Putting U.S. mollusk collections on the map: collaborative digitization and innovation

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ABSTRACT

Among biocollections, mollusks are a particularly powerful resource for a wide range of studies, including biogeography, conservation, ecology, environmental monitoring, evolutionary biology, and systematics. U.S. mollusk collections are housed in stand-alone natural history museums, at universities, and in a variety of governmental and non-governmental institutions. Differing in their histories, specializations, and uses, they share common needs for long-term development, and collectively contribute to biodiversity knowledge at regional, national, and global scales. Commitment by dedicated staff, collectors, and volunteers, institutional investments, philanthropy, and governmental funding have built and maintained these collections and their support infrastructure. Efforts by the North American malacological collection community since the early 1970s led to coordination in database design but left the data isolated in individual institutions. Collection digitization developed through a combination of individual/institutional initiatives and federally supported projects funded by the National Science Foundation (NSF) and the Institute of Museum and Library Services (IMLS). Advances in digital technology enabled the shift toward nationally and globally unified collections. Networking and collaboration were greatly accelerated by NSF's Advancing Digitization of Biodiversity Collections (ADBC) program, which created a central coordinating organization (iDigBio) and funded Thematic Collections Network (TCN) projects. One such TCN was developed to mobilize nearly 90% of the known U.S. museum-collections-based data of the U.S. Atlantic and Gulf coasts (*Mobilizing Millions of Marine Mollusks of the Eastern Seaboard*—ESB). The project, involving 16 museum collections (plus the Smithsonian Institution as federal partner), combines data from approximately 4.5 million specimens collected from the ESB region and makes them available to the TCN portal InvertEBase and other aggregators such as iDigBio and GBIF. In addition to fostering community and expanding the corpus of available digitized mollusk records through new data entry and georeferencing (GEOLocate, CoGe) and standardizing taxonomy, the project drove key innovations for the invertebrate collections community. For instance, it worked with the Biodiversity Information Standards (TDWG) group to create a new Darwin Core standard term, "Vitality", expanded GEOLocate to support complex geospatial types, integrated global elevation and bathymetric datasets directly into georeferencing workflow, and developed various education and outreach public outreach products. Synthesizing from the 15 following articles with individual histories of ESB-participating mollusk collections, several topics are discussed—such as what defines a "good" mollusk collection in the digital age and the importance of federal support for this national resource.

Additional keywords: Invertebrates, malacology, database, biodiversity, cataloging, georeference, Mollusca, natural history collections, biocollections, museums

INTRODUCTION

Biocollections and their associated data serve as archives of biological history, providing a directly accessible and dynamic record of taxa and their distributions in time and space. They are active platforms for discovery, education, and conservation biology (Meineke et al., 2019; Suarez and Tsutsui, 2004). Natural history museums also serve as repositories for specimen-linked genomic data (Card et al., 2021). Equally important, museum collections allow published specimen records to be verified and new analyses to be conducted, all of which depend on the preservation of physical vouchers.

Mollusk collections are especially valuable because mollusks are one of the most diverse animal phyla and most have a shell, making them relatively resistant to degradation and generally well sampled across broad geographic and temporal scales. Their diversity and extensive documentation make them powerful reference resources for a wide range of studies, including biogeography, conservation, ecology, environmental monitoring, evolutionary biology, systematics, and taxonomy. By spanning both historical and contemporary contexts, mollusk collections provide essential baselines for understanding biodiversity change and addressing questions across many scientific disciplines. Collections are housed in standalone natural history museums, at universities, and in a variety of governmental and non-governmental institutions. When provided with adequate resources and funding, they are cared for by curatorial staff (e.g., curators, collection managers, collection assistants, and volunteers) who ensure that specimens and their associated data are well-protected, organized, and accessible. Natural history collections were once isolated within individual institutions, but there is now growing recognition of the need for unified, global collections that integrate museum data making it universally accessible (e.g., Johnson et al., 2023). Advances in digital technology are enabling this shift, allowing data from disparate collections to be shared and accessed through virtual platforms such as the Global Biodiversity Information Facility (GBIF.org, 2025), Integrated Digitized Biocollections (idigbio.org), and InvertEBase (InvertEBase.org).

Mollusks are the second-largest animal phylum after Arthropoda, with more than 88,000 currently accepted extant species (MolluscaBase eds, 2025) and a total diversity possibly exceeding 200,000 species (Ponder et al., 2020). They inhabit nearly every aquatic and terrestrial environment, from the deep sea to tropical forests and Himalayan ponds, and display morphological and ecological disparity unparalleled among invertebrates (Giribet and Edgecombe, 2020). The large biomass of holoplanktonic pteropods, meroplanktonic larvae, and ubiquity of several squid species define mollusks as key components of marine food webs.

