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SYMPOSIUM PROCEEDINGS: THE EXPANDING ROLE OF NATURAL HISTORY COLLECTIONS

The Expanding Role of Natural History Collections

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Museum specimens serve as the bedrock of systematic and taxonomic research and provide the basis for repeatability or reinterpretation of preserved aspects of phenotypes. Specimens are also fundamental to fields such as ecology, behavior, and development. Each specimen is a record of biodiversity and documents a particular species present at a particular place at a particular time. As such, specimens can provide key evidence for biodiversity and conservation initiatives. Four aspects of natural history collections and their use are discussed here: 1) collection, curation, and use of specimens, particularly non-traditional specimens; 2) the use of specimens and technological advances in morphology, ontogeny, systematics, and taxonomy; 3) specimen use in other fields of biology and ecology; and 4) specimen use in education and outreach. Collections, and their vitality, depend on both their continued roles in traditionally supported fields (e.g., taxonomy) as well as emerging arenas (e.g., epidemiology). Just as a library that ceases buying books becomes obsolete, or at least has diminished relevance, a natural history collection that does not continue to grow by adding new specimens ultimately will limit its utility. We discuss these roles of specimens and speak directly to the need to increase the visibility of the inherent value of natural history collections and the care of the specimens they protect for future generations.

EFFORTS to collect and preserve natural history specimens date back centuries and are intimately tied to the growth of the natural sciences (Farrington, 1915). In the early stages of museums as they are understood today, from the 16th to 17th centuries, collecting efforts were intimately linked to private cabinets of curiosities, the treasures of the wealthy and aristocratic members of society, and were intended to be shown off as a status symbol (Lane, 1996). Such cabinets continued to be in vogue throughout the 18th century (Farber, 1982), and as an offshoot to this competitive assembly of collections, the efforts to catalog and classify specimens held in such collections directly led to advances in taxonomy and biology (e.g., Linnaeus's and Artedi's development of binomial nomenclature). With a shift from private cabinets to institutionalized collections of nationalistic scope (e.g., British Museum, Smithsonian Institution), particularly evident during the 18th century (Lane, 1996; Alberti, 2002), the utility of specimens to support advances in the natural sciences increased dramatically. However, despite calls to their importance and continued relevance in many fields (Lane, 1996), museum collections lost broad-based institutional support, particularly in the 20th century, due to the growing appeal for data sources that were decoupled from archived preserved specimens (e.g., rise of genetic lines of evidence originating during the New Synthesis). This loss of support and perceived "outdated" need for collections have led to continued erosion of collections of all sizes, but particularly of so-called "small" collections (Casas-Marce et al., 2012; Singer et al., 2019).

Museum specimens are the bedrock of systematic and taxonomic research and provide the basis for repeatability or reinterpretation of preserved aspects of phenotypes. Specimens are also fundamental to fields such as ecology, behavior, and development. Each specimen is a record of biodiversity and documents, through a physical object, that a particular species was present at a particular place at a particular time. As such, specimens can provide key evidence for biodiversity and conservation initiatives. Billions of specimens are housed in collections around the world (e.g., approximately 1 billion specimens in U.S. collections alone; Biodiversity Collections Network [BCoN], 2019), representing archives of physical objects of biodiversity ranging from bacteria to dinosaurs. While physical objects remain the core concept of specimens, in recent years there has been a shift in how specimens are utilized. This has led directly to vast digitization initiatives aimed at increasing the visibility and utility of specimen usage as well as downstream use of associated data (BCoN, 2019). This has been encapsulated in the concept of the so-called "extended specimen" (Webster, 2017). Connections between data from an individual specimen or shared by multiple specimens that are in some way related add to the potential utility of any one specimen. The Institute of Museum and Library Services (IMLS) estimates over 13 billion items in all collections within the U.S. (IMLS, 2019; inclusive of libraries, as well as collections

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Fig. 1. Presenters in the symposium "The Expanding Role of Natural History Collections," held at the Joint Meeting of Ichthyologists and Herpetologists, July 2019 in Snowbird, Utah. Back row (left to right): Nelson Rios, Zachary Randall, Brian Sidlauskas, Randal Singer, Michael Webster, Aaron Bauer. Middle row (left to right): Katherine Bemis, Stacy Farina, Julie Winchester, Ai Nonaka, Luiz Rocha, Katherine Maslenikov, Casey Dillman. Front row, seated (left to right): Eric Hilton, Sarah Huber, Gregory Watkins-Colwell, Dante Fenolio. Not pictured: Brad Carlson, Sara Ruane, Rachel Welicky. Photo by Mark Sabaj.

of cultural heritage). By having such collections fully digitized and available for study leads to the potential of unexpected connections between related items that bring more value to each item than any has on its own. For instance, in a hypothetical scenario, there could be archives of field notes, specimens, and photographs that are spread among university archives (where an individual researcher worked), a national museum (where they deposited specimens), and a local history museum (that has a collection of photographs documenting the history of a particular area), respectively. An actual example is a gorilla specimen from P. T. Barnum's menagerie in the Yale Peabody Museum of Natural History (YPM MAM 005956), for which photographs and other archival materials associated with this specimen as a living animal are stored at the Barnum Museum in Bridgeport, Connecticut. Further, although specimens may be stored isolated from one another, they are often collected as part of a community, whether intentionally (e.g., all fish species encountered in a particular area) or unintentionally (e.g., specimens collected that have a substantial parasite load effectively preserve the parasite fauna as well as the host). This is an aspect of the extended specimen: making connections among specimens, collections, and beyond. The advent and application of new technologies being applied to specimens, together with this extended specimen concept, offers the potential for powerful new uses of natural history specimens for the advancement of science.

