preservation methods should therefore entail ongoing conversations between researchers and NHCs to ensure that researchers are correctly preserving samples and that NHCs are prioritizing investment in specimens that will be valuable for future research.

Training initiatives. Adequate training and access to training resources is paramount to the success of the scientific enterprise. First and foremost, a renewed emphasis on training of students and staff in proper collection methods, including sample preparation and data management practices (particularly among labs and agencies not directly associated with NHCs), is essential to the continued growth and benefits of collections. Many specimen preparations are difficult and complex, and lack of training may hinder the growth of collections. Where possible, trainees should be trained in a variety of sample preparation techniques or be made aware of online training resources that are available to learn new protocols and standards. NHCs can support training by providing opportunities for volunteers or graduate/undergraduate students to learn how to prepare specimens. Principal investigators should train their lab groups on how to organize and store data and parts associated with specimens (e.g., tissues, parasites) to facilitate later transfer to collections. Graduate programs should also require training and establish expectations for those students collecting specimens as part of their research to produce data management plans for their projects, including where they will permanently archive voucher specimens, associated samples, and data.

Digitization initiatives. Current efforts are underway to digitize specimen data at many major NHCs, but for some taxa (e.g., arthropods), the great majority of specimens have yet to be processed (Cobb et al. 2019). Improvements to the digitization workflow and infrastructure have great promise for improving digitized data (Hedrick et al. 2020), and innovative solutions such as whole-drawer imaging of pinned insect specimens are increasing the speed of specimen digitization (Short et al. 2018). Future research (especially those projects relying on the data associated with specimens) will be enhanced by continuing digitization initiatives (Lendemer et al. 2019), and digitization initiatives will allow researchers to effectively assess the consequences of global change (Heberling et al. 2019, Lang et al. 2019). Researchers can contribute to digitization efforts by following institutional guidelines when preparing samples to streamline the digitization process and by advocating for publicly available data.

Digital data must also be curated, stored, and archived, which can present new challenges, such as storage of large CT scan data sets (Watanabe 2019) or digitally linking data generated from a sample (e.g., genetic sequences) across institutions and databases and back to the vouchered organism (McLean et al. 2016). Advances in data storage allow the association of massive amounts of metadata with each specimen. This has become common practice in the field of microbial genomics and metagenomics, via resources such as the open-source data management platform Qiita (www.qiita.ucsd.edu), through which users can connect all microbial sequences, mapping files, and host voucher information and metadata to the European Nucleotide Archive (ENA; www.ebi.ac.uk/ena), which is the permanent data repository of the European Bioinformatics Institute (EBI; www.ebi.ac.uk). Cross-institutional links will benefit specimen data connectivity, both enhancing the accessibility of data and reducing the chances of duplicate efforts to enter specimen data into databases. Furthermore, data aggregators and portals provide a digital account of the impact or use of each specimen, which can be used to report the impact of the collection (Lendemer et al. 2019).

Broadening participation in biological collections

The geographic representation of NHCs, their accessibility to diverse groups, and the availability of institutional support are often inequitable. Increasing the diversity of the populations of scientists participating in and being served by NHCs is likely to have benefits for the participants and the collections themselves (Campbell et al. 2013). Ways to diversify the researchers working with NHCs and the communities potentially benefiting from them include supporting global NHCs and fostering collaborations at both local and international levels, improving accessibility of collections and associated data, increasing the participation of underrepresented groups working with and within NHCs, and creating more educational and research opportunities centered around collections (Cook et al. 2014).

Increasing global support of institutional NHCs. Although NHCs worldwide are subject to many challenges, those in developing regions are disproportionately affected by limitations in training and financial support for taxonomy and collection management (Paknia et al. 2015). Limited training and career opportunities for aspiring taxonomists and collections professionals in developing regions of the world means that taxa endemic to those biodiverse areas are often underrepresented in NHCs (Paknia et al. 2015). These types of inequities can lead to large biases in data sets to the detriment of conservation and management decisions (Feeley et al. 2017).

International collaborations that prioritize activities including training, joint research initiatives, and capacity building for foreign institutions are key to building infrastructure and training local scientists. For example, training programs can involve sponsoring students and scholars to visit distant NHCs to learn techniques and network or include *in situ* initiatives in the field or at researchers' home institutions (Cook and Light 2019). Collections professionals working internationally should also prioritize support for local institutions, including training in field and museum techniques and specimen deposition to increase local access to knowledge and resources. When possible, contributing specimen preparation supplies may also help to maintain collections at local NHCs.

