The Unique Role of Federal Scientific Collections

Infrastructure Generating Benefits, Serving Diverse Agency Missions

A Report of the Interagency Working Group on Scientific Collections

Edited by

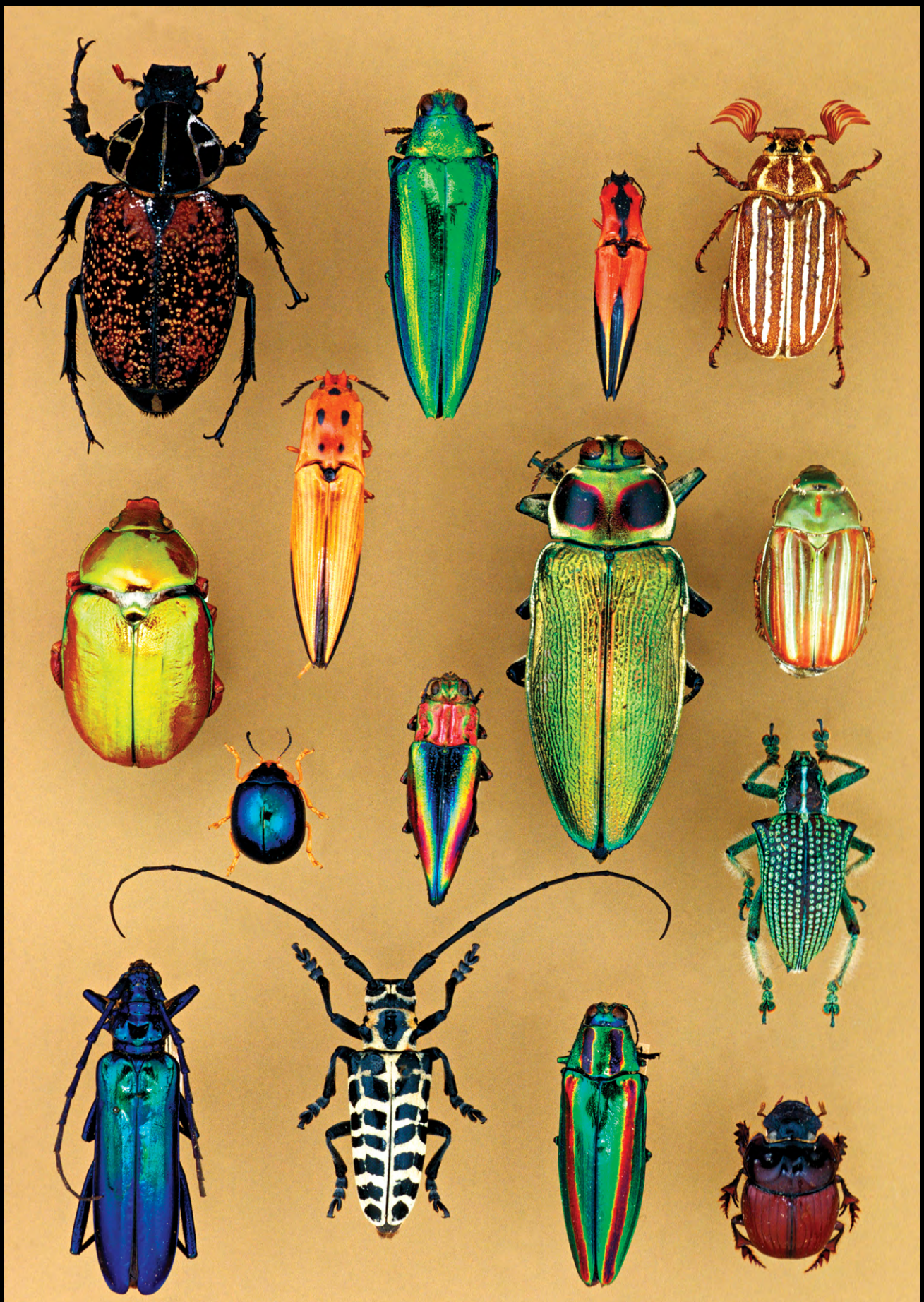
David E. Schindel, Diane C. DiEuliis, and Bruce Geyman

Smithsonian Institution

THE UNIQUE ROLE OF FEDERAL SCIENTIFIC COLLECTIONS

Infrastructure Generating Benefits, Serving Diverse Agency Missions

A Report of the
Interagency Working Group on Scientific Collections



Beetles from among the 145 million artifacts and specimens collected in the National Museum of Natural History (Smithsonian/Chip Clark)

