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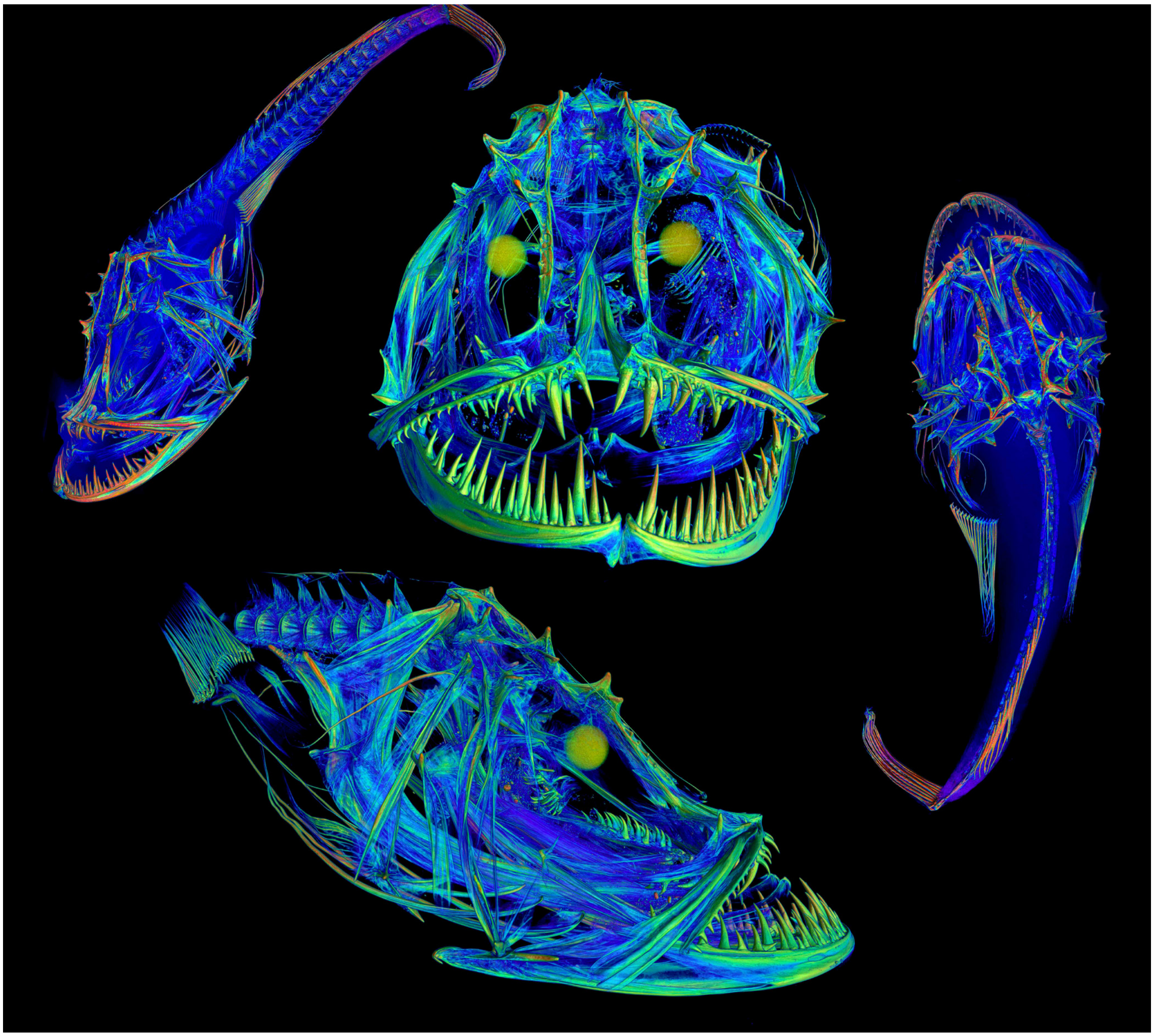

Inside: Natural History Collections as Part of National and Global Challenges

Plus: The "Juliana codex", A roadmap to NAGPRA repatriation, and MORE!