Regional expertise and taxonomic knowledge of local experts, collections staff, scientists, and members of the public is invaluable, and inclusion and support of local professionals are key to successful project outcomes (Elbroch et al. 2011). NHC initiatives that foster international collaborations, prioritize the training of young scientists, and encourage public participation in home countries can leverage community knowledge to foster a strong sense of place and pride in local communities (Haywood 2014). Moreover, it is important for researchers and NHCs to follow all in-country rules and regulations, as well as international agreements as collected samples and specimens (and associated data) are often considered valuable natural resources. One such example is the Nagoya Protocol on Access and Benefit-Sharing, an international agreement that was intended to ensure fair access and benefits from the use of genetic resources (www.cbd.int/abs). NHCs can in turn benefit from improved local support for nascent and developing projects and improved research and conservation outcomes (Ballard et al. 2017).

Broadening data accessibility. Accessibility of specimens and materials in NHCs is imperative for initiatives such as the Nagoya Protocol, as we mentioned above. Accessibility also has an important role to play in increasing the diversity of museum scientists and taxonomists. Ongoing digitization efforts have the ability to revolutionize access to museum specimens because digitized specimens allow anyone with Internet access to obtain digital images of specimens and their associated metadata (Drew et al. 2017). These specimens can also enable the digital repatriation of data associated with specimens collected historically from developing countries and now stored in distant NHCs (e.g., Brazil's Reflora project; Peterson and Gordillo-Martínez 2002, Nelson and Ellis 2018).

Digitized collections can provide an avenue for the training and education of new scientists and the public (Lacey et al. 2017, Ellwood et al. 2019, Lendemer et al. 2019). For example, many plant specimens can be identified to genus simply by examining a specimen image. Therefore, learning to identify digitized herbarium specimens can provide a valuable training tool to foster the next generation of taxonomists globally. Digitized specimens also support specimen-based educational activities and can be particularly important for those for whom NHC visits may be logistically or financially difficult (Powers et al. 2014, Drew 2015). Indeed, NHCs with robust digital infrastructures can reach a global audience, even when physical buildings are closed, or travel is restricted (Solly 2020). For instance, teachers worldwide can use digital materials to design data-driven exercises for their students such as AIM-UP (http://aimup.unm.edu) and BLUE (www.biodiversityliteracy.com). Finally, the accessibility of digitized specimens provides a valuable platform for educating and engaging the public through citizen science efforts where individuals are engaged directly in the digitization efforts (e.g., Notes from Nature; www.notesfromnature.org) or by participating in research using imaged specimens (von Konrat et al. 2018).

Although digitization efforts hold promise for increasing the diversity of stakeholders able to access NHCs, challenges still remain. The reliability, speed, and cost of Internet access are still major barriers to access for many populations. For instance, half of rural Americans and two thirds of residents living on US tribal lands still lack access to advanced broadband Internet (FCC 2015). Access issues are even more prevalent in developing countries, severely limiting the ability of many populations to access large amounts of NHC data (West 2015). Moving beyond simply making digital specimen data available and promoting active partnerships and collaborations with end users from many communities is key to realizing the transformative potential of collection digitization (Drew et al. 2017).

Increasing outreach initiatives. NHCs have the ability to increase participation of groups historically underrepresented in museum sciences through public education and outreach, training programs, and research collaborations. These activities benefit NHCs via augmenting collections and increasing public investment while simultaneously benefiting participating communities through increased knowledge, transparency, and involvement in research and community-relevant decision-making (Haywood 2014, Roger and Klistorner 2016, Ballard et al. 2017).

Increasing local collections and collections-based projects through citizen science allows NHCs to engage communities by promoting learning connected to local organisms and ecosystems (Monfils et al. 2017). For instance, sponsoring bioblitzes in nearby urban areas can add local specimens to NHCs while also contributing data to address emerging questions in urban and evolutionary ecology (Ballard et al. 2017, Schmitt et al. 2019). NHCs can also make use of existing resources such as Zooniverse (zooniverse.org) and iNaturalist (inaturalist.org) to forge a link between collections and local natural resources and wildlife through public education and participation in data collection.

In addition, NHCs offer a promising avenue to engage students, researchers, and the general public (Powers et al. 2014, Lacey et al. 2017, Ellwood et al. 2019). Museum specimens are authentic, tangible, and have the potential to intrigue and excite students of diverse backgrounds, especially when specimen-based educational approaches are place-based and address issues of local relevance to students and the public. Inquiry-based activities in particular are a strength of specimen-based education (e.g., Feldman et al. 2012). Programs that train NHC staff to work with students from underrepresented groups and partner them with students at local or affiliated universities (e.g., the Undergraduate Program at the Museum of Vertebrate Zoology, University of California, Berkeley) or institutions and professional societies serving underrepresented groups such as Historically Black Colleges and Universities (HBCUs) and the Society of the Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS) can increase the productivity of NHCs while creating a pipeline of diverse talent (Cook et al. 2014, Johnson and Gandhi 2015, Hiller et al. 2017, Lendemer et al. 2019).

