Leveraging legacy archaeological collections as proxies for climate and environmental research

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Understanding the causes and consequences of previous climate changes is essential for testing present-day climate models and projections. Archaeological sites are paleoenvironmental archives containing unique ecological baselines with data on paleoclimate transformations at a human timescale. Anthropogenic and nonanthropogenic forces have destroyed many sites, and others are under immediate threat. In the face of this loss, previously excavated collections from these sites—referred to as legacy collections—offer a source of climate and other paleoenvironmental information that may no longer exist elsewhere. Here, we 1) review obstacles to systematically using data from legacy archaeological collections, such as inconsistent or unreported field methods, inadequate records, unsatisfactory curation, and insufficient public knowledge of relevant collections; 2) suggest best practices for integrating archaeological data into climate and environmental research; and 3) summarize several studies to demonstrate the benefits and challenges of using legacy collections as archives of local and regional environmental proxies. Data from archaeological legacy collections contribute regional ecological baselines as well as serve to correct shifting baselines. They also enable regional climate reconstructions at various timescales and corroborate or refine radiocarbon dates. Such uses of legacy collections raise ethical concerns regarding ownership of and responsibility for cultural resources and highlight the importance of Indigenous involvement in planning and executing fieldwork and stewardship of cultural heritage. Finally, we discuss methodologies, practices, and policies pertaining to archaeological legacy collections and support calls for discipline-wide shifts in collections management to ensure their long-term utility in multidisciplinary research and public engagement.

archaeology | climate research | climate proxies | legacy archaeological collections

Archaeological sites are underutilized and threatened sources of paleoclimate and other paleoenvironmental proxies, often with strong contextual and temporal control (a comprehensive discussion of classes of archaeological materials used for climate studies is in table S1 of ref. 1 as well as refs. 2 and 3). Archaeological sites contain records of environmental and ecological change on human timescales, thereby allowing us to reconstruct environments, identify discrete climate events over short- and medium-term scales (4), and relate climate to human behavior. For example, Lambrides and Weisler (5) use tuna remains to study El Niño variability in the Marshall Islands, Sewell et al. (6) use springbok teeth from Sterkfontein and Swartkrans to assess the impact of climate-driven environmental changes on hominin evolution in South Africa, Li et al. (7) use archaeological phytoliths and charcoal to characterize paleoclimates in central China over the last 3,000 years, and Roffet-Salque et al. (8) use lipid residues from Çatalhöyük, Turkey, as proxies for precipitation patterns across the 8.2-ky B.P. (before present) climate event. Weiss et al. (9) identified a 300-year drought in northern Mesopotamia beginning at 4200 calendar years B.P. (cal B.P.) by analyzing sediments at an archaeological site, Tell Leilan. This 4200-cal B.P. event is now recognized as the boundary

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between the Middle and Late Holocene (International Chronostratigraphic Chart, v2019/05; http://www.stratigraphy.org/ICSchart/ChronostratChart2019-05.jpg). Case studies provided in this paper provide examples of archaeological environmental records, including legacy ones, that serve to correct shifting baselines (10, 11).

Anthropogenic and nonanthropogenic forces are destroying sources of climate data such as those noted above. Farming and urbanization threaten many archaeological sites as do sea-level rise (SLR), flooding, storm surge, erosion, and fire in addition to climate-driven human migration and development (12, 13). Threats to archaeological sites are particularly troubling because these sites are important receptacles of cultural heritage and often primary sources of information for climate history extending over recent millennia (1, 4, 14). Many legacy archaeological collections contain climate signals that no longer exist except at these sites. These collections offer unique perspectives and data of potentially great use in climate research even after sites are destroyed. Such materials provide crucial data on the causes and consequences of changes in previous climate regimes necessary to test models of future climate changes and to plan for them. Stratigraphic associations in archaeological sites offer unique perspectives on local and regional links among climate, environment, and human behavior and more broadly, offer global perspectives on human responses to climate change. In addition to evidence of changing climates, indicators of environmental change (e.g., attributes such as soils) or ecological change (e.g., processes such as the hydrological cycle)—two phenomena that may be related to or independent of climate—also exist in archaeological sites. The potential of archaeological sites to inform these fields of research, however, is often unrealized, in part because of the time and expense required to conduct archaeological excavations and analyses conforming to modern legal, professional, and ethical standards.