THE UNIQUE ROLE OF FEDERAL SCIENTIFIC COLLECTIONS

Infrastructure Generating Benefits, Serving Diverse Agency Missions

A Report of the
Interagency Working Group on Scientific Collections

Edited by
David E. Schindel, Diane C. DiEuliis, and Bruce Geyman

Smithsonian
Scholarly Press

WASHINGTON, D.C.
2023

Cover images (top to bottom): USGS hydrologist Tia Scott collecting a water quality sample from an eastern New York stream (Photo by Carolyn Van Alstyne, courtesy of USGS). Remotely operated vehicle Deep Discoverer is back on deck of NOAA Ship *Okeanos Explorer* after a coral- and sponge-filled dive at Beethoven Ridge in the northern Pacific (Photo by Art Howard, courtesy of NOAA). Donald Merrit, a research biologist for the University of Maryland's Horn Point Center for Environmental Studies, pilots a boat from which ARS chemists Laura McConnell (left) and Jennifer Harman-Fetcho collect samples of oysters, water, and sediment from the Choptank River on Maryland's Eastern Shore (Photo by Scott Bauer, courtesy of USDA/ARS). Laura Reynolds, a CDC Epidemic Intelligence Service officer, takes a blood sample from a veterinary clinic staff during a canine leptospirosis outbreak in Phoenix, Arizona (Photo by Sarah Guagliardo, courtesy of CDC). Researchers collect winter water samples from Toolik Lake, Alaska, a field site monitored by the NEON Program (Photo courtesy of the National Ecological Observatory Network/Battelle).

Published by SMITHSONIAN INSTITUTION SCHOLARLY PRESS
P.O. Box 37012, MRC 957, Washington, D.C. 20013-7012
https://scholarlypress.si.edu

Suggested Citation
Interagency Working Group on Scientific Collections (IWGSC). 2023. "The Unique Role of Federal Scientific Collections: Infrastructure Generating Benefits, Serving Diverse Agency Missions." A Report of the IWGSC. Washington, DC: Smithsonian Institution Scholarly Press. https://doi.org/10.5479/si.24559996

Disclaimer
The findings and conclusions in this report do not necessarily represent the official position of any participating agency or contributor.

ISBN (online): 978-1-944466-62-6
ISBN (print): 978-1-944466-63-3

Publication date (online): 29 November 2023

Contents

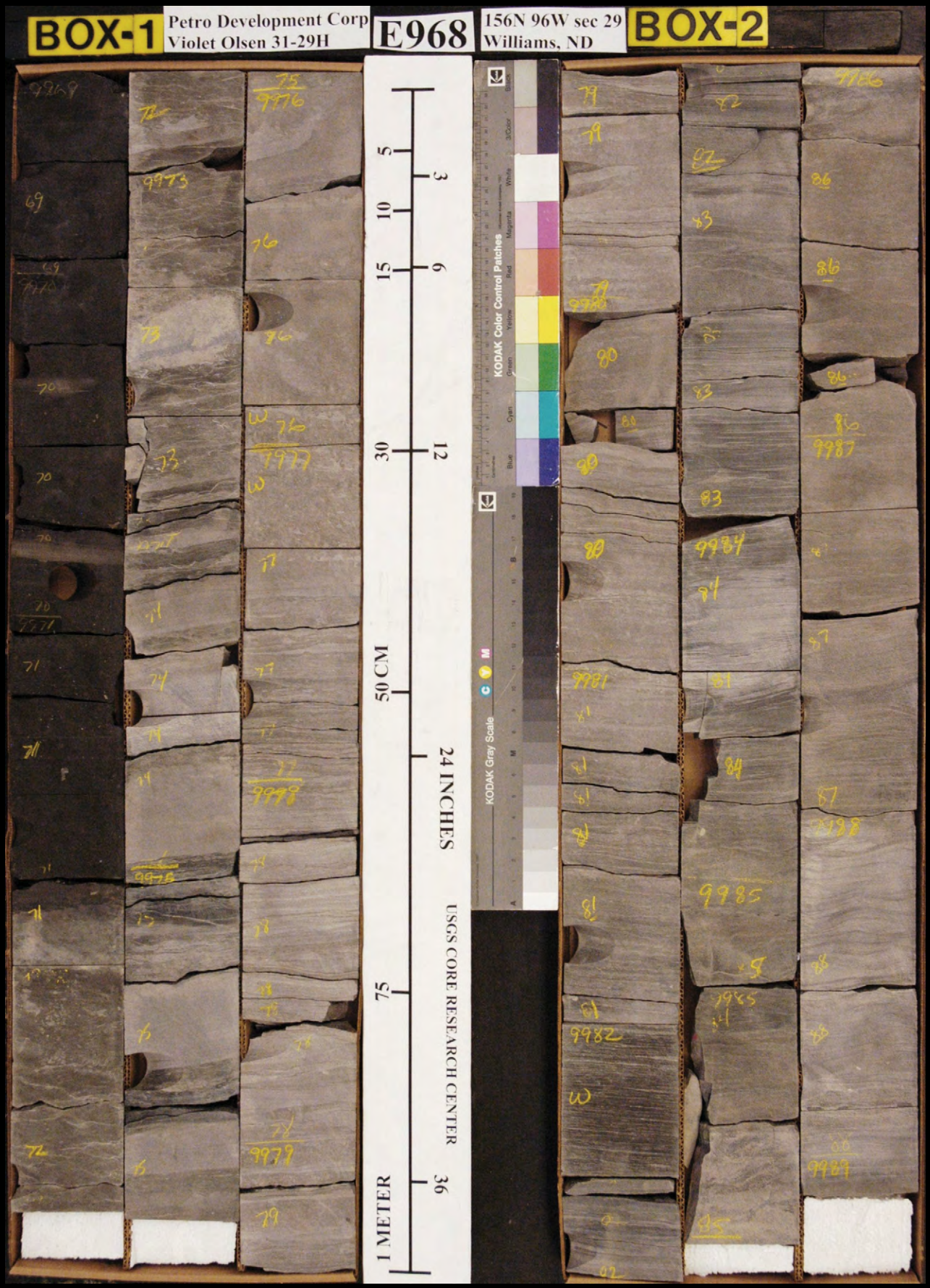
Inside the paleobiology collection in the National Museum of Natural History, Washington, DC (Smithsonian/Chip Clark)