Mollusks are also important as the basis of major global fisheries, and impact human agriculture as terrestrial pests, invasive species (aquatic and terrestrial), and as intermediate hosts for parasitic diseases such as schistosomiasis (Stothard and Rollinson, 1997) and rat lungworm (Qvarnstrom and Bishop, 2013). The calcareous shells of mollusks record skeletal ontogeny and growth histories, making them invaluable for paleontological,

environmental, and climate research (Schöne et al., 2005; Fortunato, 2015; Herbert et al., 2022). Despite their diversity, many molluscan lineages are highly threatened, and they have suffered more modern extinctions than any other animal group (Williams et al., 1993; Lydeard et al., 2004; Régnier et al., 2009; Lopes-Lima et al., 2018).

The diversity, both systematic and ecological, and the aesthetic appeal and durability of molluscan shells have long attracted a broad community of enthusiasts, including professional biologists, students, volunteers, and dedicated hobbyists. Museum collections have long supported studies of systematics, genetic and evolutionary theory (Eldredge and Gould, 1972; Gachelin and Opinel, 2008; Holmes et al., 2016), and ecology, conservation, and disease (Bakker et al., 2020), among others. Professional biologists recognize that mollusk collections have been, and continue to be, a fundamental resource in understanding these fields (Sturm et al., 2006; Glaubrecht, 2009).

Building and sustaining collections depends on both professionals and non-professionals. Curatorial staff develop and provide long-term, taxon-specific conservation care; maintain and share biodiversity databases; facilitate collections use by multiple audiences; and train students and volunteers in biocollections techniques. Professional organizations such as the Society for the Preservation of Natural History Collections, together with initiatives like iDigBio, help support this work by fostering collaboration, mentorship, and exchange of knowledge across institutions. Non-professional malacologists significantly contribute to the development of natural history collections, and to a greater degree than in most other biological disciplines (Clench, 1957; Solem, 1975; Pearce, 2006; Bouchet et al., 2016). As pointed out by Solem (1975: 223), "one unusual feature of malacological work is the great number and size of private collections and the degree to which systematic and faunistic work on mollusks is dependent upon collecting efforts and publications by 'non-professionals,' people not employed as malacologists and university biologists. Probably 85% of the mollusks in major institutional collections today are materials collected by amateurs rather than professional biologists." This population of mollusk-enthusiasts has contributed enormously to naming species (Leber, 2019). Notably, non-professional taxonomists have been responsible for describing more than 60% of new species in Europe, underscoring their essential role in expanding biodiversity knowledge (Fontaine et al., 2012). For example, Peñas and Rolán (2010) named 207 species of Pyramidellidae in a single study, published when the authors were a retired economist and pediatrician, respectively. The collaborative network formed by amateur and professional molluscan taxonomists and collectors has thus expanded both the breadth and depth of museum-based mollusk collections, enhancing their scientific and educational value. At a more regional scale, Malacological or Shell Clubs play a formative role in attracting new members who may become avocational or professional malacologists. Several have a close relationship with, or were even founded within, formal museum collections. Among the oldest in the U.S. is the Boston Malacological Club, founded in 1910, which continues to meet monthly in the Museum of Comparative Zoology at Harvard University. Some shell clubs in the U.S. provide financial assistance to students via small grants. The national organization devoted to the appreciation of mollusks and shells, Conchologists of America, provides grants for malacological research to students and early-career scientists, helping bridge any perceived gap between enthusiasts and professionals (a few authors of this report have received COA grants in the past) (COA, 2025).

Collections differ in their histories, specializations, and uses, but share common needs for long-term investment, often overlap in collectors and collecting events, and collectively contribute to biodiversity knowledge at regional, national, and global scales. A questionnaire-based survey (Sierwald et al., 2018) identified 81 U.S. and five Canadian institutional natural history collections that together hold at least 8.3 million mollusk lots representing some 100 million specimens. Until 2014, this enormous mollusk data resource was available only by searching individual collection databases (if they existed) or through onsite visits to museums. However, the U.S. National Science Foundation's ADBC program (Advancing Digitization of Biodiversity Collections) worked to change that by funding a series of Thematic Collections Networks (TCNs). These TCN projects were developed to unlock the research potential of collections, although not themselves providing research support. The 15 collections highlighted in this volume are all part of the Eastern Seaboard (ESB) TCN, along with the collections of Florida Fish and Wildlife Research Institute (FWRI) and the federal partner NMNH. Together, they house and manage approximately 90% of the mollusk lots from the U.S. Atlantic and Gulf coasts that have been deposited in U.S. and Canadian institutions.

The assembled papers explore the development of the institutions and collections associated with the ESB project, and discuss project outcomes including a collaborative approach to specimen digitization, georeferencing, and data mobilization (Bieler, 2025; Criales et al., 2025; Dietl et al., 2025; Duda et al., 2025, Goodheart and Mikkelsen, 2025; Groves, 2025; Kittle and Shea, 2025; Leal and Whitt, 2025; Mikkelsen et al., 2025; Pearce et al., 2025; Petway et al., 2025; Rosenberg and Callomon, 2025; Slapcinsky et al., 2025; Smith, 2025; Trimble et al., 2025).