This paper and others that follow in these proceedings address the emerging roles of specimens, and were born from a symposium held at the Joint Meeting of Ichthyologists and Herpetologists in July 2019 at Snowbird, Utah (Fig. 1). The specific topics of presentations made during the symposium were wide-ranging (Appendix 1), but all were united by the notion that there is a continued need to increase the visibility of the inherent and critical values of natural history museums and the importance of the care of the specimens they protect for future generations. There have been several recent discussions of the importance of natural history collections and the value of specimens from a variety of perspectives, and with a variety of motives (Lane, 1996;

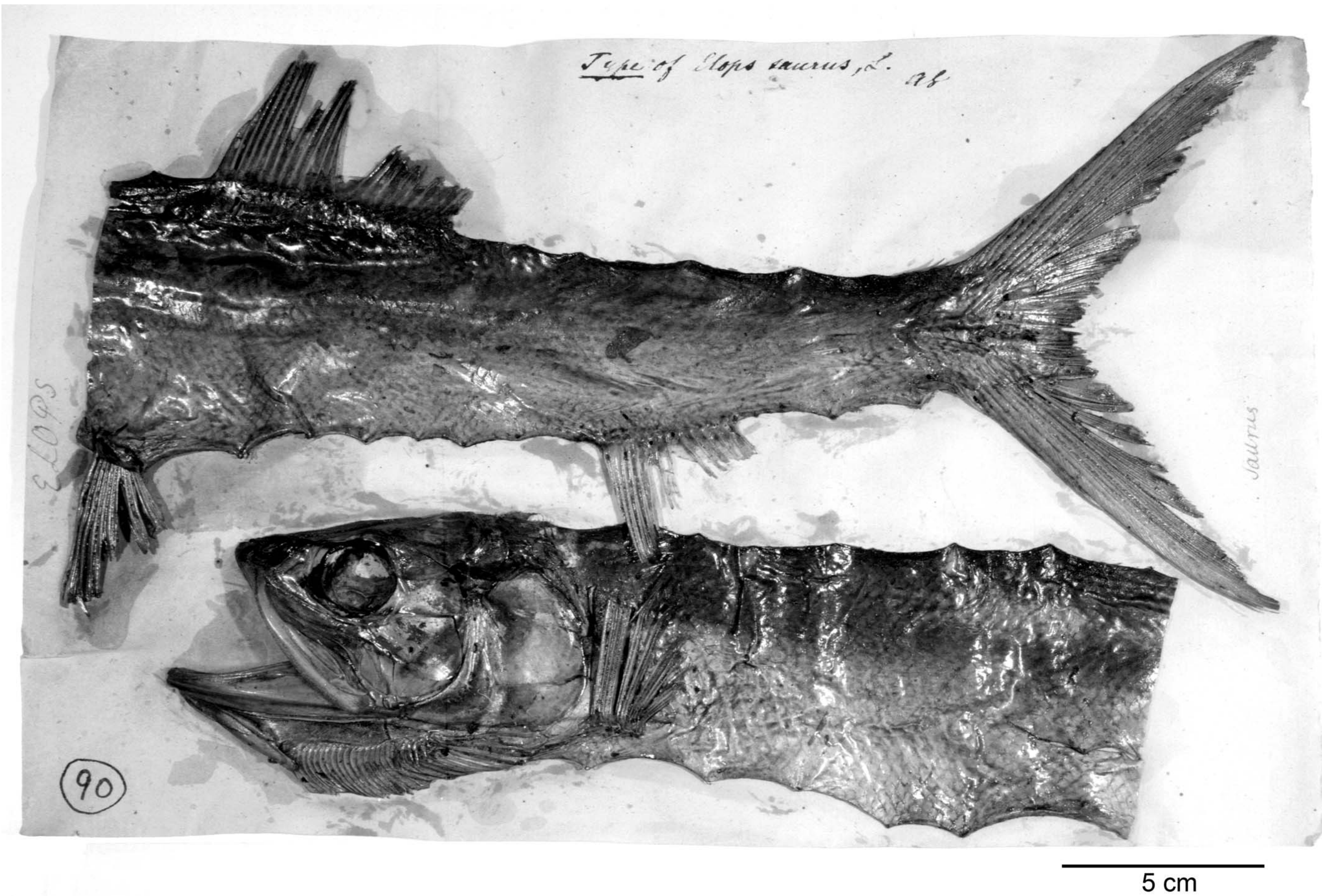

Fig. 2. The lectotype of *Elops saurus* Linnaeus, 1766 (LINN 90). This specimen is preserved as a dry, pressed specimen that was collected by Alexander Garden (1730–1791) in South Carolina (USA) and sent to Linnaeus in 1763 (information from Linnean Society of London). Photo courtesy of William E. Bemis.

Suarez and Tsutsui, 2004; Bradley et al., 2014; Kamenski et al., 2016; McLean et al., 2016; Schindel and Cook, 2018; Watanabe, 2019; Bakker et al., 2020). Collections, and their vitality, depend on both their continued roles in traditionally supported fields (e.g., taxonomy) as well as emerging arenas (e.g., epidemiology). One of the unique qualities of collections is that they preserve historical data, offering insight into past events. However, collections must not become stagnant. Just as a library that ceases buying books becomes obsolete, or at least has diminished impact and relevance, a natural history collection that does not continue to grow by adding new specimens immediately limits its utility. Four aspects of natural history collections and their use are discussed here: 1) collection, curation, and use of specimens, particularly non-traditional specimens; 2) the use of specimens and technological advances in morphology, ontogeny, systematics, and taxonomy; 3) specimen use in other fields of biology and ecology; and 4) specimen use in education and as beacons for public engagement in science.

WHAT IS A "SPECIMEN"?

> *Together, a preserved organism and its label are a scientific specimen that has great intrinsic value. Separately, the label is a piece of paper with meaningless inscriptions upon it, and the plant, spider, microbe, mushroom, or bird, though carefully preserved, is just so much dead organic matter.* (Lane, 1996: 536)

The answer to this sub-titular question may seem obvious to those who work with collections. However, there is value in reflecting on the concept of a specimen in light of the emerging roles of natural history collections. Each discipline—ichthyology, herpetology, and other natural sciences—has its own traditional approach to preserving research specimens. These approaches may change over time. For instance, the mid-to-late 18th-century Linnean approach to preserving fishes as flattened, dried specimens on herbarium sheets (Fig. 2) gave way to alcohol preservation (Fig. 3). With these changes, so the utility of the specimen changes. For example, the preservation of the whole animal allows for radiography to examine internal structures, as well as gut contents and other aspects of the animal's biology. However, by and large, researchers of specific biological disciplines have come to expect the kinds of specimens that will be encountered in collections. For ichthyology and herpetology, the dominant type of specimens is of course fluid-preserved, alcohol-stored whole-body specimens. In ichthyological collections, these are typically found as lots, with all specimens of a single species from a single collection event. In contrast, in herpetological collections, each adult individual is often given a unique identifier; larvae and egg masses