Large archaeological collections exist within thousands of repositories around the world. These legacy collections contain valuable climate evidence that should be incorporated routinely and extensively into climate research. Archaeologists intentionally recover material during field projects and create critical associated records under the stewardship and preservation principles that others should be able to use them (Principles 1 and 7: https://www.saa.org/career-practice/ethics-in-professional-archaeology) (15, 16). Museums and other repositories accession these collections, providing for their care with the goals of preserving collections in trust for the public and making those collections accessible for exhibition, instruction, and research. Often, the collections are owned by state or federal agencies and entrusted to museums and repositories for long-term curation. Legacy collections include those recovered and curated many years ago as well as those generated more recently. They contain materials that are available without the time or expense of new surveys and excavations. Well-curated legacy collections are particularly relevant as researchers identify new questions that can be addressed using innovative perspectives and analytical procedures. In some cases, both the original site and similar sites are now gone, leaving only these legacy collections as records of what is lost—including climate data. In this context, incorporating legacy data into climate and other environmental research is imperative.

Legacy Collections in Action

Tree Rings, Climate, and Collections. People have used wood for many purposes for millennia. Wood is generally well preserved in dry or water-saturated environments. Some archaeological collections contain significant wood objects and pieces of trees that record annual patterns of local precipitation, temperature, and related factors. Tree-ring research began in the early 1900s CE (common era) to date sites occupied by ancient peoples (17). The Laboratory of Tree-Ring Research (LTRR) at the University of Arizona curates over 2 million tree-ring specimens from hundreds of archaeological sites on federal, state, tribal, and private lands in the United States and elsewhere. This collection has advanced dendrochronology (creation and use of tree-ring sequences for dating), and it has yielded accurate, continuous dating sequences spanning over 2,000 y in the American Southwest (17) and potentially, over 10,000 y in the White Mountains of California (18). Other long sequences (8,000 to 10,000 y) exist for the Aegean, the Balkans, and the eastern Mediterranean (17, 19–21). Tree-ring specimens curated at the LTRR and at over 10 other tree-ring laboratories and research centers worldwide also are used for dendroarchaeology (the study of the interrelationships between past climate and human cultures), dendroclimatology (the study of former climates), and dendroecology (the study of past forest ecosystems, including impacts from fire, hurricanes, and other events) (22). Research topics that can be pursued using archaeological tree-ring specimens are facilitated by open access databases. The LTRR is housing and cataloging hundreds of thousands of federal specimens from the US Department of the Interior to make them more knowable to researchers and eventually, to make them open access.

The International Tree-Ring Data Bank (ITRDB), hosted by the National Oceanic and Atmospheric Administration (NOAA), is a model for how other legacy collections could be organized for accessibility and research utility (23). It has datasets from the past 8,000 y for 226 tree species from ∼4,000 locations and all continents except Antarctica. Researchers use the ITRDB to reconstruct megadroughts in the southwestern United States dating back almost 800 y. These studies are based on a tree-ring record partially derived from well-preserved wood sourced from archaeological sites, with implications for the dissolution of Anasazi settlements ca. 670 B.P. and the correspondence of these events to shifts in climate and environment (24–26). A tree-ring chronology from northeast Virginia (United States) also situates our understanding of human responses to climate change within the context of vulnerability. The failure of the English settlement at Roanoke, Virginia (United States) between 1587 and 1591 CE likely is due to one of the most extreme droughts experienced in that region during the past 700 years (27). The full research potential of tree-ring specimens in archaeological collections, however, can only be realized through the ITRDB if materials are adequately cataloged at their home institutions before being entered into this database.