Acronyms of collections-bearing institutions (and collections identifiers, if different) in the ESB collaborative

AMNH – American Museum of Natural History, New York, New York
ANSP – The Academy of Natural Sciences of Philadelphia, Pennsylvania.

BMSM – Bailey Matthews National Shell Museum & Aquarium (BMNSMA), Sanibel, Florida, previously the Bailey Matthews Shell Museum
CM – Carnegie Museum of Natural History, Pittsburgh, Pennsylvania
DelMNS – Delaware Museum of Nature and Science, previously Delaware Museum of Natural History (see DMNH), Wilmington, Delaware
DMNH – original acronym retained by DelMNS for cataloging purposes
FMNH – Field Museum of Natural History, Chicago, Illinois
FWRI – Fish and Wildlife Research Institute, St. Petersburg, Florida, previously Florida Marine Research Institute
HBOM – Harbor Branch Oceanographic Museum, Fort Pierce, Florida, at Harbor Branch Oceanographic Institute, Florida Atlantic University; previously Indian River Coastal Zone Museum
HMNS – Houston Museum of Nature and Science, Houston, Texas
LACM – (Los Angeles County Museum) original acronym retained by NHMLA for cataloging purposes (see NHMLA)
MCZ – Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts
NHMLA – Natural History Museum of Los Angeles County, previously Los Angeles County Museum (LACM), Los Angeles, California
NMNH – National Museum of Natural History, formerly United States National Museum (USNM), Smithsonian Institution, Washington, D.C.
NCSM – North Carolina State Museum of Natural Sciences, Raleigh, North Carolina
PRI – Paleontological Research Institution, Ithaca, New York
UF – Florida Museum of Natural History, University of Florida, Gainesville, Florida
UMML – original acronym for the University of Miami Marine Laboratory, Rosenstiel School of Marine, Atmospheric, and Earth Science, retained by VMIC for cataloging (see VMIC)
UMMZ – University of Michigan Museum of Zoology, Ann Arbor, Michigan
VMIC – Voss Marine Invertebrate Collection, formerly University of Miami Laboratory, Rosenstiel School of Marine, Atmospheric, and Earth Science, Miami, Florida
YPM – Yale Peabody Museum, New Haven, Connecticut [information technology partner]

Other acronyms and abbreviations (several others explained within text)

ADBC – Advancing Digitization of Biodiversity Collections (NSF program, archived, now Infrastructure Capacity for Biological Research)
AMU – American Malacological Union (now AMS)
AMS – American Malacological Society, ams.wildapricot.org
CSM – Council of Systematic Malacologists
CoGe: Collaborative Georeferencing, coge.geo-locate.org
GBIF – Global Biodiversity Information Facility, gbif.org
HMNH – Harvard Museum of Natural History, www.hmnh.harvard.edu
iDigBio – Integrated Digitized Biocollections, idigbio.org
IMLS – U.S. Institute of Museum and Library Services, imls.gov
NASA – U.S. National Aeronautics and Space Administration, www.nasa.gov
NSF – U.S. National Science Foundation, www.nsf.org
OBIS – Ocean Biodiversity Information System, obis.org
PEN – Partner to Existing TCN (as part of ADBC)
REST API – Representational State Transfer Application Programming Interface
TCN – Thematic Collections Network (as part of ADBC)
TDWG – Biodiversity Information Standards (previously Taxonomic Databases Working Group), tdgw.org

RESULTS

Different Origins

The organizations that house the North American mollusk collections differ greatly in their ages, origin, histories, and overall scope. Some were created with the express goal of building a large multi-faceted natural history museum that spans collections, research, and public outreach (e.g., CM, FMNH, MCZ, UMMZ). Others had a more focused taxonomic goal (DelMNS), meant to showcase the nature and resources of a particular region (HBOM, HMNS) or state (NCSM), or to house research material from the institutional research staff and surveys of a particular region (e.g., HBOM, NHMLA). Several were initially developed as teaching collections to support university coursework (UF, UMML). Many of these institutions were founded through the philanthropy of individuals or groups. Mollusk collections frequently were early parts of a museum's holdings, often as a special focus because of a founder's interest or as a result of deposited exhibition or research material. Many of today's collections began with a particular "starter-kit": one or several seed collections that were purchased, resulted from sponsored expeditions, came from major individual donations, or were gifted "duplicate sets" from older institutions such as ANSP or USNM. Depending on the nature of the institution (e.g., university museums with strong focus on research activities and formal education [e.g., MCZ, UF, UMMZ]; primarily public-facing museums with large exhibition spaces [e.g., AMNH, BMSM, CM, HMNS, NHMLA], specialized research collections without public front [UMML/VMIC, HBOM]), the collections grew variously, through staff research activities, expeditions, targeted purchases, deposited voucher material from students and external researchers, ad-hoc donations from scientists and private collectors, and the absorption of "orphaned" collections from other institutions.

The individual history of each collection is narrated in the accompanying papers.