MICROFOSSILS
What's happening here?

A collection of whale skulls at the National Museum of Natural History, Washington, DC (Smithsonian/Chip Clark),

Specimens of gold in the native state housed at the Hall of Geology, Gems, and Minerals, National Museum of Natural History, Washington, DC (Smithsonian)


Gold!



(Above) Two boxes of slabbed sections of toil bearing rock core from the Bakken Formtaion, Williams County, North Dakota, laid out for comparative analysis at the USGS Core Research Center examination room at the Denver Federal Center (USGS/Public Domain)

Foreword

I am pleased to present, on behalf of the White House Office of Science and Technology Policy (OSTP), this report, *The Unique Role of Federal Scientific Collections:Infrastructure Generating Benefits, Serving Diverse Agency Missions*, which describes the remarkably diverse scope of Federal scientific collections and how they advance a wide variety of agency missions and benefit the American people. This is a report of the Interagency Working Group on Scientific Collections (IWGSC), originally established under the America COMPETES Act of 2007, that is being published by Smithsonian Institution Scholarly Press. Like its 2020 predecessor, *Economic Analyses of Federal Scientific Collections: Methods for Documenting Costs and Benefits*, this report focuses on the scientific collections owned and managed by the departments and agencies of the United States government. These collections range from moon rocks to dinosaurs to viruses to insects to human tissues, and they are an irreplaceable part of the cumulative evidence upon which science depends. They play a central role in supporting many regulatory, management, and policy decisions on issues as diverse as biomedicine, environmental quality, biodiversity, climate change, and cultural equity. They provide the voucher specimens, reference standards, and genomic materials that ensure rigor and reproducibility in scientific research in multiple disciplines. As shown by the numerous case studies presented throughout this report, collections throughout the country are found playing some surprising roles in achieving the missions of Federal agencies. Scientific collections, both those owned by the Federal government and those held by a diverse array of institutions across the country, have been rightly identified as a critical form of distributed research and development (R&D) infrastructure in the 2021 National Science and Technology Council report *National Strategic Overview for Research and Development Infrastructure*. In the present report, the IWGSC makes a timely and compelling case that scientific collections have been critical in the past to the advancement of science and discovery and will be important and valuable in enabling R&D to tackle the societal and scientific challenges of the twenty-first century.

(Above) Astronauts Alan Shepherd, Jr. and Edgar Mitchell examine rocks collected during the Apollo 14 mission to the Moon (NASA)

Kei Koizumi

Acting Executive Director of the National Science and Technology Council

Principal Deputy Director for Policy

White House Office of Science and Technology Policy

Executive Summary

Scientific research and development (R&D) are essential activities in the government, private, and academic sectors of American society. Scientific collections, both living and non-living, are critical components of the Federal government's R&D infrastructure, essential for ensuring national security, protecting the public's health and its safe food supply, promoting innovation and economic growth, and protecting the environment, among others. To pursue their long-term missions, Federal departments and agencies have created and preserve scientific collections to address new and unpredictable challenges to society and to establish long-term baseline histories for the analysis of change, often using new analytical technologies. With some exceptions related to national security, Federal scientific collections are made available to all qualified researchers to maximize benefits to the nation, because critical samples and keys to new innovation are often found in scientific disciplines that aren't obvious.