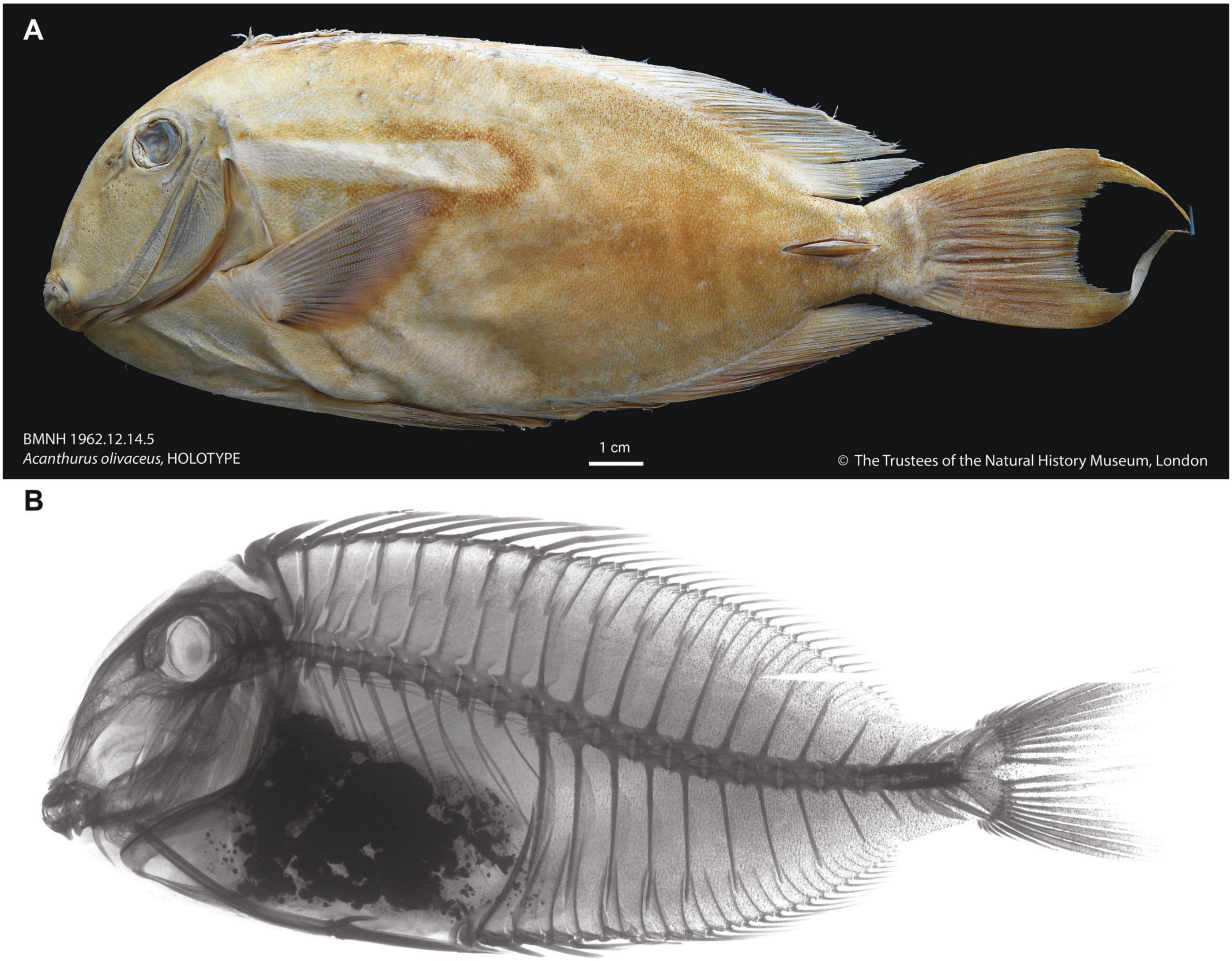

Fig. 3. The holotype of *Acanthurus olivaceus* Bloch and Schneider, 1801 ex Forster (NHMUK 1962.12.14.5). (A) Fluid-preserved specimen collected in 1774 in Tahiti (Society Islands, French Polynesia, South Pacific) by Johann Reinhold Forster (1729–1798), the naturalist on James Cook's second voyage (information from *Eschmeyer's Catalog of Fishes*). (B) Radiograph of the specimen, showing details of its skeletal anatomy as well as aspects of its gut contents. Photos courtesy of James Maclaine and Nemo Martin (NHM), © The Trustees of The Natural History Museum, London.

are treated as lots. Associated samples (e.g., tissues), metadata (e.g., collection locality), and other information (e.g., photographs) related to these specimens are ideally linked to the physical specimen and available in a searchable database. It has become standard practice to separate any individual ichthyological specimen that has been altered in any way from the other specimens of a lot as a way of clarifying this alteration (e.g., a specimen that has been prepared as a cleared and stained specimen) and making it easier to cite the use of an individual specimen and track the history of its alteration. As techniques continue to be developed (e.g., contrast enhanced staining for soft tissue reconstruction of computed tomography), the importance of this detailed record of any and all alteration of a specimen, no matter how seemingly innocuous or reversable, is critical to track the long-term impacts on the specimen by these techniques.

The concept of what constitutes a specimen has been growing beyond the traditional types of specimens (e.g., fluid-preserved and skeletal specimens). Although not ideal, digital images may be archived as voucher specimens for tissue samples, as a proxy for voucher specimens that are too large to preserve or that are unable to be collected whole, for instance. This image, however, can be viewed as a representation of the physical object, and therefore the specimen. Specimens can provide a range of biological information, including diet, parasite loads, age and growth, and fecundity (see below). There are also instances where a preserved specimen may be found to include undescribed taxa. For example, Vecchione and Young (1998) described a new family of squid (Magnapinnidae) based in part on a specimen taken from the stomach contents of a specimen of *Alepisaurus ferox*. Such synergy between collections, specimen-based research, and other areas of biological sciences will only increase into the future.