Cataloging Before the Digital Age

Before the digital age, mollusk collection data was managed through paper-based cataloging systems in all but the youngest (BMSM) institutions. Museums relied on accession ledgers, in which each row represented a specimen lot and columns recorded data such as locality, date of collection, collector, and means of collecting. Most collections used a lot-based cataloging system, assigning consecutive numbers to lots that contain one to many specimens from the same collecting event. Collections variously assigned multiple number series for different molluscan classes (e.g., CM, HBOM) or to distinguish between dry and alcohol-preserved lots, as they can be stored in different locations (e.g., MCZ). Supporting files were maintained separately for field notes, permits, and other information to further document the specimens and maintain compliance with regional and international laws and regulations. Private collections that were passed on to institutional collections often used card catalogs in which handwritten or typed entries summarized taxonomic names, provenance, and other details. Although these systems captured essential information, they were difficult to search, prone to redundancy and inconsistencies, and cumbersome to update when taxonomic or locality information was refined. The lack of standardization across collections further limited data integration and made large-scale comparative studies nearly impossible (Lane, 1996). As a result, maintaining accurate and accessible specimen records remained a persistent challenge until the advent of computer databases, the widespread digitization of collection data and images, and community-wide efforts to standardize taxonomic names.

Digitization of U.S. Mollusk Collections

In an article on curation of invertebrate collections, Emerson and Ross (1965: 337) of the AMNH stated that "The ideal method for cataloging specimens and the retrieval of catalogue and specimen information would be a punch card or magnetic tape system. Vast amounts of information could be stored in a relatively small space and retrieved within seconds. Unfortunately, none of the museums in the United States has yet installed such a system." A few years later, Manning (1969) described that just such a system had become reality, developed for Smithsonian's Crustacea collection and funded by the U.S. Department of Health, Education, and Welfare. This was quickly followed by the information management computer system SELGEM (SELf GEnerating Master; Creighton and Crockett, 1971), developed and distributed by the Smithsonian Institution, which remained in use in various collections for several decades. By the early 1970s, the need for joint planning and standardization of mollusk collection development in North America had become evident. Malacologists representing many of the major molluscan collections formed the Council of Systematic Malacologists (CSM), with the primary objective to formulate goals, priorities, and policies concerning the growth, development, and use of molluscan resources in systematic collections (Anonymous, 1973). CSM served as the representative malacological organization to the Association of Systematic Collections (now Natural Science Collections Alliance) and became an affiliate organization of the American Malacological Union (now Society) in 1977. Until its dissolution in 1997, CSM served as a coordinating force, frequently addressing topics by analyzing community-wide questionnaires. Among the most relevant here was the 1973–1974 survey of Recent mollusk collections resources concerning their sizes, staffing, taxonomic strengths, and habitat coverage by Field Museum curator Alan Solem (1975) and its 1980 follow-up by Florida State Museum (later Florida Museum of Natural History) curator Fred Thompson (1982). A CSM-sponsored paper by Solem et al. (1981) suggested standards for the physical management of malacological collections. Solem's (1975) conclusion was that "Without additional personnel and support for EDP [electronic data processing] of collections, the vast potential of molluscan collections to monitor changes in environmental conditions and quality will remain untapped." A decade later, another CSM effort, the "computer database exchange survey" of 1987–1988 (Lindberg, 1988) reported on the incompatibility of databases of the digitized U.S. mollusk collections and argued for unified standards and protocols in the malacological community. The effort subsequently resulted in a broader call for commonality in data structures in systematic collections (Lindberg, 1991).

Digitization of label data into a more-or-less standardized database field structure was a first step. Early examples, besides the mentioned SELGEM system (which was adopted, among others, by ANSP, HBOM, and UF) include the development of the CURATOR software at NHMLA. Practical in-house needs, such as accurate knowledge of holdings and the printing of labels and catalog cards (e.g., HBOM; Mikkelsen, 1986), were often the driving force behind initial digitization. Flat-file databases (e.g., Conetics C/Base at FMNH) or spreadsheet-based records were upgraded to relational databases as they became available, including Ashton-Tate's dBASE (DelMNS), Borland's (later Corel's) Paradox (ANSP, CM, FMNH), Microsoft Access (BMSM, FWRI, UF), or Claris's FileMaker Pro (AMNH, ANSP, MCZ). Federally supported database software development (e.g., Muse project, later Specify) drove innovations and collaborations, and over time, most collections adopted dedicated management systems (e.g., Arctos, EMu, Specify) to replace the general-purpose platforms. Many institutions created publicly accessible websites providing access to their collection data. Community-driven developments came next, most importantly the international agreement on

the Darwin Core data standard for publishing and integrating biodiversity information (since 1998) that facilitates exchange and aggregation across software platforms (Wieczorek et al., 2012). The authoritative taxonomic name database World Register of Marine Species (WoRMS.org; since 2007) and its expanded version for mollusks, MolluscaBase.org (since 2014), accelerated and standardized collaborative digitization efforts. Aggregation of the data from individual collections into larger, regional and global data portals (e.g., GBIF, OBIS, InvertEBase.org) opened data access to new, often non-specialist, user communities and allowed for novel large-scale analyses (Ball-Damerow et al., 2019, and references therein).