Taken together, these approaches can help build an informed and creative community that will be more capable of integrating across disciplines as they attempt to tackle challenges including

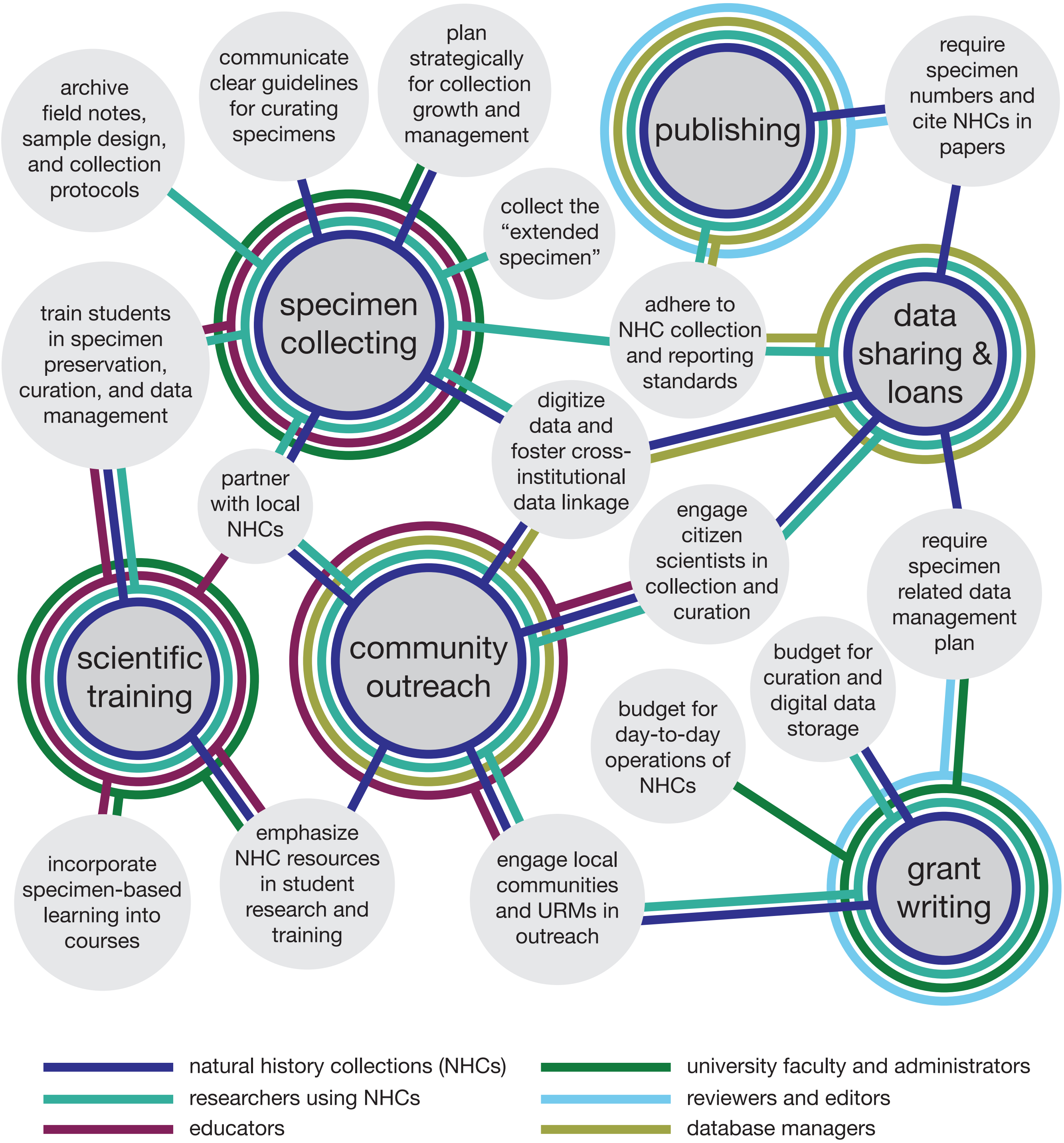

Figure 4. Recommendations for how diverse members of the scientific community can support NHCs. Line colors indicate tasks that can be performed by each actor.

the impacts of our rapidly changing environment on human health, food security, biological persistence, and future issues affecting communities across the globe (Ellwood et al. 2019).

Conclusions

NHCs hold the primary record of organismal diversity, a substantial proportion of which no longer exists. Collectively, NHCs represent a vital resource for researchers, teachers, and the general public. Ensuring that NHCs continue to serve as valuable scientific resources into the future requires the combined efforts of the scientific community to acknowledge the importance of NHCs, and to contribute to efforts to fund, curate, and expand collections (figure 4). Continued conversations between NHCs, the scientific community, and the public will help achieve these aims.

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