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Using Natural History Collections to Address National and Global Challenges

By Barbara M. Thiers

Dinosaurs, eggshells, fossilized mouse footprints, bird skins, whale skeletons, pressed plants, cross-sections of redwood trees, pinned insects and yeast cells are all examples of the archive of life that we call natural history specimens. These specimens are part of collections maintained by institutions such as freestanding museums, universities, botanical gardens, parks and governmental research facilities. Collectively, the world's natural history collections number 2.5-3 billion specimens (estimate from Krishtalka et al. 2016). The greatest concentration of natural history collections is in Europe, where collecting such specimens began in the 16th century. In the U.S. there are approximately 1436 organizations with natural history collections (iDigBio collections catalog https://www.idigbio.org/portal/collections), with the estimated total number of specimens between 500 million and one billion.

Caring for natural history collections for the indefinite future represents a significant long-term commitment of space, staff and equipment. However, because natural history collections are the fundamental source of information about life on earth, past present and future, such investment is well justified.

USES OF NATURAL HISTORY SPECIMENS

The primary use envisioned for natural history specimens by scientists such as Carl Linnaeus, was as a reference for visual comparison of one type with another, and characterizing the distinguishing features of each type. Linnaeus used this technique to categorize all forms of life in the many editions of Systema Naturae, his compendium of living things. We continue to use specimens in this way, because we still have not completed the work that Linnaeus began 250 years ago. Scientists continue to discover new forms of life every year, and in some groups, such a fungi, scientists estimate that perhaps 93% of fungi remain unnamed (Mora et al. 2011).

The uses of natural history collections go well beyond biodiversity inventory, however. Today such collections are being studied to help understand the evolution of life on earth, long and short term changes in climate and seasonality, the genetic make-up and histories of organisms that impact human and animal health, and the impact and distribution of invasive species.

The sheer volume of well documented specimens allows comparisons to be made of individual specimens collected in different times and places, which can be used to document changes over time, including long term climate change. By comparing collection dates with the reproductive stage represented in the specimen, for example, we can develop an understanding of the phenology of an organism, that is, the timing of its life phases. When collections of a species are available over a broad time horizon, it is possible to determine whether there have been shifts in the timing of life events such as leaf out and flowering in plants, metamorphosis in insects and weaning in mammals. Phenological studies using plant specimens collected over a broad time horizon have shown that climate change is influencing the timing of flowering in plants (Davis et al., 2015). Such a shift has the potential to disrupt their process of pollination by insects such as bees, resulting in a failure of the flower to complete its reproductive cycle, and starvation for the bees.

Figure 1: Tiger moth (Chetone angulosa) from Costa Rica, collected by Allen Young, photographed by Andre Poremski at the Milwaukee Public Museum. Insects are usually preserved as dried specimens, held in place by pins. We still know only a tiny fraction of the insect biodiversity on earth, but these organisms play key roles in the ecosystem such as pollination, disease vectors and destruction of crops. Making collections of insects is the best way to build a knowledge of their full range of diversity and their impact on the lives of other organisms.
Photo courtesy of the Milwaukee Public Museum.

Figure 2: Specimen of a gentian plant (Gentiana calycosa) from Wyoming. Collected Drs. Noel and Patricia Holmgren. Courtesy of the C. V. Starr Virtual Herbarium of the New York Botanical Garden. Plant specimens are pressed and dried and stored in special cabinets in collections called herbaria. Scientists use these specimens to identify plant species, to understand flowering times and how these have changed in response to enivornmental factors, and to sample DNA in order to understand how one species is related to another.   Herbarium specimens such as this one from the Intermountain West have been used to determine what species should be included in ecological \restoration projects.
Photo courtesy of New York Botanical Gardens.