Federal Support of Digitization

Collection digitization in this community developed through a combination of individual/institutional initiatives and federally supported projects funded by NSF and the Institute of Museum and Library Services (IMLS). Networking and collaboration in the U.S. biological collection community was greatly accelerated by NSF's Advancing Digitization of Biodiversity Collections (ADBC) program announced in 2015, which created a central coordinating organization (iDigBio) and funded Thematic Collections Network (TCN) projects that could be further expanded by adding collections as Partners to Existing Networks (PENs). One such TCN project, *InvertEBase,* was designed to digitize and compare species-rich terrestrial and freshwater invertebrate faunas in North America and involved 13 mollusk and arthropod collections. The project, spearheaded by FMNH (Sierwald and Bieler, 2014–2021), also included the mollusk collections of Auburn University (Bond et al., 2014–2019), Chicago Academy of Sciences (Roberts and Kimmel, 2016–2019), Delaware Museum of Nature and Science (Shea, 2014–2020), Museum of Northern Arizona (Stevens and Alpert, 2018–2021), University of Colorado at Boulder (Elder [subsequently Li], 2020–2025), and University of Michigan (O'Foighil and Lee, 2014–2019). Additional collections, including CM, joined the network as unfunded partners. The project developed a unified portal for the collections (InvertEBase.org) using the open-source software Symbiota designed to manage and mobilize biodiversity data (Symbiota.org). This data portal obviated the need for each collection to host its own digital catalog and enabled the public to search, map, and download data of interest, as well as create and curate custom checklists. InvertEBase.org also provided data management and collaborative digitization tools that could improve the efficiency of data capture and georeferencing. The arthropod collections of the original InvertEBase project subsequently merged with the *Symbiota Collections of Arthropods Network* (SCAN), allowing InvertEBase to focus on invertebrates other than terrestrial arthropods. InvertEBase grew to host terrestrial, freshwater, and marine collection data from many other institutions, merged the data from the Smithsonian Tropical Research Institute's portal, and also became the platform for other TCNs, including the 18-institution *Documenting Marine Biodiversity through Digitization of Invertebrate Collections* (DigIn) project led by NHMLA that largely focused on non-molluscan marine invertebrate collections. Another mollusk-themed TCN project, involving seven institutions and spearheaded by the Bishop Museum in Honolulu to enhance access to taxonomic data and biogeographic data of highly imperiled Pacific Island land snails, developed its own shared Symbiota portal, the *Pacific Island Land Snail Biodiversity Repository*, PILSBRy.org. As part of the InvertEBase effort, the U.S. mollusk collections community was polled for its status (Sierwald et al., 2018) and needs (Shea et al., 2018). Among the priorities identified were the imaging of primary types, expanding taxonomic authority files, and initiating collaborative georeferencing.

None of the prior TCN projects had focused exclusively on living marine mollusks, and a new TCN was developed to mobilize much of the U.S. collections-based data of the eastern seaboard (*Mobilizing Millions of Marine Mollusks of the Eastern Seaboard*—ESB). The project, led by FMNH (Bieler and Sierwald, 2020–2026), currently involves 16 collections (plus NMNH as a federal partner) with approximately 4.5 million specimens from the ESB region and includes the collections of Academy of Natural Sciences of Philadelphia, Pennsylvania (Rosenberg, 2020–2024); Bailey Matthews National Shell Museum & Aquarium, Sanibel, Florida (Leal, 2020–2026); Carnegie Museum of Natural History, Pittsburgh, Pennsylvania (Pearce, 2020–2024); Delaware Museum of Nature and Science, Wilmington, Delaware (Shea, 2020–2025); Florida Museum of Natural History, Gainesville (Slapcinsky, 2020–2025); Fish and Wildlife Research Institute, St. Petersburg, Florida (Larson [later Fuchs], 2020–2025); Harbor Branch Oceanographic Museum, Ft. Pierce, Florida (Hanisak [later Wright] 2020–2026); Houston Museum of Nature and Science, Texas (Petway, 2020–2025); Natural History Museum of Los Angeles County, Los Angeles, California (Vendetti, 2020–2024); Museum of Comparative Zoology, Harvard University, Cambridge, Massachusetts (Giribet, 2020–2025); North Carolina State Museum of Natural Sciences, Raleigh (Smith and Bogan, 2020–2026); Paleontological Research Institution, Ithaca, New York (Dietl, 2021–2024; PEN); Rosenstiel School of Marine, Atmospheric, and Earth Science, Miami, Florida (Traylor-Knowles, 2020–2025); University of Michigan Museum of Zoology, Ann Arbor, Michigan (Duda, 2020–2024); and the American Museum of Natural History, New York (pending PEN application). The starting points of these collections at the beginning of the ESB project varied widely. Whereas some had long experience with digitization projects (and frequently had already participated in other NSF-sponsored efforts such as earlier TCN projects), others were joining the digitally networked collection community for the first time (e.g., HBOM, HMNS) or even started their digitization process via the project (UMML/VMIC).