In addition to the curation of data and other information related to specimens, the type of material that is curated has also diversified. For example, fish otoliths (e.g., Maslenikov,

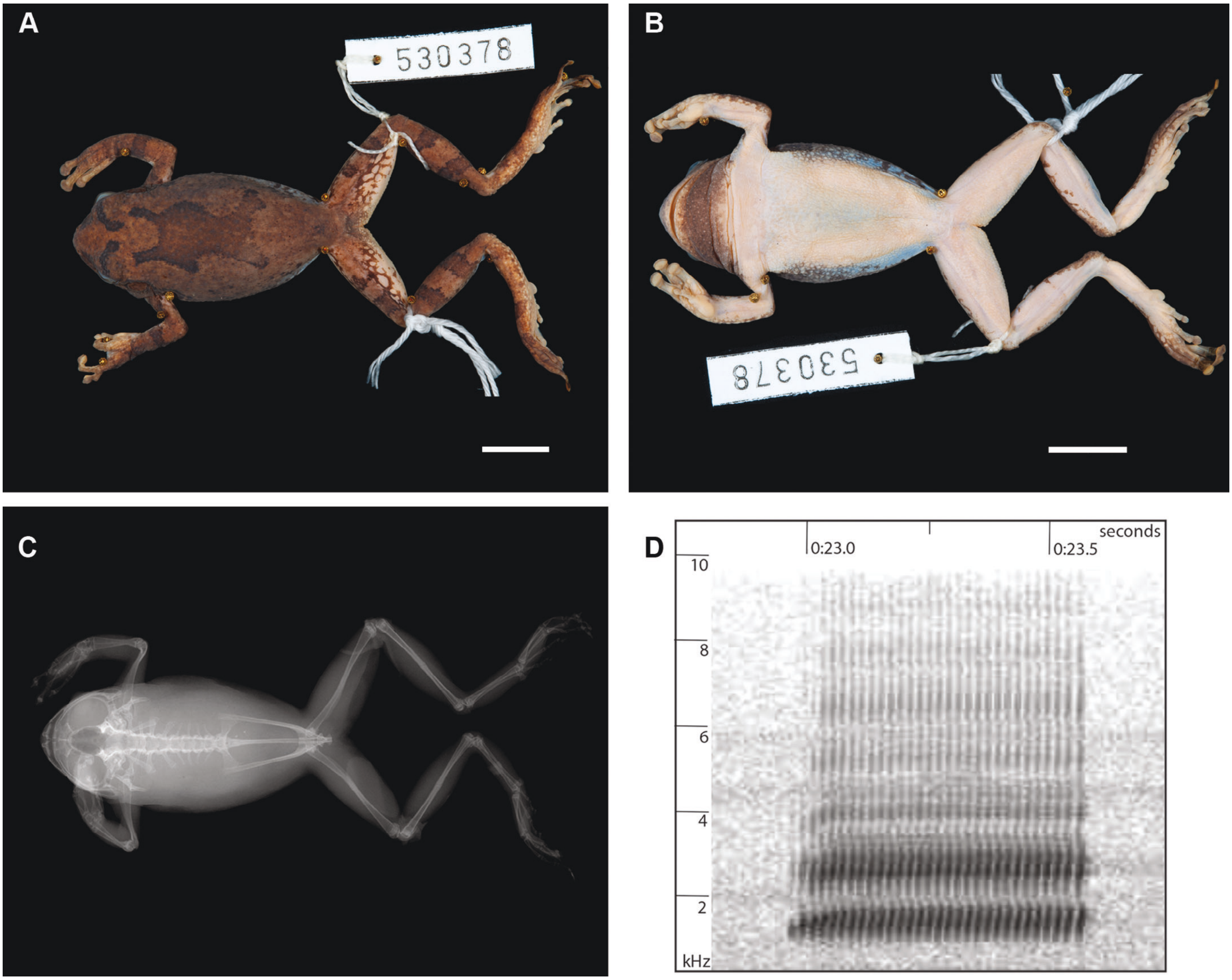

Fig. 4. A specimen of Cope's Gray Tree Frog (*Dryophytes chrysoscelis* (Cope, 1880); USNM 530378) collected in 1982 in Virginia Beach, Virginia. Prior to collection, the call of this frog was recorded, and this recording is archived in the Macaulay Library (Cornell University). (A) Photo of specimen in dorsal view. (B) Photo of specimen in ventral view. (C) Radiograph of the specimen. (D) Sonogram of this specimen's call (ML205607). Images in A, B taken by Esther Langan, and C, taken by Ken Tighe; images received from Steve Gotte (USNM).

2021, this volume), turtle eggs (Montanari, 2018), histological slides (Williston, 2016), and other non-traditional specimen preparations have become recognized as important for accessioning into natural history collections. The physical object is, of course, the root of the specimen, but the associated data also are part of the specimen, and require curation and preservation in their own right. For example, these specimens include the associated recordings of anuran calls (Fig. 4) and videography and photography of specimens *in situ* made prior to collection that record behaviors (Nonaka et al., 2021). More generally, specimens can be viewed as including any aspect of the specimen that can be archived, curated, and used to advance the understanding of its biology, including data points related to the physical object. Said another way, the value of a specimen is not only inherent in the specimen itself, but, perhaps more importantly, it also comes from the use and study of the specimen and all the information that is contained by the context of its collection. By expanding the concept of the specimen to include not only the physical object itself but also the associated aspects of the object that are recorded both pre- and post-collection, the potential uses of that specimen also increase.

NEW APPROACHES FOR THE STUDY OF SPECIMENS

> *An explosion of advancing methods in recent decades has opened new avenues of research that can exploit invaluable historical material*. (Sumner-Rooney and Sigwart, 2017: 73)

Advances in the natural sciences often come from applying a novel use of specimens, techniques, or other technological advances in the study of morphology, ontogeny, systematics, and taxonomy (Sumner-Rooney and Sigwart, 2017). The novel use of a technique applied to the study of specimens can be seen as a trigger for the widespread application of that technology, similar to hype patterns that are often used to describe the use of technological innovations in industries, as well as academia (van Lente et al., 2013). Hilton et al. (2015) recently reviewed the use of new technologies in the study of fish morphology specifically, but this can be extended to the study of reptiles and amphibians. Most recent technologies being applied to specimens involve new imaging technologies (e.g., Lauridsen et al., 2011), including the use of Z-stacking of images to increase depth of field (particularly in microscopic studies) as well as computed tomography (CT) scanning. This application of new imaging methods for specimens is undoubtedly in conjunction with a rise in digitization and data mobilization efforts (Nelson and Ellis, 2018).