Examples of current recent uses for systematic biology collections

1. Comparing individual documented specimens to understand long and short term changes in climate over time

2. Identifying disease vectors and their genetic makeups and histories

3. Continuing to fill in and refine our understanding of the evolution of life on earth, as well as the major disruptions of the past, which can help us model possible futures

4. Continuing to discover, classify and name forms of life that are still unknown to science

Techniques for extracting DNA from natural history collections were developed in the 1990s and have improved steadily since then. An entire new field called 'museomics' focuses on exploring the genetic diversity that can be recovered from natural history collections. DNA from natural history collections of species for which living tissue was not available informed the Open Tree of Life, a synthesis of our understanding of how major lineages of life are related to one another (Hinchliff et al, 2015). New and more powerful tools for sequencing DNA, known as next generation sequencing, are yielding even richer information from specimens. This finer-grained sequence data has led to the discovery of a new hominid species from sequencing small bone fragments, characterization of the genetic makeup of extinct organisms such as the Tasmanian tiger, as well as contributing to an understanding of the evolution of disease and pesticide resistance in plants (Bakker 2017).

The study of carbon and other isotopes in preserved specimens is also yielding rich new information. The ratio of isotopes of carbon in biological material can be used to estimate the age of that material, a process known as carbon-14 dating. Isotope content can also be used to infer diet, migratory patterns, and disease transmission in organisms from the current age as well as fossils. (McLean et al., 2016).

Natural history collections are also being used to solve problems with direct implications for human health and safety. In the 1990s, a Hantavirus (Bunyaviridae) caused a pulmonary infection that was fatal for most people who contracted it. Public health officials could not identify the primary carrier of this disease until evidence of the virus was found in museum tissue collections of deer mice from the American Southwest (Yates 2002).

Invasive species in the U.S. cause environmental damage and loss totalling more than $130 billion per year. A plant commonly known as Cheatgrass, (*Bromus tectorum*), one of the most damaging invasive species, crowds out wheat plantations and fodder crops.

Figure 3: Central Michigan University student Heather Glon learning field techniques for making biodiversity collections, courtesy of Anna Monfils. Training the next generation of biodiversity scientists is one of the core uses of natural history collections. Photo by Anna Monfils.

Cheatgrass is native to Europe and Central Asia, where it does not exhibit the invasive tendencies that it does in North America. Comparison of genetic information between plants from the species' native range and those from historical and modern herbarium collections in North America (Novak & Mack, 2001), revealed that cheatgrass was introduced multiple times to North America from different areas of its native habitat. It was not until these different strains interbred in North America, that the species developed its invasive qualities.

Figure 4: University of Florida Museum Research Assistant Zachary Randall photographing a fish using a "squeeze tank" apparatus (glass plate in tank presses the fish forward to keep it oriented properly for photography. Fish are a critical component of aquatic ecosystems and a source of food for humans and other animals, and are also of interest as pets and sport. Imaging fish specimens facilitates the identification of fish and determination of their size and reproductive status, which may be an indicator of the health of a body of water. Photography by Kirsten Grace. Photo courtesy of University of Florida Museum.

Examples of data portals of
natural history specimens that are freely available (many others are limited to use by specialized
scientific communities)

<u>Technical but open</u>
Idigbio portal (US) https://www.idigbio.org/portal

Brazil (available to anyone) http://www.splink.org.br/index?lang=en

Atlas of Living Australia https://www.ala.org.au/

Note also the attempt to provide information of interest to the public, which as of this publication has educational resources available but is in redevelopment as a core resource:

Encyclopedia of Life http://eol.org/"

DIGITIZATION AND NEW FRONTIERS IN ACCESS

Unlocking the wealth of data held by natural history specimens becomes even more powerful when available in electronic form. Beginning in the 1970s, collections-holding organizations began transcribing basic collections metadata such as the name of the organism, where and when it was collected, and by whom, into structured database applications. As data standards were developed it became increasingly possible to marshall data on collections held around the world for comparative research.

By the early 2000s, natural history collections began imaging selected specimens to augment electronic records. The subsequent decrease in the cost of equipment and data storage has allowed specimen imaging to become an essential part of specimen digitization, vastly increasing the amount of data made available for a specimen. Specimen imaging techniques vary from one type of organism to another, from instant capture cameras for flat herbarium specimens, "squeeze tanks" for fish, whole-drawer scanning for insects, and 3D scanning to investigate the internal structures of vertebrates, both current and fossilized. These advances have made worldwide collaborations easier, less expensive and quicker, as well as allowing a wider range of research.