Collaboration Drives Innovation

The ESB project not only fostered community and expanded the corpus of available digitized mollusk records but also drove key innovations for the invertebrate collections community. One important development was the creation of a new Darwin Core data standard for the vitality of a specimen at time of collection. Mollusks are often dead-collected; their shells can persist for thousands of years and are subject to taphonomic processes including post-mortem transport. Only live-collected specimens reflect where the animal actually lived, so distinguishing between live- and dead-collected material is essential. Such a distinction had not been made in collections databases, and data aggregators (such as GBIF) therefore reflect distributions of molluscan species that are not fully suited to detect shorter-term changes. The ESB project developed a set of criteria for indicating the collecting event status of specimens in a lot as "live", "dead", "subfossil," or "unknown", and worked with the Biodiversity Information Standards (TDWG) group to create a new standard term, "Vitality", and a recommended standardized vocabulary to make such information available to data aggregators.

Prior to digitization, locality records were entirely textual and could not be reliably mapped (Wieczorek et al., 2004). As research increasingly addressed species distributions and conservation planning, museum data needed precise geographic coordinates (Nelson et al., 2012). The adoption of georeferencing accelerated with shared tools and standards. Platforms like GEOLocate provided protocols to convert textual descriptions into latitude and longitude with documented uncertainty (Rios and Bart, 2010), while TCN networks enabled institutions to pool data and perform collaborative georeferencing via CoGe, greatly increasing efficiency (Page et al., 2015). Modern databases can record multiple georeference points and associated uncertainties for a single locality (explained below), enhancing the accuracy and utility of collection data.

As part of the ESB project, GEOLocate was extended to support complex geospatial types, moving beyond the traditional model of single points with optional radii and/or polygons. The platform can now represent localities as collections of points, lines, and polygons (including polygons with interior holes), providing a more flexible means of modeling collection events. Each geometry can be annotated with entity-specific metadata, such as start and stop coordinates for a trawl, tracks across multiple sampling stations, or depth values attached to individual points. This richer representation allows georeferences to better capture the ecological and spatial complexity of molluscan collecting practices, such as delineating habitats around islands or along coastlines.

A second major innovation was the integration of global elevation and bathymetric datasets directly into georeferencing workflows. More than three terabytes of raster data were compiled from three authoritative sources: the General Bathymetric Chart of the Oceans (GEBCO 2023), providing global bathymetric and terrestrial elevation coverage at 15 arc-second resolution; NASA's Shuttle Radar Topography Mission (SRTM) v003, offering terrestrial elevation data at 1 arc-second (30 m) resolution between 60°N and 60°S; and Terra Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) v003, extending comparable 1 arc-second coverage between 83°N and 83°S. To deliver these datasets sustainably, we developed a raster-based index and query solution designed for low-cost, cloud-based object storage systems accessible via REST APIs. This approach significantly reduced hosting costs, ensuring longer-term sustainably, while also enabling real-time querying so that elevation and depth values could be dynamically merged into georeferencing results as users edited results.

We also developed new geospatial gazetteers to improve place name resolution and locality interpretation. These combine biodiversity-derived locality information from existing specimen databases, including FishNet2 (www.fishnet2.net) and MCZBase (MCZ's application of Arctos) with authoritative marine and geographic reference datasets such as the National Geospatial-Intelligence Agency (NGA) Geographic Names Server (GNS) Undersea Features and the International Hydrographic Organization (IHO) World Seas dataset. Together, these gazetteers extend coverage across terrestrial, freshwater, and marine environments, providing improved support for interpreting biodiversity-relevant localities in both coastal and open-ocean settings, as well as on land.

Yet another area in which the ESB project has had an impact is the conceptualization of georeferencing. As databases expand to include more fields, and as mapping tools, gazetteers, and depth data information improve, many lots are georeferenced more than once. Often the newly refined georeference merely overwrites the old one. GeoLocate, however, promotes a one-to-many relationship between georeferences and collection records, allowing multiple georeferences for a single lot depending on purpose. For example, placing points on a modern map is relatively straightforward with current technology. More complex goals might involve accounting for historical changes in place outlines (e.g., shape of a sandy island, size of a municipality) or incorporating taxonomy. Taxonomic context can be especially labor-intensive: littorinid snails, which live in the intertidal zone, would require a different polygon than a subtidal species, even when the original site description provided by the collector was identical. In its georeferencing, the ESB project incorporates site descriptions and depth but does not yet factor in taxonomy or collection date. Future iterations will further refine our georeferences to account for these specimen- and time-based factors.