Fisheries of the Past, Present, and Future. Archaeological collections contain important proxies (e.g., biogeographic information, quantified taxonomic attributions, data on fish body size and growth habits, biogeochemical attributes) for reconstructing paleoenvironments and documenting environmental and climate change. These environmental proxies demonstrate that present-day landscapes are the product of anthropogenic and nonanthropogenic modifications over centuries, millennia, or more. In coastal settings, changes in attributes, such as mean sea level, temperature, and precipitation, reconfigure landscapes, altering marine ecosystems. Archaeological collections contain a historical record of such changes and associated human responses (28–31). Data from these collections enable us to assess the degree to which environments change over time, to consider when and why they change, and to distinguish between causes and consequences despite differences in site structure and function, archaeological recovery methods, sample sizes, quality of surviving records, and similar problems.

Archaeological collections offer a historical record of fishing on regional and local scales, a baseline against which to assess the health of 21st-century fisheries (32). Legacy collections from the southeastern Atlantic coast of continental North America offer quantified trends in fish ubiquity, diversity, and mean trophic level in vertebrate collections from 2760 BCE (before common era) to 1800s CE. These data indicate that people sustained a broad-based estuarine fishery prior to 1500s CE despite changes in biogeochemical and cultural environments (33–35). Mean trophic level began to rise ca. 1500 CE when European-sponsored colonization began. This increase is particularly marked after 1670 CE, continuing until the late 1800s CE when it began to decline. Fishing now uses new technologies to take large numbers of previously underutilized groups of animals from previously unexploited locations. Meanwhile, new farming methods, industrialization, and urbanization degrade estuarine health, further reducing estuaries' ability to function as nurseries. In addition to anthropogenic changes stressing estuaries and fish stocks, environmental changes associated with global climatic events, such as the Little Ice Age, and anthropogenic climate changes in the 20th and 21st centuries likely affected all aspects of the regional fishery.

The time depth offered by the archaeological record permits broader analysis of cultural and environmental impacts on coastal fisheries than is traditionally available to fishery biologists who generally work at a decadal scale. Fisheries managers would benefit from incorporating archaeological data into their research. Coastal archaeological sites are, however, vanishing rapidly. Although all of the collections used in this example were excavated after 1970 CE, several of the sites are gone or will be within the decade due to urbanization, storm damage, SLR-induced erosion, and similar assaults. The remaining sites are at risk, underscoring the importance of using best practices to curate legacy collections (e.g., ref. 36).

Creating Legacy Collections from Disappearing Shell Middens. Coastal shell-bearing sites along the Gulf of Maine (GOM) preserve the remains of even small-bodied fishes, invaluable sources of past climate and other environmental data that address the pitfalls of "shifting baselines" (10, 11, 37, 38). Such data are vital for maintaining healthy fisheries, particularly when rapid warming of the GOM outpaces that of most of the world's oceans (39, 40). One key ecological change in the GOM occurred during the transition from the Late Archaic into the Susquehanna period, ca. 4200 B.P., after which warm-water swordfish largely disappear from the archaeological record. This may signal a transition from a warm- to cold-water ecosystem in the GOM, which may be related to broader climate processes between 4200 and 3900 B.P. (37, 38, 41). The archaeofisheries record for the millennium prior to ca. 4200 B.P. may offer a baseline for warmer than recent conditions in the GOM. SLR since 4200 B.P. has destroyed or submerged most Late Archaic coastal sites, however, and remaining sites are disappearing rapidly, lending urgency to the use of existing legacy collections and the creation of additional ones whenever the opportunity arises (36).