The scientific collections owned, maintained, and managed by the Federal government differ in important ways from similar collections in the private and academic sectors. Federal R&D priorities reflect changing national needs, as expressed through legislation and regulations that evolve over time, and the Federal budgets that implement them while also addressing emerging priorities. Federal scientific collections serve the public good by providing access to objects of scientific value regardless of where, when, by whom, or for what reasons they were originally collected and preserved.

The White House National Science and Technology Council's Interagency Working Group on Scientific Collections (IWGSC) has, since 2005, convened representatives from 24 Federal departments and agencies that rely on scientific collections. IWGSC has produced a series of studies, reports, and other information resources aimed at improving policies, transparency, accessibility, management, and the assessment of costs and benefits related to Federal scientific collections. This report summarizes these IWGSC achievements and its future directions, and presents 21 case studies of the varied ways that Federal scientific collections have served the nation in diverse areas of American life.

(Left) A glimpse of the invertebrate zoology collection of the National Museum of Natural History (Smithsonian/Chip Clark)

Acknowledgments

The Office of Science and Technology's (OSTP) Interagency Working Group for Scientific Collections (IWGSC) consists of representatives from 24 Federal departments and agencies, each of which owns, manages, and/or provides financial support for scientific collections across a wide spectrum of scientific disciplines. This report is the result of several years of collaboration among and contributions by more than 90 representatives of the Federal government departments and agencies, shown below.

The goal of this advisory report is to demonstrate to departments, agencies, OSTP, and other stakeholders that Federal scientific collections are a unique and valuable component of the nation's research and development (R&D) infrastructure. The report does not represent official policies of IWGSC member agencies, including those of the co-chairs and authors, or of OSTP.

In developing this report, agency representatives were asked to contribute examples of past uses of objects in their collections that had led to significant benefits to the country. Diane DiEuliis (DoD/NDU) and Mark Metz (USDA/ARS) led the effort to solicit and review these examples. Thomas Olszewski (IDA Science and Technology Policy Institute) supported this effort under an interagency agreement with and funded by OSTP. Following reviews by IWGSC members and OSTP, David Schindel (Smithsonian) worked with IWGSC members and their agency colleagues to add several vignettes and revise others, resulting in the 21 vignettes presented in this report. Vignettes have credit statements that identify principal authors, at the discretion of agencies.

The narrative text that frames the vignettes is the product of two years of discussions at IWGSC's monthly meetings, reflecting collaboration and contributions of IWGSC's agency representatives. IWGSC's Co-chairs Scott Miller (Smithsonian), Dionne Toombs (USDA/Office of the Chief Scientist), and Kevin Hackett (USDA/ARS, acting co-chair for Dionne Toombs) and IWGSC Executive Secretary Diane DiEuliis led these discussions.

Tom Olszewski prepared a first draft of the narrative sections, and David Schindel revised and added new narrative sections in response to reviews by IWGSC members and OSTP. Dr. Olszewski also worked assiduously to locate and obtain all of the images in the report. Bruce Geyman (USGS) designed and formatted the report in close collaboration with the authors and contributors. Eileen Graham (Smithsonian) provided invaluable support in managing all these processes.

IWGSC is grateful to the Smithsonian Institution Scholarly Press (SISP) for publishing this IWGSC report, following the 2020 publication of Economic Analyses of Federal Scientific Collections: Methods for Documenting Costs and Benefits. Ginger Minkiewicz, SISP's Director, provided the leadership and technical support that were essential in publishing this report.

IWGSC Member Departments and Agencies

Agency for International Development

Department of Agriculture

- Agricultural Research Service
- Animal and Plant Health Inspection Service
- Forest Service
- Natural Resources Conservation Service
- Office of the Chief Scientist

Department of Commerce

- National Institute of Standards and Technology
- National Oceanic and Atmospheric Administration
- United States Patent and Trademark Office

Department of Defense

Department of Energy

Department of Homeland Security

Department of Justice, Federal Bureau of Investigation

Department of Health and Human Services

- Centers for Disease Control and Prevention
- Food and Drug Administration
- National Institutes of Health

Department of State

Department of the Interior

- Bureau of Land Management
- National Park Service
- United States Geological Survey

Department of Transportation

Department of Veterans Affairs

Environmental Protection Agency

National Aeronautics and Space Administration

National Science Foundation

Smithsonian Institution

Botanical specimen (*Argyroxiphium sandwicense*) housed in the U.S. National Herbarium, National Museum of Natural History, Washington, DC, collected from Mouna Kea, Hawai'i during the 1838–1842 U.S. Exploring Expedition led by LT Charles Wilkes, USN. Specimens and artifacts collected by the expedition became the foundation of the Smithsonian collection. (Smithsonian)