Education and Outreach

Permanent exhibitions dedicated to "shells" were a staple of natural history museums until the mid-20th century, after which mollusk displays became increasingly integrated

into broader biological topics at most ESB institutions. Kittle and Shea (2025: figs 8–12) provide examples of such changes at DelMNS. At FMNH, specimens that had been on the display since the late 1800s passed through a series of long-term exhibitions (Bieler, 2025: fig. 10) and are currently shown in the *What is an Animal* hall. Newly collected mollusk specimens from ongoing research programs and digitized as part of the ESB project are featured in FMNH's conservation-focused *Restoring Earth* exhibition. Two institutions with a particular strong focus on Mollusca (BMNSMA, HMNS) recently opened new galleries. After considerable damage caused by Hurricane Ian in September 2022, BMNSMA reopened the exhibits and aquariums of its *Living Gallery of Sea Life* in March 2024 and the first half of its *Great Hall of Shells* in May 2025. This section of the completely refurbished *Great Hall* includes a collection of eight shell exhibitions with themes such as *Beauty and Diversity*, *Time and Evolution*, and *Global Distribution*, the latter discussing the influence of plate tectonics on the distribution of mollusks (Leal, 2025a). The second half of BMNSMA's *Great Hall* opened in early October 2025, and includes exhibits on *Florida Fossil Shells*, *Southwest Florida Mollusks*, *Deep-sea Mollusks*, *Florida Land Snails*, and *Conservation of Mollusks*, among many others (BMNSMA, 2025). HMNS is one of the few museums nationally with permanent exhibit halls dedicated to malacology. These exhibits are presented in the George W. Strake Hall of Malacology and in the adjacent George and Mary Josephine Hamman Hall of Coastal Ecology. With 44 exhibit cases displaying thousands of mollusks and shells, the Strake Hall of Malacology alone represents the largest display of its kind in the U.S.

Mollusks have remained a feature of temporary museum exhibitions, such as in the AMNH/FMNH-created *Pearls—a Natural History* traveling exhibit (Landman et al., 2001). Other recent temporary mollusk-related exhibits have been associated with collaborative research projects. An example is the "popup" *Evolution on the Half-Shell* exhibit by the NSF-funded *Bivalve-Tree-of-Life* project (e.g., Bieler et al., 2014), which also led to the development of mollusk-based teaching resources at PRI (Mikkelsen and Henne, 2011), and a mollusk exhibit at the Harvard Museum of Natural History (the public-facing counterpart of the MCZ) titled *Mollusks: Shelled Masters of the Marine Realm*. Part of the latter exhibit was subsequently incorporated into a permanent installation in the *Putnam Gallery of Marine Life* at the HMNH. In 2025, PRI opened *Marvelous Mollusks: The Secret World of Shells*, providing an overview of the entire phylum by featuring more than 500 specimens from the collection.

Mollusk-focused outreach activities are often aimed at raising awareness of collections in general, and the biology and scientific utility of mollusk collections in particular. Collections-based ephemeral publications directed at the general public (e.g., DelMNS's *Millions of Mollusks* lookbook) can raise such awareness in small and engaging doses. Free online field guides to mollusks of Illinois and Hawai'i were developed as part of NSF-funded TCN projects at FMNH[1]. At NHMLA, mollusk specimens, including those digitized via ESB, have been the focus of outreach activities at annual single-day events including, *Adventures in Nature* camp, *Girls in STEM*, *NatureFest*, *Haunted Museum*, and invited programs such as the American Association of University Women's *STEM SAVVY* Middle School Girls' Science Day. The use of biocollections in formal educational environments to build future STEM workforce has increased due to digitization efforts (Cook et al., 2014; Powers et al., 2014; Ellwood et al., 2020), including as a resource for course-based research for undergraduates (Krumm et al., 2024), graduate students, and post-docs, especially at university-associated collections such as UMMZ. And the instant availability of georeferenced and imaged data to the general public is a benefit to natural history enthusiasts as well as entities with collections management responsibilities, such as local governments. Since 1998, BMNSMA has been producing and publishing online the *Southwest Florida Shells*[2] guide. The dynamic guide is updated on a regular basis and includes illustrations and descriptions of more than 400 species of mollusks from this part of the eastern seaboard area (Leal, 2025b).

While detailed locality data are generally imperative to the scientific study of mollusks in collections, shells without locality data have value as well. Such specimens have been assembled into educational kits distributed to public schools, individual educators, and families (e.g., BMNSMA, FMNH, NHMLA), and made available to various destructive analyses (e.g., shell structure; deriving DNA from shells).

In addition to being integrated into many of the above ongoing programs, the ESB project also engaged the general public in other ways. Social media posts on various platforms, including regular postings of a *Mollusk of the Month* and an iNaturalist project[3] have created pathways for the public's discovery of mollusks from the U.S. Atlantic and Gulf coasts. To date, the Facebook group has in excess of 2,000 members and the iNaturalist project has collected over 154,000 observations, which are routinely reviewed by ESB-affiliated malacologists and added as "Research Grade" observations to data portals including GBIF.org and InvertEBase.org. Targeting even wider audiences, public media have become involved in showcasing mollusk collections and their role and impact. Episodes of the *Changing Seas* television series by South Florida PBS (2017, 2023) illustrate the relevance of museum-generated mollusk data in conservation research (2017) and the role of private collectors in documenting biodiversity (2023; featuring the ESB TCN project).