Previous GOM excavations did not use screens to recover artifacts, limiting use of samples to explore fisheries and other environmental questions (42–45). Because of this, Robinson and Heller (46) returned to three surviving Late Archaic sites to recover column samples for fine-screen analysis of the small-bodied fish component of these sites. One of these sites, Waterside, experienced a 2-m SLR between the original 1940 excavation and 2013, prompting Robinson and Heller (46) to recover additional samples from that site to curate at the University of Maine (UM) in trust for future study. The intentional creation of this GOM legacy collection was complicated when Robinson passed away without recording plans for long-term management, use, and storage of the samples. This highlights the importance of keeping thorough and accessible records on a daily basis at all stages of research. This example also suggests future directions for integrating similar archaeological data into global environmental research. In addition to issues of preservation and curation discussed below (*Incorporating Legacy Collections into Environmental Research*), long-term care also includes ensuring access by researchers and Indigenous community members, making certain that people know about the materials by posting records or metadata to online accessible databases, and identifying the last known location of the collection in publications (47, 48).

The Intersection of Legacy Collections and Indigenous Stakeholders

Legacy collections often represent the archaeological heritage of Indigenous communities. Efforts to formalize Indigenous stakeholder involvement in research design and implementation as well as in long-term management, use, and interpretation of archaeological collections is more common than in the past (49–51). Direct involvement of Indigenous communities at all stages is crucial for many reasons. Indigenous peoples are often on the frontlines of climate change and have first-hand knowledge of climate impacts on their communities and cultural heritage, including the destructive effects of SLR, storm surge, and erosion on settlements, infrastructure, and sacred sites. These communities are actively involved in assessing their vulnerability and anticipating needed adaptations and mitigation potentials, including comprehensive planning for resettlement (52–54). The federally recognized Native Village of Kivalina, Alaska, for example, has advocated strongly for relocation (necessary because of the destructive impacts of SLR and storm surge on the village) with a focus on community resilience (55). Legacy collections entail obligations and long-term curatorial responsibilities, such as defining the cultural significance and sensitivity of materials, which may impact the availability of specific materials for research. Indigenous input in collections management in addition to research planning and fieldwork execution is key in defining guidelines for the just and appropriate use of cultural resources.

At the UM, many legacy collections are the result of a cultural resources management contract between the UM and Bangor Hydro-Electric Company (Bangor Hydro) in response to federal relicensing obligations for dams on the Penobscot River—the ancestral territory of the Penobscot Indian Nation (Penobscot Nation). At present, two of the authors (S.H. and B.N.) are active in management, including use and access, of the UM's collections. Studies supported by Bangor Hydro focused on geoarchaeology, regional climate research, and paleoenvironmental reconstructions in the Penobscot River Valley (56–59). When Bangor Hydro ended their contract with the UM, the university was left with curatorial responsibility for collections but without adequate financial support for long-term curation. Funding constraints mean there is no full-time staff managing the collections; B.N. currently oversees collections with the assistance of graduate students.

Regardless, these materials already have contributed to important regional climate reconstructions (ref. 14, pp. 378 to 381).

In May 2018, the Penobscot Nation and the UM entered into a Memorandum of Understanding (MOU) formalizing shared decision making regarding materials and research activities involving Penobscot cultural heritage (http://umaine.edu/nativeamericanprograms/wp-content/uploads/sites/320/2018/05/Penobscot-Nation-UMaine-MOU.pdf). Two important practices articulated in this document reflect the spirit of shared collection management responsibilities. The first is the initiation of a cataloging system acknowledging Penobscot rights to determine cultural significance and sensitivities of archaeological and ethnographic collections. The second is a commitment by both parties to collaborate on a collection management policy and to share decision making about access to digital and other information. This MOU is consistent with emerging museum and Indigenous community practices acknowledging Indigenous perspectives on collection management and affirming Indigenous peoples' rights over their heritage resources (60, 61). The evolving relationship between the UM and the Penobscot Nation, underscored by the MOU, is a model for other tribes and institutions both within and outside of Maine and will drive curatorial improvements for the UM collections. This exchange follows many of the principles outlined by the Indian Arts Research Center at the School for Advanced Research in its "Community museum guidelines for collaboration" between museums and Native communities (62). Content management systems codeveloped by Indigenous peoples allow these communities to establish parameters for access to heritage materials (e.g., ethnographic collections, imagery, video, and archaeological collections) (63). This can increase access to collections by researchers while ensuring that research use is approved by Indigenous communities.