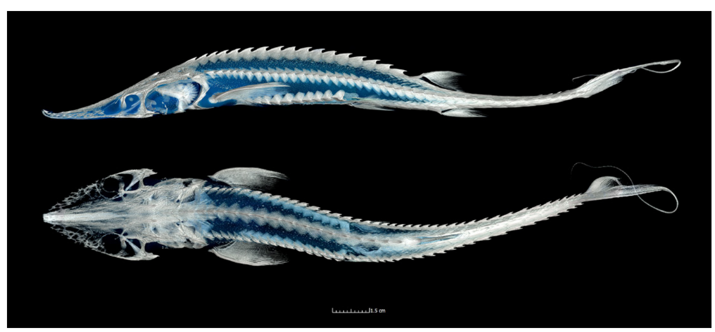

Figure 5: A colorized high-resolution computed tomography reconstruction of a Shovelnose Sturgeon, Scaphirhynchus platorynchus (UF 14545). Natural history specimens can be used to examine the inner structure of an animal without destroying it. The ability to examine bones and other structures in this way, and to rotate the image to see other views, allows the ability not only to understand the structure of the organism and relate it to others, but also can be used by engineers to design buildings and robots. Image by Zach Randall, Florida. Photo courtesy of University of Florida Museum.

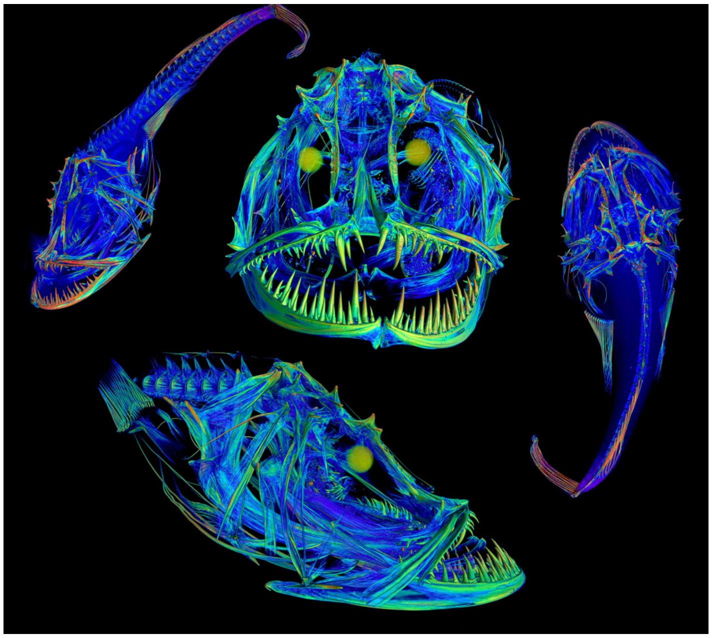

Figure 6: High-resolution computed tomography reconstruction of an Angler, Lophius piscatorius (UF 118531). This reconstruction was colorized to show high and low density areas. Natural history specimens can be used to examine the inner structure of an animal without destroying it. The ability to examine bones and other structures in this way, and to rotate the image to see other views, allows the ability not only to understand the structure of the organism and relate it to others, but also can be used by engineers to design buildings and robots. Image by Zach Randall,-Florida. Photo courtesy of University of Florida Museum

Digitization of natural history collections in the United States has advanced significantly during the past decade through a funding program by the National Science Foundation (NSF) called Advancing the Digitization of Biodiversity Collections. This ten year program provides funding for a central organizing hub, called iDigBio, which is a joint effort between the University of Florida and Florida State University. The program also funds Thematic Collections Networks, collaborative groups of collection institutions who receive funds to digitize specimens related to particular research themes. These networks have digitized specimens related to reconstruction of climates in past geological ages, the relationship between insects and plants, the evolution of bird song, and documentation of biodiversity of fungi worldwide, among other topics. The iDigBio data portal (https://www.idigbio.org/portal) serves these data (and specimen data from other sources as well). As of September 27 2018, the portal provides access to about 115 million specimens, of which about 46% each are plants and animals, and the remainder are protists and fungi.