Computed-tomography, which was first applied to the study of fish morphology in the 1980s, has grown tremendously in recent years. This tracks the advances in the technology of CT-scanning and new applications of refined staining techniques (Gignac et al., 2016; Gignac and Kley, 2018), such that ever-smaller samples can be digitally rendered and new aspects of soft tissues can be visualized (e.g., Fig. 5). Further, the use of CT technology has been extended, in ever increasing levels of detail, to study specimens largely inaccessible, namely paleontological specimens (e.g., Daza and Bauer, 2012; Daza et al., 2018). As Hilton et al. (2015) suggest (also G. D. Johnson, pers. comm.), the adoption and refinement of CT-scanning mirrors the attraction of researchers to clearing and double staining in the 1960s and 1970s, following the first use of trypsin and alcian staining. Until that time clearing and staining was limited to alizarin staining for bone and potassium hydroxide clearing, which did not produce fully transparent specimens. As more and more researchers applied this technique to the study of morphology, broader questions began to be addressed, and more comparative datasets have been established. Another analogous situation relevant to the use of specimens can be found in the advances in genetic research of the study of organisms in the 1990s and 2000s. Following the advances in sequencing and the subsequent reduction in cost of sample preparation and ease of analysis, the field of genetic systematics and other traditionally whole-specimen-based lines of inquiry exploded. With the advent of Next Generation Sequencing, it is expected that another round of application of this new technology to broader and broader studies will occur. In an informal survey of colleagues and collections, requests for tissue samples are now outpacing requests for whole specimens. A related and potentially problematic trend is that very few individuals request the voucher specimens from which the tissue sample is derived, with little or no interest in first-hand identification of the taxon.

No matter what technological advances are applied to specimens and used to gather biological data, it is important to keep in mind that the specimen—the physical object—is the basis for all interpretations. This reinforces that the care of specimens and the tracking of their use is of the utmost importance. Even application of non-overtly damaging sampling methods may have unforeseen effects on the long-term integrity of specimens. All sampling methodology applied to specimens, no matter how apparently benign, should be noted in specimen records so that in the future such effects can be better understood. Further, it is important to note that new technologies must be used in concert with direct observations—dissection, measurements, and meristic data, for instance.

BEYOND SYSTEMATICS AND TAXONOMY

> *All biological sciences must admit their obligations to natural history museums for many of the data which have aided in their development.* (Farrington, 1915: 208)

While taxonomy and associated fields of study (e.g., systematics and morphology) remain the primary use of natural history specimens, the potential uses of specimens include studies related to human health (e.g., tracking epidemics and environmental contaminants), agricultural impacts (e.g., identification of pest species), habitat loss, biological invasions, and global climate change (Suarez and Tsutsui, 2004). Although most widely viewed as homes of systematic and taxonomic research, museums and collections have been associated for a long while with broad ecological research programs. For instance, Noble (1930) documented the then-growing program in physiology, behavior, and ecology of amphibians, reptiles, and fishes, including experimental research on living specimens at the American Museum of Natural History (AMNH). "The advance of biology resembles the growth of a tree in that while branches may be thrust out in all directions there are certain zones of growth near the apex which carry the tree upward. These zones of growth lie today [i.e., in 1930] in the experimental approach to problems of species, structures, and functions." (Noble, 1930: 482). This trend was not limited to stand-alone museums, such as the AMNH, which was the focus of Noble's essay. For example, Sunderland (2013) ties the changes of directorship at the Museum of Vertebrate Zoology (MVZ, University of California, Berkeley) in the mid-1900s to the development of infrastructure (e.g., live animal facilities) and building of new collections (e.g., anatomical specimens, chromosomal preparations, frozen tissues), complementing similar developments to accommodate studies of animal behavior at AMNH under Noble's leadership. There have been a number of reviews of the value of specimens to fields outside of so-called traditional uses (e.g., Pyke and Ehrlich, 2010; Lendemer et al., 2020), and the reader is directed to such reviews for more examples and discussion. Our intent here is to highlight some examples of uses of herpetological and ichthyological collections in broader biological studies.

Study of museum specimens using new imaging techniques, has led, for instance, to a better understanding of the surface structure of skin to better understand the interface between organisms, including fishes, reptiles, and amphibians, and their environment (Wainwright et al., 2017). Such new inferences can provide bio-inspiration for technological advances (e.g., Ditsche and Summers, 2019).

The specimens of natural history collections record not only the presence of a particular species at a particular place at a particular time, but also the connections with other individuals collected and preserved at the same time. It is this aspect of collections that lead to them being important resources for ecological studies, environmental impact assessments, biodiversity monitoring, and formulation of conservation plans (Lane, 1996). Although there are biases in the building of collections that will limit how they can be used in an ecological sense (i.e., often not everything that is collected is preserved, and there is often no quantitative aspect to the collection design), there are intrinsic values of collections to ecological studies, and associated disciplines