DISCUSSION/OUTLOOK

What makes a "good" malacological collection? Several conditions that Solem (1975) had deemed essential for a

[1]https://science.fieldmuseum.org/fieldguides
[2]https://www.shellmuseum.org/shell-guide
[3]https://www.inaturalist.org/projects/eastern-seaboard-mollusks

functional institutional mollusk collection—including the necessary ownership of complete runs of malacological journals as well as of extensive map and reprint collections—are no longer limiting factors because of technological advances (e.g., digital journal subscriptions and online mapping applications) and resources such as the Biodiversity Heritage Library (BHL). Certain Information Technology (IT) requirements called for during earlier phases of collections digitization (e.g., maintenance of institutional websites capable of data posting) are now being replaced by communal data portals such as InvertEBase, increasingly optimized for direct data entry and complex searches and mapping functions. A minimum collection size, once considered necessary to attract visiting researchers, has become less necessary with the online pooling of specimen data and images. Moreover, onsite storage/maintenance of data has become less critical with cloud storage options and within-portal management, the latter currently of special interest for smaller collections and those with limited in-house IT support.

Some fundamentals, however, have not changed. Biological collections are expensive to maintain, and their museums have committed, expressly or tacitly, to retain and preserve their holdings in perpetuity. This requires large, climate-controlled physical spaces with insurance coverage and fire-protection—especially for alcohol-preserved collections. Without consistent environmental conditions in their storage environment, specimens can sustain physical damage and deteriorate. Adequate staffing levels are necessary to maintain the collection and provide access to specimens and associated data by visit, loan, subsampling (e.g., tissues for molecular studies), imaging, and sample shipment. Sufficient funding through local budgets or outside sources must support physical and digital needs such as specimen drawers and cabinets, laboratory supplies, building maintenance, data storage, and IT support. In contrast to institutional activities like formal education or public exhibitions, collection costs cannot be offset by tuition or entry fees. In fact, the global sharing (and, often repatriation) of biodiversity collection data depends on free access. An increasing number of institutions release collection data under the Creative Commons Zero (CC0) public domain waiver following Open Data Commons standards.

The incompatibility of free access and service fees can leave curatorial staff facing uphill battles for institutional resource allocations, as shown in numerous individual mollusk collection histories in this volume. Such budget allocation is especially challenging in times of economic downturn or when original benefactors fade away and new generations of administrators or trustees have different interests. Many universities and colleges have accordingly divested themselves of their former mollusk collections. While this creates opportunities for remaining institutions to expand their holdings, the receiving collection must find yet more funding to support the additional material. Persistent leadership and care by curatorial individuals (e.g. faculty, professional collections staff, and volunteers) is crucial but requires sufficient financial support. The histories of the collections herein illustrate the importance of long-term institutional commitment, federal grants, philanthropy, or a combination thereof. Federal support is especially helpful for improving infrastructure, enabling technology shifts, and for supporting innovative collaborative projects (including the ESB TCN). Philanthropy may range from individual donations to seed funds for entire institutions. Whatever the source, sufficient funds are crucial to both basic museum collection operations and meaningful development.

Mollusk collections function and develop best when they are integrated with the institution's research programs and aligned with other vital programmatic goals such as teaching, public education, and outreach. Today, a "good" malacological collection is one that (1) contains relevant specimen material that is taxonomically identified (to a feasible level) and associated with collecting-event data that can contribute to mapping in time and space; (2) is professionally maintained, adequately staffed, and resourced in a setting that provides archival-quality long-term stability; (3) provides open access to physical specimens and their derivatives (cryo-preserved tissue, DNA, RNA, proteins, venoms, etc.); (4) provides open access to digitized specimen data via relevant data aggregators, including high quality images, scans, and/or video recordings of living and preserved specimens; (5) maintains mutually beneficial connections with professional institutions and private collectors and actively participates in community activities that continuously improve data quality (e.g., through collaborative georeferencing or shared taxonomic updates); (6) responds to needs and opportunities; and (7) is routinely used by professionals inside and outside the home institution. Note that these factors are not about a collection's overall size, but rather its data quality, utility, and availability to multiple audiences.

Some problems faced by today's collections will need to be addressed at a much broader level—including financial sustainability, coordination of an increasingly complicated international regulatory landscape, and issues concerning the transport of fluid-preserved material and international specimen shipping. However, other topics of interest to the larger biocollections community can be addressed and solved as part of smaller collaborative efforts—as evidenced by our approach to the "vitality" standard and the innovations in georeferencing workflows in the ESB TCN project.

Digitized malacological collections are a large, growing, and ever-changing primary data source essential for understanding our Earth—past, present, and future. The following articles about our individual collections provide insights into how this collective resource has developed over time, from regional centers of molluscan collecting and research, to a growing national biodiversity collection with global impact. Each collection will likely continue on a trajectory largely determined by funding priorities of its home institution. As we have demonstrated, our collaborative work has expanded the usefulness of our data in research, education, and outreach activities. Strong

financial and user support is needed to continue to protect and improve this national resource into the future.

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