Incorporating Legacy Collections into Environmental Research

Curation and Recordkeeping. A number of challenges complicate use of legacy collections in environmental research. Some early excavators enjoyed private financing that permitted them to devote time and energy to aspects of field and laboratory work that are seldom feasible now (such as labeling every bone in a zooarchaeological collection and creating hand-drawn illustrations). However, there were also methodological differences, such as failing to use a screen during excavation. Insufficient fieldnotes and records or shortcomings in early destructive analytical techniques also produced less than ideal relative and absolute dates for objects and assemblages, which impede studies requiring information at interdecadal or finer resolution. Inconsistent or unknown excavation techniques limit the utility of some older collections.

Despite challenges to using legacy collections, there are ways to overcome these obstacles (64–66). Archaeological recordkeeping and curation methods have improved, often in response to present-day encounters with lost, inadequate, or separated records that plague older collections. More rigorous curation standards at the federal level require that many collections are housed in secure, climate-controlled storage, and improvements in catalog maintenance and creation of searchable databases have led to standards for all levels of repositories.

Insufficient discoverability of relevant collections continues to be an obstacle to their inclusion in research. In the United States, State Historic Preservation Offices maintain records of archaeological investigations in each state, including information about the repositories that house them. Some federal and state agencies have independent databases, although each agency maintains records in different ways constrained by the unit's mission, space, funding, and staff. Some universities and public museums make their catalogs accessible to the public using the internet, although many state laws prohibit releasing precise locations to the public. The Smithsonian Institution's National Museum of Natural History (NMNH) maintains public online databases for its collections and archives, excluding human remains, sacred objects, and other culturally sensitive materials. They include digital illustrations or photographs of many objects, encouraging researchers to investigate archaeological materials curated by the NMNH and thus, enhancing their significance through ongoing or future research by offsite users. The Smithsonian works with Indigenous and other stakeholders to assess collections' cultural sensitivity and to make decisions regarding restrictions for some materials. This practice is similar to that outlined in the MOU between the UM and the Penobscot Nation, but because the Smithsonian's NMNH holdings are large, these decisions generally are conducted on a case-by-case basis. Communication between Indigenous peoples and the Smithsonian is invited through a program called Recovering Voices that does outreach through Smithsonian-funded indigenous community visits as well as the NMNH Repatriation Office when evaluating United States repatriation requests or by departmental interactions through visits arranged by foreign embassies. Visiting researchers, interactions with Indigenous stakeholders and communities, and ongoing research by museum staff impact both the interpretation of collections and Indigenous stakeholder participation in this process (51).

Sharing and updating legacy collections through other nondiscipline-specific databases are other ways to encourage their use in interdisciplinary research. The ITRDB and the Global Registry of Scientific Collections (GRSciColl; discussed below) are examples of including archaeological, paleoclimatological, paleoenvironmental, and paleoecological data in scientific databases, which can enhance their use in disciplines outside of archaeology (Table 1 has other examples). The quality and quantity of electronic data from each repository, however, are highly variable in terms of organization, level of detail, and accessibility.

Accessing Legacy Collections. Methods and philosophies for curation of archaeological collections (both objects and associated records) vary widely. The laws and protocols of the country of origin govern many of these decisions, which may or may not be incorporated into a letter of transfer if the materials left their country of origin for a foreign institution. Policies and procedures of the curation facility may be different in public vs. private institutions, which may hold materials as a short- or long-term loan, under a curation agreement, or with a permanent transfer of ownership. After the passage of years or decades, it may be difficult to find relevant documents, assuming that they existed in the first place.

Access to and use of these collections depend on several factors, the most important (in the United States) being ownership of the land where objects were collected. This is directly linked to who owns and is responsible for curation of these collections (47, 67). Although other countries (e.g., Peru) may assert national ownership of their archaeological heritage, in the United States, property law dictates that landowners own the resulting collection unless the landowner donates it to a repository (67).