Introduction

Research and development (R&D) in science and technology are critical activities for the missions of many of the Federal government's departments and agencies. Scientific investigations that lead to discoveries and progress commonly rest on the analysis of physical objects, ranging from rock cores drilled and extracted from Earth's crust, to plants, animals, microbes, and fossils from diverse environments and through history, to extraterrestrial samples from the moon and beyond, among many others. They have been collected by Federal agencies since shortly after the nation's founding, and many of them have been retained and preserved since then as government property. Long-term preservation ensures that future generations will have access to them, to verify previous analyses and to conduct new analyses that extract new types of information from them. This document presents 21 "vignettes" that illustrate the value generated by the objects in these collections. These objects continue to have value decades or centuries after the research for which they were collected was completed (e.g., Vignettes 4 and 11). When a need for analysis of specific objects arises, the cost of not having access to them can be devastating.

The benefits flowing from scientific collections are diverse and far reaching. Discoveries that started with these objects have led to technological innovations, economic growth, and new job opportunities. New analytical capabilities continue to appear, allowing researchers to learn from these objects after decades or more of storage (see Vignettes 11 and 19). For example, protecting the public's health and safety has often relied on the continued availability of critical reference samples, sometimes many years after they were set aside for future use (Vignettes 2 and 3). The scope and size of these collections are not widely known or appreciated, but preserving them protects and serves the United States through an uncertain future. This report presents a small sampling of their diversity and the benefits the nation derives from them.

In 2006, the White House Office of Science and Technology Policy (OSTP) established the Interagency Working Group on Scientific Collections (IWGSC): "(1) To evaluate the state of object-based scientific collections at, supported by, or used by U.S. Federal agencies or in federally supported activities; (2) Foster the coordination of collections activities across the Federal agencies; and (3) Increase government and public awareness of the importance and use of collections."[1] By 2009, IWGSC had published the "Green Report,"[2] which defined "object-based scientific collections"[3]; reported the results of a first-ever survey of collections owned, operated, and supported by the Federal government; outlined the benefits provided to the nation by these collections; and presented recommendations that formed the basis of IWGSC's Program of Work for the years that followed. The survey revealed the enormous diversity of these collections across agencies and scientific disciplines, and provided the first glimpse at the number of them, the enormous number of objects they contain, and the great variation among their uses and management. Throughout its ensuing work, IWGSC's members have come to appreciate and learn from these differences in mission, use, management, and benefits. From their interagency activities, IWGSC members have found best practices that address shared challenges, and IWGSC has produced tangible deliverables in response to recommendations made in 2009 (see Figure 1).

(Above) Cover of the 2009 OSTP/IWGSC "Green Report," *Scientific Collections: Mission-Critical Infrastructure for Federal Science Agencies*

IWGSC's work has focused on "institutional" scientific collections.[4] These consist of objects that are preserved long-term for future research use in diverse fields of science and technology, such as anthropology, archaeology, biology, biomedicine, earth and space sciences, history of science, and applied fields such as agriculture, materials science, and technology development. As defined by IWGSC, the collections also include any documentation that is tied directly to objects in the collection, such as field notes and maps. Libraries, archives, and other data repositories are not considered institutional scientific collections by IWGSC, because the objects they contain are not themselves used as sources of new analytical data. Some scientific collections consist of objects that are renewable, such as living organisms that can be bred for experimental research or for developing new agricultural strains (Vignettes 11 and 13). An object in renewable collections can be consumed completely by destructive analytical methods without depleting the future supply. Other renewable collections contain highly characterized objects that are essential as regulatory standards for calibrating instruments. Other collections consist of non-renewable objects; each one is unique and cannot be replaced if consumed during research (see Vignettes 7, 8, and 18). Fossils, artifacts, and preserved plants and animals are common examples.

This document reports on the progress that IWGSC has made and the impact it has had during the decade that followed publication of the Green Report (see Figure 1 and the following section). OSTP called for implementation of three recommendations in the Green Report, and these were included in the America COMPETES Reauthorization Act of 2010.[5] These mandates led IWGSC to:

- Improve access to Federal collections by creating the Global Registry of Scientific Collections (GRSciColl),[6] an online registry that includes Federal institutions and their collections;
- Propose standards for the content of agency policies governing the management of Federal collections,[7] and coordinating development and publication of these policies through a new online IWGSC Clearinghouse;[8] and
- Develop a framework and standard practices for calculating the operating costs of Federal collections, and to identify five methodologies for documenting the benefits generated from their intramural and extramural use.[9]

The body of IWGSC's work since publication of the Green Report has equipped agencies with more evidence-based approaches to managing their collections and increasing their measurable benefits. Building on more than a decade of interagency, cross-disciplinary collaboration, IWGSC is in an unprecedented position to help agencies ensure access to the collections that will be critical in meeting scientific and societal challenges, such as confronting emerging infectious diseases; addressing global climate change; sustaining economic growth through technological innovation; strengthening our international alliances through research partnerships; and increasing the diversity and productivity of America's science and technology (S&T) workforce.