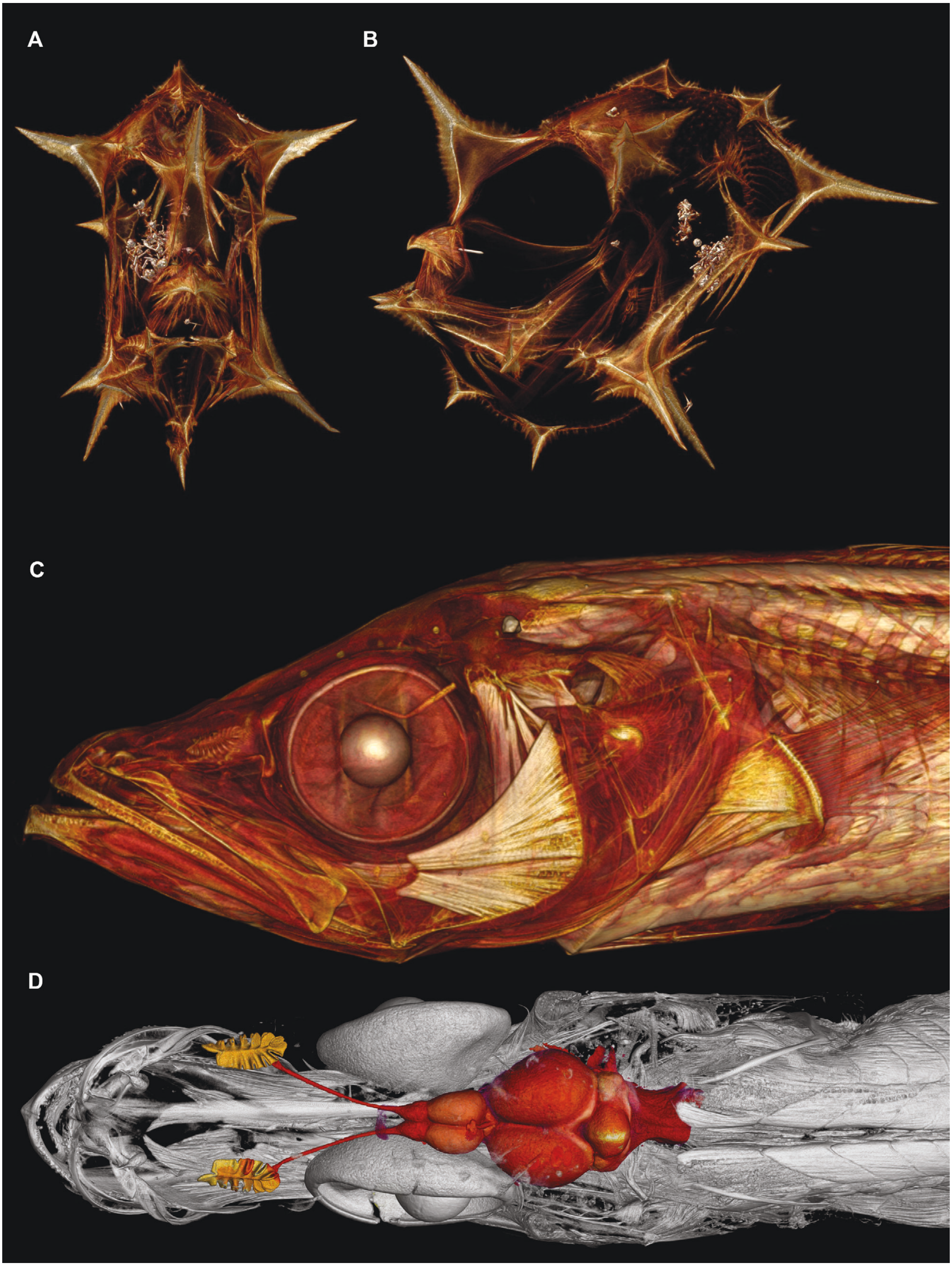

Fig. 5. High resolution micro-computed tomography reconstructions of larval specimens. (A) Frontal and (B) lateral views of a larval specimen of the Slender Ocean Sunfish, *Ranzania laevis* (VIMS 32062). (C) Lateral (VIMS 33314) and (D) dorsal (VIMS 33317) views of larval specimens of *Pleuragramma antarcticum* that were stained with phosphotungstic acid (PTA) prior to scanning, allowing the visualization of soft tissues, including muscles (C) and brain and nasal rosettes (D). Images in A, B, generated by Adam Summers, and C, D, generated by Edward Stanley.

such as fisheries science. Most fundamentally the value is that you cannot study or manage what cannot be identified (Collette and Vecchione, 1995). Even well-studied, commercially exploited and encountered faunae continue to become better understood (e.g., Western North Atlantic), with new taxa being described. A host of new uses for historically collected specimens are providing greater insight into contaminant analyses (Hill et al., 2010), trophic analyses (e.g., through stable isotope analysis; Fanelli et al., 2016), temporal changes in diet (Manoel and Azevedo-Santos, 2018; Reiserer et al., 2018; Wiseman et al., 2019), life history variation (Caruso and Rissler, 2019), community ecology and global change (Meineke et al., 2018; Schmitt et al., 2018), and the rise of infectious diseases (Ouellet et al., 2005; Richards-Hrdlicka, 2013). Survey programs provide a tremendous source of samples and data. At the same time, collections provide a centralized location for specimens that are organized and easily accessible for future use. Importantly, collections provide a continuity of care for specimens. Further, collections provide access to data, which is often a requisite for federally funded research. Although there are several examples of well-developed relationships between survey programs and collections (Maslenikov, 2021, this volume), survey programs are often operated without any connection to natural history collections, despite the reciprocal value-added benefits each can provide the other (Lane, 1996).

FOR THE PUBLIC GOOD

> *Engagement with natural history is endlessly rewarding in all its forms; collections not only enable people to form their first connections with nature, but to cultivate a lifetime of increased understanding of, and delight in, the natural world.* (Hewitt, 2016)

The use of preserved specimens, and of natural history collections generally, in education has long been recognized (Baker, 1923) and is a core function of virtually all museums whether or not they are directly linked to a university (Frost, 1998). Specimens are used in graduate and undergraduate classes to illustrate and augment laboratory and lecture material, and are invaluable resources for introducing students to key concepts in biology (Cook et al., 2014). Indeed, many collections (such as those associated with universities) are not only used by students at the institution but also may be built by the students themselves through the course of class field trips (Kohlstedt, 1988). During the 1800s, collections were regarded as selling points to students and faculty alike: “Natural history museums continued to be built, expanded, and publicized as part of the claim to be a comprehensive college or university” (Kohlstedt, 1988: 31). Imaging of specimens and digitization of collections have broadened the impact and connections that students may have with specimens. For instance, new developments in didactic methods and online course technologies have allowed specimens to be studied digitally (e.g., Sidlauskas et al., 2021, this volume). Further, natural history collections are at the center of several initiatives to capitalize on student interest in local examples of core biological phenomena. For example, the NSF-supported program Advancing Integration of Museums into Undergraduate Programs (AIM-UP!) developed modules to provide inquiry-based experiences for students using digitized collection data and specimens (Cook et al., 2014). Such programs provide models for increasing the ways in which specimens and collection data are used in the classroom. There does appear to be a conflict between the recognition of the value of collections for education generally and administrative support for collections, particularly at universities (although not solely; see Mayer et al., 2014). Several recent examples of loss of support of collections have been profiled in the media (e.g., Kaplan, 2017). This may relate to broader loss of support for natural history generally in college curricula (Tewksbury et al., 2014; Able, 2016; Barrows et al., 2016).