Each category of land owner—federal, state, tribal, and private—has rights and responsibilities that strongly influence how specific collections are acquired, managed, accessed, and deaccessioned.

Table 1. Databases containing information about archaeological materials

Database name	Collections	Spatial and temporal extent	Institution	URL
ITRDB	Dendrochronology	International, past 8,000 y	NOAA	https://www.ncdc.noaa.gov/data-access/paleoclimatology-data/datasets/tree-ring
GRSciColl	Interdisciplinary object-based scientific collections	International, human origins	Global Biodiversity Information Facility	http://scicoll.org/grscicoll.html
Smithsonian Institution NMNH Database	Smithsonian NMNH's collections data	International, human origins to historic times	NMNH, Smithsonian Institution	https://collections.nmnh.si.edu/search/
Ancient Maize Map	Ancient maize	Americas, 8,311 cal y B.P. to present	Lab of Archaeology at University of British Columbia	http://en.ancientmaize.com/
The Digital Archaeological Record	Records of archaeological investigations	International, Pliocene to present	Digital Antiquity, Arizona State University	https://www.tdar.org/
Vertnet	Biodiversity data	International, Pleistocene	Individuals from University of California, Berkeley; University of Colorado; University of Kansas; and Tulane University	http://vertnet.org/

Laws, regulations, and policies set the requirements and standards for long-term care of archaeological collections recovered from specific lands by university-based researchers, cultural resources management firms, or government archaeologists if federal land, funds, or permits are involved. For example, the US federal regulations for Curation of Federally-Owned and Administered Archeological Collections (36 CFR 79) lay out standards for curating federal collections recovered under the authority of four federal laws enacted between 1906 and 1979 (47). These regulations were issued in 1990 and cover federal legacy collections in both federal and nonfederal repositories. State, tribal, and local laws and policies often dictate the curation standards for collections from lands owned by those entities.

Because a primary goal of public museums and repositories is to make collections accessible, the curatorial responsibility of cataloging is critical for researchers and others to locate relevant objects, associated records, and entire collections. Digital catalogs may be available through the website of a particular repository if applicable laws, rules, and regulations permit this and where funds and staff expertise support this effort (see the Smithsonian example above). Creating and maintaining large collection catalogs in digital formats, however, entail challenges. Bulk samples (a term often used for a group of similar objects, such as potsherds, lithic flakes, or biological materials, bagged together from the same provenience, or unprocessed soil samples) may be insufficiently described in catalogs if included at all. These artifacts and samples may not have been revisited for decades, may be too small for some analyses, may have degraded over time, or may lack sufficient records or fieldnotes to address archaeological, climate, or other environmental research questions. In order for these data and materials to be used, they must be publicly available.

Some disciplines prioritize development of databases, such as IDigBio (Integrated Digitized Biocollections) for biology and GRSciColl (Global Registry of Scientific Collections) for many scientific collections, but both require significant funding and technical support. As a whole, the discipline of archaeology has not yet undertaken a similar endeavor, but an effort was made to add fields to GRSciColl that would make it helpful to researchers wanting to find and use archaeological collections. Unfortunately, lack of funding derailed this initiative, although some archaeological collections are included in the database. GRSciColl is now hosted by the Global Biodiversity Information Facility, which makes those archaeological data that were incorporated more accessible to users worldwide. Some site- or region-specific archaeological databases do exist. The Digital Archaeological Archive of Comparative Slavery (DAACS), created and maintained by the Department of Archaeology at Monticello, makes materials and information available for research, teaching, and private study. The DAACS promotes itself as a "community resource." Regardless of their geographic or temporal breadth, these databases are most useful if records are up to date and accurate.

Some programs and funds encourage the use of legacy collections in interdisciplinary studies. The Robert S. Peabody Institute of Archaeology (RSPIA) has the Linda S. Cordell Memorial Research Award to support research using that institution's collections. Jessica Watson (68), for instance, used a Linda S. Cordell Memorial Research Award to investigate environmental change using legacy zooarchaeological collections from the RSPIA for her dissertation on Late Holocene human environmental interactions on Martha's Vineyard. The Martha's Vineyard collections are well curated with detailed field forms, maps, plans, and images, increasing their utility and making them easier to incorporate into interdisciplinary research.