Like the Green Report, this "Blue Report" describes the enormous diversity of Federal object-based scientific collections, the reasons why the government maintains and supports them, and the diverse benefits they provide to the American people. The decision to add any object to an institutional collection commits the holding agency to pay for all the services that enable and promote that object's future use. These services are essentially identical across departments, agencies, organizational missions, and scientific disciplines and are described in "IWGSC's Decadal Program of Work" below. Decisions about what to preserve are difficult because future needs are usually unpredictable. The likelihood

that any particular object in a collection will eventually be used for research can be small. Conversely, the decision not to add an object creates a risk of not having a valuable asset if the need for it arises later. As the vignettes presented in this report demonstrate, having these collections and managing them well often proves indispensable for the country's well-being and prosperity.

The examples of high-impact uses of collections presented as vignettes in this report fall into two categories. Most of the vignettes describe how the use of objects in a Federal collection generated benefits in the research area for which they were collected (e.g., Vignette 2). Others are about the use of objects for purposes that weren't anticipated by the agency that collected and preserved those objects. For example, Vignette 8 describes archaeologists' discovery of the remains of trees while excavating Native American sites on Federal lands. These remains led to the creation of a Federal collection in a university-based research center devoted to tree rings, a leading contributor to climate change research. IWGSC recognizes that the outcomes in the second category can't be predicted or planned for, but they can be made more probable by making information about collections and their contents more broadly available, especially across disciplines. An October 2014 IWGSC workshop, cosponsored by Scientific Collections International,[10] focused on detecting, characterizing, mitigating, and predicting emerging infectious diseases.[11] Biomedical sample collections, as well as collections devoted to biodiversity research, veterinary sciences, and agriculture, all have important roles to play, but only if information about the collections and their contents are well-characterized and widely accessible. Promoting cross-disciplinary awareness and access to relevant scientific collections remains an IWGSC priority.

The Interagency Working Group on Scientific Collections

Origins. The U.S. government has maintained scientific collections for numerous purposes almost since the nation's founding, with all but a very few unknown by the public. That changed in 2006, when, in the course of an informational tour of Federal collections, the President's Science Advisor, Dr. Jack Marburger, was shocked to learn that the National Animal Parasite Collection was housed in a former rabbit barn. Around that same time, public and Congressional attention was captured by a decision to discard nearly 10,000 samples of infectious bacteria in the Special Pathogens Laboratory at the Veterans Affairs Medical Center in Pittsburgh, Pennsylvania. Samples of the pathogen causing Legionnaire's disease were destroyed, among many other rare strains of disease agents. The House Science and Technology Committee declared, "It is incomprehensible that there are no policies in place to ban arbitrary and capricious management decisions by administrators without any assessment of the value of the collection and its potential use in other research."[12]

For these and other reasons, the Interagency Working Group on Scientific Collections (IWGSC) was established by the White House National Science and Technology Council (NSTC) in June 2006 with the following mandate:

> Recognizing that object-based collections provide the fundamental infrastructure for contemporary and future scientific advancements, the IWGSC will address the scientific, environmental, societal, and national security needs for such collections, including an assessment of current collections resources; an evaluation of requirements to maintain and further develop these resources, including workforce needs; an assessment of how to integrate and optimize current resources; and an evaluation of gaps and research and development needs. In addition, the IWGSC will work to further international cooperation in collections activities and issues.[13]

Role. Since its creation, IWGSC has grown to include more than 80 representatives from 24 Federal departments and agencies that are responsible for Federal scientific collections, provide Federal funding to non-Federal collections, and/or have direct policy relevance to Federal collections. Figure 1 shows the history of IWGSC and its major achievements and deliverables. IWGSC operates as a convening body for exchanging information on the management and initiatives within member departments and agencies, and for identifying shared interests and goals. IWGSC then forms task groups that gather data and formulate options, subsequently reporting back to IWGSC's members at its monthly meetings. When a consensus emerges, the task group formulates a program of work that will lead to tangible deliverables. The three deliverables mandated by law and produced by IWGSC, described above, have shown that consensus in IWGSC sets the stage for improvements in the management, use, and impact of Federal scientific collections. The authority to change policies and initiate new activities for Federal collections rests with IWGSC's member agencies, but these members look to IWGSC as a source of best practices and innovations that emerge from interagency and cross-disciplinary interactions.