Digitization of natural history specimens is a key priority elsewhere in the world as well. Australia was one of the first countries to make digitization of natural history specimens a national priority, and their resulting Atlas of Living Australia (https://www.ala.org.au/) has now become key to natural resource management, conservation and STEM education. SpeciesLink contains records for about one million digitized natural specimens from Brazil (http://splink.cria.org.br/index) and provides the basis for Brazil 2020, an ambitious project to document the plants of this megadiverse country. Many European natural history collections have long-standing digitization projects, but soon these will be coordinated through a project called DISSCo, which has the goal of positioning European natural history collections at the center of "data–driven scientific excellence and innovation in environmental research, climate changes, food security and bioeconomy." (http://dissco.eu/).

The effort required to digitize our wealth of natural history specimens is enormous, but so are the benefits. Shared online, digital representations of specimens give scholars everywhere access to the world's collections. Such access is especially important in developing countries, whose earliest natural history collections, often made on European exploring expeditions, are usually stored in European collections. For larger museums whose collections have never been inventoried adequately, digitization gives them an understanding of their own holdings, which can inform future research and exhibition, as well as accessions policies. Museums allow "digital loans" of specimens to scholars rather than sending physical specimens through the mail, as has been the standard practice for centuries.

The vast amount of data available already has permitted the analysis of broad patterns of diversity across landscapes. When specimen occurrence information is combined with geographical data sets such as rainfall, elevation, soil type, etc. in a Geographical Information System (GIS) we can gain insight into the factors that control where they can live. Using future projections for sea level rise and temperature, we can develop predictive models for how species will respond to future environmental change (Elith & Leathwick, 2009). The very large number of images that have resulted from specimen digitization provide an excellent opportunity to test recently developed neural net and artificial intelligence tools that may eventually aid in identification of unknowns (Carranza-Rojas et al., 2017) and the recognition of novel structures that may be useful in biomimicry, or the investigation of finding solutions to human technology problems in nature's systems (Libby et al., 2012).

Digitization has not only created increased access to collections for researchers, but to members of the public as well. Broadening the use of collections and resulting data was an objective of the NIBA strategic plan and of NSF's ADBC program as well. Following some successful pilot projects, the BLUE (Biodiversity Literacy in Undergraduate Education) initiative has been funded by NSF to build partnerships among biodiversity and education researchers to develop educational materials for using natural history collections in the college classroom. These materials are meant to support the training of diverse, competent, and engaged young biologists who are well prepared for a broad set of career paths generating and utilizing biodiversity data to address scientific issues of critical national and global importance (www.biodiversityliteracy.org).

Digitization has also led to increased public participation in collections. Using online platforms such as Notes from Nature (www.notesfromnature.org), citizens help natural history collections to transcribe specimen labels and improve their knowledge of biology and geography along the way – volunteers have transcribed data from more than 300,000 specimens so far! An annual event held in mid-October each year known as Worldwide Engagement for Digitizing Biocollections, or WeDigBio, is a 4-day event that engages participants online and onsite in digitizing natural history collections (Ellwood et al., 2018). Museums, herbaria, universities, and other institutions host on-site as well as on-line events and provide the opportunity to meet likeminded people in person, and connect electronically with people in other transcription events around the world.

2020 marks the end of the current Advancing Digitization of Biological Collections program by NSF, We are now looking ahead to what the next decade will hold for biological collections. Although we have made a lot of progress, we still have many years of digitizing to create a complete digital representation of our biodiversity archive in the U.S. Although great strides have been made in broadening the use of collections in research and education, we know we have still barely scraped the surface of the knowledge our collection heritage can provide, especially in the very important areas of food security, maintaining healthy ecosystems and creating a data-literate workforce.

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Barbara M. Thiers is Vice President and Patricia K. Holmgren Director of the William and Lynda Steere Herbarium, New York Botanical Garden, Bronx NY. She may be reached at bthiers@nybg.org

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On the cover:

Pictured: A high-resolution computed tomography reconstruction of an Angler, *Lophius piscatoris*. Natural history specimens can be used to examine the inner structure of an animal without destroying it. Learning about unlocking the wealth of data held by natural history specimens by making them available in electronic form.

Full story on page 11.