Journal Policies on Reporting Legacy Collection Locations. Journal reporting guidelines vary within archaeology and more broadly, anthropology. Although increasing numbers of journals are committed to making published research open access (free for readers; often at the expense of the publishing author), not all prominent publications have collection, manuscript, or data archiving policies to which authors must adhere in order to ensure that their work is reproducible by others. Several US journals published by Cambridge University Press for the Society for American Archaeology (*Advances in Archaeological Practice*, *American Antiquity*, and *Latin American Antiquity*) require authors to include a "Data Availability Statement" in their manuscripts, informing readers about the location of collections, records, and digital data. *Intersecciones en Antropología* (Facultad de Ciencias Sociales de la Universidad Nacional del Centro de la Provincia de

Buenos Aires), an Argentina-based journal, requests specific information, including the name of the collection and accession numbers for data or materials as well as the physical location of data. *Open Archaeology* (De Gruyter; Poland) also requires authors to state where primary data and materials may be obtained. Some journals do not have specific collection reporting policies, but instead require authors to cite their data. This policy indirectly suggests a collection's location and availability for future research. These include *Journal of Archaeological Science* (Elsevier; the Netherlands) and *Geoarchaeology* (Wiley; the United States). *Geoarchaeology* adheres to FAIR (findable, accessible, interoperable and reusable) Data Principles, which require data to be findable, accessible, interoperable, and reusable (69). Many major publications do not, however, have collection or data access policies.

Leading scientific journals, such as *Science*, *Nature*, and PNAS, publish research that uses archaeological, paleontological, or other paleoecological data sourced from archaeological sites. They have strict collection reporting policies: *Science* requires that paleontological specimens "must be deposited in a public museum or repository and available for research," and *Nature* stipulates that authors "[i]ndicate where the specimens have been deposited to permit free access by other researchers." PNAS requires authors to make all materials and data essential to the research available to readers, and databases must be cited. Data reporting policies for these journals apply primarily to data in a digital format, protocols, code, and statistical analyses, which must be made available for readers in a public repository, online supplemental information, institutional website, or similar forum. While the primary focus of these publications is not archaeology, the rise of interdisciplinary research that involves archaeological materials means that journals should adopt specific guidelines for all authors for reporting collection locations and data.

The lack of systematic reporting requirements means that archaeological collections are not always cited in a way that makes the methods used transparent and the data both accessible and reproducible. Strengthening collections citation requirements in publications and cultural resource management reports is one way of increasing the utility and use of legacy collections in climate (and other) research (48). This is particularly important as publication is sometimes the only reliable method of preserving collections-derived information when institutions or repositories are unable to curate materials in perpetuity. Key to these goals is reporting where collections are housed and when possible, assuring that they are available for research regardless of the resources of the host facility.

Discussion

Use of legacy collections from museums and other types of repositories permeates the biological, earth, and human sciences, with several high-profile articles advocating for collection care, preservation research, and public engagement (70–73). Often, archaeological and anthropological collections are not mentioned in these discussions, although these collections have much to offer both to research and to education on issues of broad significance to science and society, including applications to public health, conservation biology, and endangered languages and knowledge (48, 74). Many ecological, environmental, and climate studies benefit from the long-term high temporal resolution of archaeological sites and proxies, and the examples outlined here have much to offer these larger dialogues. To help make this clear, we have placed our research within the larger context of the value of legacy collections around the world for science and society (48, 70–72, 74).