Figure 1. Timeline of IWGSC history and work products

IWGSC's Decadal Program of Work

The publication of this report marks an inflection point for IWGSC. With the successful implementation of the priority initiatives recommended in the Green Report, IWGSC has, for several months, been developing options for a new Program of Work aligned with the Federal government's priorities for S&T and informed by years of interagency collaboration. As illustrated by the vignettes in this report, the vast scope and size of Federal collections make them critical infrastructure for R&D. Now their holding agencies must respond to new and emerging realities: a global pandemic; economic uncertainty in the face of international competition; social and economic inequality; the ever-growing dangers of environmental hazards and inequities; and global climate change.

In the months following publication of this report, IWGSC will finalize its Decadal Program of Work. This process will include IWGSC's member agencies as well as relevant NSTC units, non-Federal institutions (especially universities and colleges), and international counterparts that share the U.S. government's focus on these priorities. This process will result in a Program of Work that will be transmitted to OSTP and NSTC approximately six months after publication of this report. The Program of Work will identify the task groups that will be formed, the scope of work for each task group, the organizations that have expressed interest in participating in each task group, and the relevance of each task group to priorities, policies, and/or practices with crosscutting importance to IWGSC member agencies.

IWGSC has identified the following areas of common interest and emerging opportunities. The most compelling topics will be selected and incorporated into the future Program of Work.

A. Diversifying and expanding the cross-disciplinary use of collections: Climate Change and Emerging Infectious Diseases. Federal collections related to global climate change can be found in many different departments and agencies (see Vignettes 6–10), and the same is true for infectious diseases. Knowledge of these collections may not extend to all the research communities that need them, limiting their potential use for important research. IWGSC can play an important role in identifying ways to broaden access and use of collections in these two critical government priorities. Task groups devoted to these issues could convene IWGSC members, participants in related NSTC activities (e.g., Biosafety/Biosecurity, open data access, Synthetic Biology, Bioeconomy), and non-Federal experts in these research areas with the goal of:

- Inventorying the types of scientific collections that can contribute to progress in these areas of national importance;
- Compiling information on the governance of and physical access to these collections, and the status of online access to and searchability of data connected to those collections;
- Identifying obstacles to the use of these collections by researchers and others in scientific disciplines other than the one responsible for their stewardship; and
- Recommending strategies and develop a roadmap to overcome obstacles, to help make cross-disciplinary use of Federal scientific collections a standard practice.

B. Education and Workforce Development. The skills necessary for collection management are changing rapidly to include data science and new preservation technologies (e.g., cryopreservation), to name a few. The Federal collections workforce will need to be diverse, to understand and appreciate the different perspectives of international partners, Tribal Nations, and others with their own traditions and policies concerning ownership, intellectual property rights, international access, and benefit sharing. A task group devoted to this activity could:

- Engage relevant U.S. organizations involved in workforce development (e.g., Institution for Museum and Library Studies, the American Association of Museums);
- Engage relevant staff from the National Science Foundation (NSF), National Institutes of Health (NIH), and other Federal grant-making agencies with missions in workforce development;
- Engage with members of the National Research Council's NSF-supported study committee that produced a 2015 report on the growing need for skills in digital curation;[14]
- Identify leading universities, colleges and other providers of professional training, especially Minority-Serving Institutions, with capabilities in library and data science and fields of science in which collections are well developed; and
- Convene workshops and planning activities that produce a roadmap to a future collections workforce that is more diverse and capable in the new era of "big data," evidence-based management, and cooperation with diverse stakeholders.

C. Promoting Growth in the U.S. Bioeconomy. Federal biological collections are large, diverse, and distributed across many different departments and agencies. Many IWGSC member agencies share an interest in the bioeconomy with other NSTC organizations.[15] A task group devoted to this topic could begin with a scoping study to determine the range of collections that could help to promote economic growth in this sector, then develop recommendations for activities that would capitalize on related opportunities.

D. Increasing Access and Impact through Digitization. The digitization of scientific collections takes several forms, and IWGSC member agencies have made progress in different ways and to varying degrees. IWGSC is not involved in decisions concerning digitization within its member agencies or their efforts to obtain appropriations for them. However, IWGSC can play an important role in helping member agencies formulate their plans for digitization by:

- Providing a forum for information exchange among Federal collections to share information, experiences, and solutions in designing digitization programs and obtaining funding for them; and
- Identifying leading Federal, non-Federal, and non-U.S. digitization initiatives, including those that have developed and/or employ new technology and workflows, and organizing presentations to interested IWGSC member agency staff.