Perhaps of greater value than the importance of collections to college and university curricula, at least in some respects, is the role specimens can have in primary and secondary education (i.e., K–12), both in formal and informal ways. Specimens can be valuable catalysts for attracting young students to pursue specimen-based careers in biology. While there are distinct challenges to incorporating specimens into K–12 educational opportunities (e.g., lack of accessibility to collections, insufficient background knowledge, etc.), these can be overcome (Powers et al., 2014).

The relationship between collections and K–12 education in some ways mirrors the relationship between collections and the general public. Specimens provide the basis for intrinsic fascination with the natural world. Outreach events with specimens as tangible objects (Fig. 6) often provide the draw for people to want to know more about biology and nature. Beyond general outreach events, specimens and natural history collections generally provide an ideal platform for the public to become engaged in science and support the collections through volunteer programs and community science opportunities, in the field, in the collection, and online (Sforzi et al., 2018). Several online platforms exist that engage the public in collections-based science, including Notes from Nature (https://www.zooniverse.org) and iNaturalist (https://www.inaturalist.org; Heberling and Isaac, 2018). This exposure to natural history collections increases the public understanding of what collections are and their inherent value. Most importantly, they provide a tangible connection between members of the public and collections, which gives people a sense of ownership and investment in the collections. It is this connection that people have with collections that make these resources part of not only the natural heritage of a region, but also its cultural heritage (Ferner et al., 2005).

WHAT DOES THE FUTURE HOLD FOR SPECIMENS AND COLLECTIONS?

> *At the time of collection and preservation it is impossible to predict how specimens might be used in future studies.* (Anderson and Pietsch, 1997: 9)

Natural history collections have always made use of technologies and innovations adopted from other fields. Throughout their history, natural history collections have always incorporated equipment and methods used by other industries, whether it be reusing old food containers for fluid-preserved specimens or repurposing cigar boxes for the storage of insect specimens. Current best practices include an array of methods and tools that are standard to natural history collections but were initially invented for other

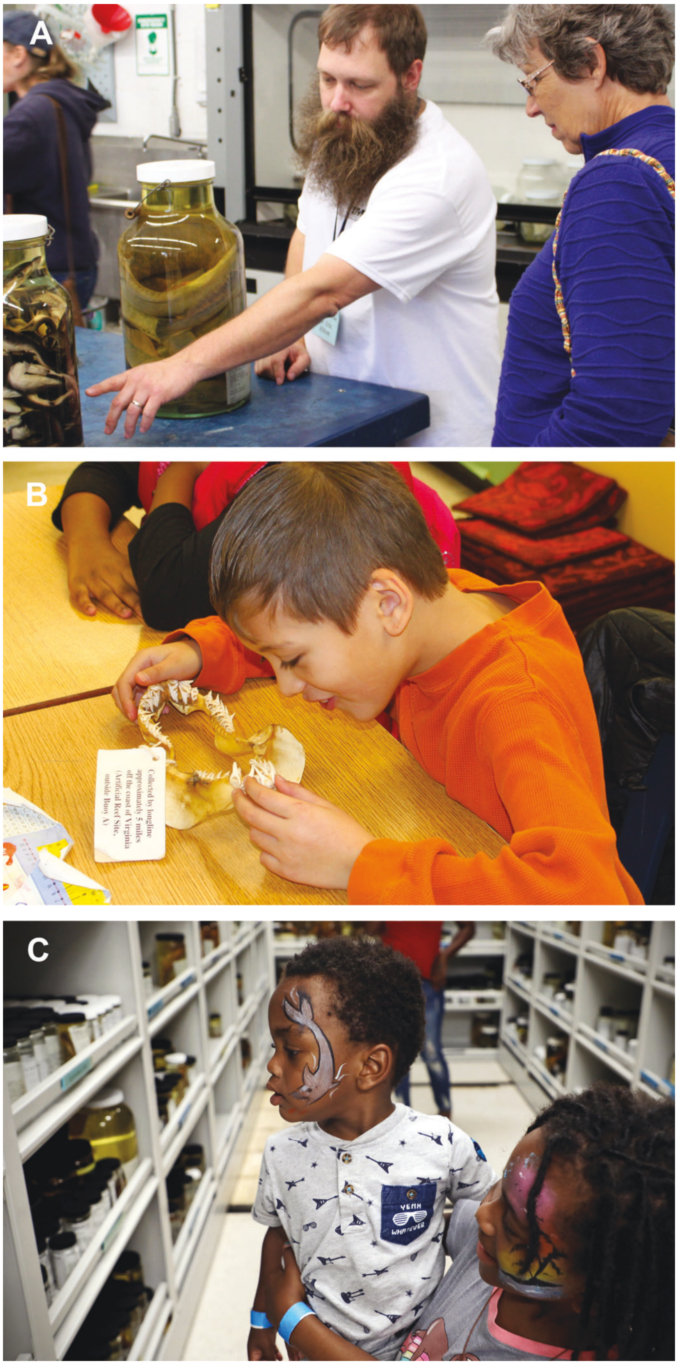

Fig. 6. Specimens being used for public engagement. (A) VIMS Marine Science Day, 2013 (photo by VIMS staff). (B) Student looking at a specimen in a classroom event, 2013 (photo by David Malmquist). (C) Children looking at specimens during tour of the VIMS Nunnally Ichthyology Collection, 2019 (photo by Aileen Devlin). Photos courtesy of VIMS News & Media Services.

purposes (Table 1). The use of electronic databases, tissue samples, robotics, CT-scanning, and even the use of formalin-fixation are all standard practices in contemporary collection management that were initially developed for other purposes. Innovations within the biomedical field seem to lend themselves most readily to morphological studies more broadly. Given this, an examination of the top ten biomedical innovations for 2019 reveals some surprises and may provide clues as to the future of collection management and use (Table 2). As the types of technologies applied to the management and study of natural history specimens expand, the range of users of these specimens and their associated data will continue to grow. For instance, an underappreciated use of collections relates to the role of reference collections in identifying and possibly mitigating emerging infectious diseases (DiEuliis et al., 2020). Such value of collections, particularly with immediate application to human health, agriculture, and fisheries, needs to be further considered, with funding opportunities put in place to support collections growth and maintenance.