The southeastern Atlantic fisheries and the GOM examples in this paper focus on past climate and environmental changes and associated fisheries trends. They also demonstrate the challenges and benefits of using legacy collections. One study used existing legacy collections, while the other required new excavation designed to create and preserve a legacy record for the future. In both cases, remaining archaeological sites are threatened due to primary and secondary impacts of climate change and urbanization (13). These examples provide key insights into creating legacy collections for future research. In the GOM case, the decision to collect fish component samples was made in the field, not during the planning phase. Project planning should explicitly consider and prepare for the creation of a legacy collection (47, 48). Because the collection should survive the original excavators, materials and records for all archaeological excavations and subsequent studies should be inherently clear, explicit, extensive, and accessible. Many studies, such as the southeastern Atlantic coastal plain example, would not be possible without curated legacy collections and associated data.

As part of comprehensive planning, it is vital to consider curation requirements for legacy materials and repositories' ability to meet those needs in perpetuity. Discipline-wide changes are needed to make such considerations routine, particularly given that the broad range of sample types recovered from archaeological sites presents substantially different curation needs. For example, while some samples from the GOM sites are stored in dry boxes at the UM, materials from the Seabrook Marsh site (preserved when a salt marsh formed over the living surface) must remain fully saturated in seawater in cold storage to avoid formation of sulfuric acid and gypsum crystals (75). Preserving such samples is critical for future research. For instance, many of the collections used in the southeastern Atlantic coastal plain case study represent the last records of vanishing coasts and the wealth of healthy fisheries that sustained human life for millennia, records that would be lost forever without proper curation. Providing appropriate care for curated samples is a key component to creating enduring legacy collections, which requires that research designs routinely include long-term plans for collection management (47, 48). Future archaeological investigations must budget for long-term collection curation, and they must continue to consider carefully the volume and curation needs of object-based collections and their associated records, particularly in regard to the creation of legacy collections (47, 48, 76). We recognize, however, that it is still critical to excavate sites threatened with imminent destruction, even if all curation needs cannot be met in the short term.

As the Penobscot River Valley Collections case makes clear, collection management relationships with tribal partners are long term, indefinite, and evolving. As institutions become more attuned to Indigenous rights to cultural heritage, they must develop innovative and appropriate approaches to comanaging legacy collections. At the end of Bangor Hydro's contract, the UM assumed curatorial responsibility for collections without adequate financial support for long-term curation. Public institutions curating legacy collections that represent Indigenous heritage must plan for the long-term responsibilities and obligations associated with accumulating such collections. Relationships between institutions and Indigenous stakeholders do not end when the project ends; hence, sound financial and human resource planning and practices must be implemented to ensure good stewardship of the collections as well as the relationships with stakeholders.

To facilitate the use of legacy collections in climate research, collections must be cataloged and entered into databases, which must then be maintained despite software and hardware upgrades. Publication in scholarly journals and cultural resource management reports also presents a valuable method of sharing and promoting this information, and it is important for journals and other academic publications to include guidelines on reporting requirements for metadata as well as other data in supplementary materials. When this happens, their scientific contribution is greatly enhanced: the wide use of tree-ring data in various interdisciplinary studies is partially due to the availability of these data and the fact that they are recognized within the larger scientific community as reliable proxy records.

Conclusion

Climate research, particularly that focused on changes occurring on scales relevant to human lifespans, can be greatly enhanced by archaeological data. Sites containing these data are disappearing quickly in the face of urbanization, changing coastlines, and a myriad of other anthropogenic and nonhuman factors. Many of these contexts and associated data are unique, and their destruction means that records of local and regional climate, environmental, and ecological information are lost. Legacy collections contain a wealth of baseline climate data needed to develop temporal and spatial sequences, calibrate chronologies at all scales, and constrain absolutely dated materials or events. Expanding participation of Indigenous communities also refines our understanding of artifacts and delineates how collections may be of use in future research. Increasing the use of archaeological materials requires that the best practices outlined in this paper become standard throughout the discipline. In particular, consistent reporting requirements for publications and databases, increased planning for collections management—including budgets for long-term curation of materials and associated records and data—and advancing institutional practices promoting and advertising databases across all research disciplines will increase the value of legacy collections in climate research.

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