In conclusion, the role that natural history collections and the specimens that they contain play in modern biological sciences are as diverse as the collections themselves. Because they are the foundation of understanding and describing biodiversity, there remains a need to continue collecting activities, including general collections (Patterson, 2002; Rocha et al., 2014). Many habitats remain poorly sampled, and the biodiversity of many regions of the world remain poorly understood. Scientific collecting has been shown to be unlikely to negatively impact a fauna (Rocha et al., 2014), and there are far more direct (e.g., commercial and recreational fishing) and indirect (e.g., habitat loss and introduced species) pressures that exert greater challenges to the existence of taxa. This is not to say that collections should be made indiscriminately. As is the case for mammals (Patterson, 2002) and other taxonomic groups, there are codes of ethics for careful and responsible collecting in ichthyology and herpetology. Scientific collectors are bound by both legal and ethical obligations for their activities and to abide by these. Coupled to the importance of collecting activities is the need for continued support of collections from both institutional sources as well as external funding opportunities (e.g., IMLS; Schindel and Cook, 2018). As observed by Sumner-Rooney and Sigwart (2017: 82), “Museum collections remain under threat, and funding for collections research is in a highly vulnerable position across the world.” Those of us who use specimens, resources, and data from natural history specimens—no matter in what format—have an obligation to advocate for the continued support of collections in general.

DATA ACCESSIBILITY

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Table 1. Some standard natural history collection practices initially developed for other intentions.

Standard practice	History	Approximate year adopted by collections
Formalin-fixation	Discovered 1859; mostly in construction and textiles	Probably first used for collections 1905 (Simmons, 2014)
Genomics	DNA 1957 (1962 structure)	First collections use early 1970s
Electronic databases	Developed in 1960s; first relational databases 1974 and 1977	1967 first museum database (GRIPHOS); mostly art
Computed tomography	1972 invented; 1974 first clinical use in medicine	1980s microCT scans in research; 1988 first museum specimen CT scans (†*Archaeopteryx*, Haubitz et al., 1988; *Latimeria*, Schultze and Cloutier, 1991)

Table 2. Potential innovations for collections based upon "Top 10 medical innovations for 2019" (from Saleh, 2018).

Innovation	BioMed use	Potential collections use
Pharmacogenomic testing	To utilize the patient's own genetic characteristics and build a treatment plain tailored to them.	Because of the need to examine large numbers of genes, likely in a short period of time, there will likely be improvements to molecular data acquisition and analysis methods that can be utilized for non-medical studies.
Artificial intelligence	Help physicians identify pathology on diagnostic scans; interpret large collections of electronic health data.	Could be useful data-mining aggregated electronic collection records as well as GenBank, GBIF, and other data providers to search for patterns or help identify patterns within the data housed in collection databases.
Immunotherapy	To treat solid-tumor types, such as melanoma and non-small cell lung cancer and potentially other tumor types.	Likely will provide novel molecular-based techniques for tagging specific tissue types which could prove useful in embryologic studies or studies of pathology.
3-D printing	Health products are being 3D printed that are specific to the patient, including prosthetics, implants, and airway stents, including printing using living cells.	Significant improvements in printing models for educational use. Potential for printing anatomical features which could be studied *ex vivo* or implanted into model organisms to better understand functionality.
Virtual reality/mixed reality	Primarily used to visualize pathology and for teaching students utilizing realistic scenarios with reduced risk.	Already in use for augmenting exhibits and for teaching.
Robotic surgery	Currently robots are used in a variety of surgeries including spinal and endovascular. Fine-scale surgery with smaller incisions results in faster recover.	While robotic surgery itself might not make its way into collection practices, improvements in robotic movements and optical systems could result in improved high-throughput imaging and scanning processes or new means to image existing specimens, including tissue collections.
RNA therapeutics	RNA genetic abnormalities include antisense nucleotides that can cause rare genetic diseases, cancer, and neurologic illnesses. Therapeutics are being developed that can treat the RNA abnormality.	New techniques pertaining to RNA sequencing or nucleotide editing will likely result. New methods of storing samples for RNA analysis could also result in improved molecular collection storage methods.

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APPENDIX 1

Presentations given at the symposium "The Expanding Role of Natural History Collections," held at the Joint Meeting of Ichthyologists and Herpetologists, July, 2019 in Snowbird, Utah.

1. Webster, M. What is the 'Extended Specimen'?
2. Hilton, E. J., G. Watkins-Colwell, S. K. Huber. The expanding role of natural history collections
3. Singer, R. Big heads or long tails: how every fish collection matters in collections-based biodiversity research

4. Maslenikov, K. Specimens by the millions: managing large, specialized collections at the University of Washington Fish Collection
5. Nonaka, A., J. Milisen, B. Mundy, G. D. Johnson. Blackwater diving: an exciting window into the planktonic arena and its potential to enhance the quality of larval fish collections
6. Fenolio, D., T. Sutton. Photographic documentation of deep-water fishes by the DEEPEND Consortium on the Gulf of Mexico
7. Bauer, A. Herpetology in a world at war: natural history collections and global conflict
8. Lambert, M., A. Roddy, C. Gosser, C. Mettler, W. Robinson, B. Carlson. Reptile sex ratios in museum collections are associated with climate change and phylogeny
9. Welicky, R., K. Leslie, E. Fiorenza, N. Mastick, K. Maslenikov, L. Tornabene, C. Wood. Natural history collections as time capsules: assessing a century of change in disease burden and trophic level of marine fishes
10. Dillman, C. Natural history collections as repositories of evolutionary change
11. Ruane, S. Old museum specimens for modern molecular systematics
12. Farina, S. Reciprocal value of museum vouchers to collections and to functional morphology research
13. Bemis, K., J. Tyler, E. Stanley, E. Hilton. Dentition of living and fossil porcupinefishes (Tetraodontiformes: Diodontidae) studied using CT scanning: implications for systematics of isolated fossil jaws
14. Randall, Z., K. Love, E. Stanley, M. Sabaj, L. Page, D. Blackburn. oVert: lessons learned for high-throughput scanning across the fishes tree of life
15. Winchester, J., D. Boyer, T. Ryan, T. McGeary. How MorphoSource is helping museum collections to connect specimens to 3D and 2D media and to the broader world
16. Rios, N. A blockchain inspired model for natural history collections data
17. Rocha, L. Preserved specimens benefit public education and generate compelling exhibits
18. Sidlauskas, B. Teaching ichthyology online with a virtual specimen collection
19. Watkins-Colwell, G. Predicting the future of natural history collections and specimen usage