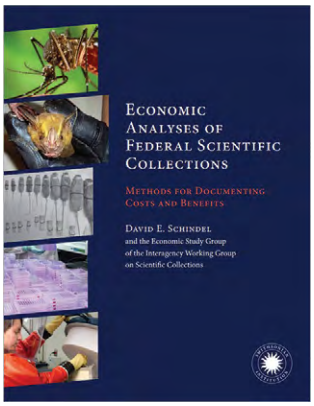
See "Digital Representation of Objects in Federal Scientific Collections" below for a more detailed discussion on digitization.

E. Access and Benefit Sharing Related to Federal collections. Access to and use of objects in Federal scientific collections can be affected by laws, regulations, and policies that limit allowable uses and require specific benefit sharing. These typically vary by type of material; in what countries, how, and by whom they are collected; and any international treaties governing them. The United States is a party to some, but not all, of the United Nations Conventions, though it has agreed to abide by national laws related to them. The role of Federal collections in the development of commercial products and processes has raised questions concerning benefit sharing with the government. On one hand, agencies may wish to derive income from commercially successful inventions that were created or improved based on use of their collections. On the other hand, the private sector's unfettered use of objects in Federal collections may contribute to product development and market returns, and intellectual property protection for related inventions may incentivize additional innovation and national economic growth. A task group devoted to these subjects could be charged with raising awareness of these issues by organizing a series of webinars that would bring together

counterpart organizations and networks in other countries and regions that are devoted to scientific collections. IWGSC representatives from the Department of State and the U.S. Agency for International Development should play a leadership role in this task group. The goal of its webinars will be to:

- Exchange information on the roles of collections as major research infrastructure in Federal versus non-Federal, and U.S. versus non-U.S. contexts;
- Monitor policy developments and keep participants updated through regular information exchange;
- Compare best practices concerning international access and use of scientific objects,
- Document benefits derived from international use; and
- Identify areas of conflicting and common interest, and develop roadmaps for resolving conflicts and pursuing shared goals.

F. Promoting and Improving Evidence-Based Cost Management. IWGSC's 2020 economic study report recommended standard methodologies for documenting the costs and benefits associated with scientific collections.[16] A task group led by IWGSC representatives from a limited number of departments or agencies could:



- Review how costs and benefits of selected collections are currently documented;
- Conduct pilot programs on those selected collections that result in new documentation of costs and benefits using one or more of the methods recommended in IWGSC's 2020 economic study report;
- Disseminate the results of the pilot studies to all IWGSC members and non-Federal collection communities; and
- Provide guidance to other agencies and non-Federal institutions that choose to test different methods.

The new Program of Work will build on successful implementation of three recommendations endorsed by OSTP and incorporated into the America COMPETES Reauthorization Act. IWGSC's new Program of Work will include the following:

- **Facilitating the development of agency policies governing the management and use of their collections.** Goal: Facilitate the development of agency policies for collections from all IWGSC member departments and agencies that have not done so; review them and provide feedback, and assist during their final clearance process;
- **Improving access to agency policies for collections through the IWGSC Clearinghouse.** Goal: Publish in a timely manner 100% of the new collections policy documents through the IWGSC Clearinghouse as they are completed and cleared by IWGSC's member departments and agencies; and
- **Improving access to information about Federal Collections.** Capitalizing on recent improvements in GRSciColl's capabilities, IWGSC will help member agencies expand and improve the information about their scientific collections that is available through the registry. Goal: Complete the registration of 90% of institutions with Federal collections and 75% of their largest collections.

The Special Role of Federal Scientific Collections

Federal departments and agencies are not alone in creating and maintaining institutional collections for R&D. Many universities, colleges, research institutions, and private companies are also home to fundamental research and applied development projects. Research in America's university system and private industry grew rapidly during and after World War II. The Federal mission in S&T has fueled this growth in important ways. In general, university-based projects focus on the interests of individual researchers or small R&D teams. In private industry, R&D aligns with perceived market opportunities. As a result, research directions in these two sectors can change over time, and interest in using any particular set of objects in a scientific collection may not be long-lived. Without stable, long-term research needs, the creation, maintenance, and use of large object-based collections covering longer spans of time can be challenging and difficult to justify for university and industrial research organizations

Federal collections are different in one important aspect: Projects that contribute objects to Federal collections are generally related to the long-term missions of departments and agencies, not the priorities of individuals or research teams. Their missions are stable over time, being aligned with Federal appropriations, legislation, regulation, and/or other purposes that serve the United States and the welfare of its citizens. These connections make Federal scientific collections unique:

- Objects can be collected and preserved for a particular purpose for many generations, creating the ability to study processes, like global climate change, that unfold over decades and even centuries.
- An agency's mission commonly serves several different interests. For example, the mission to improve public health may rely on fundamental research leading to scientific discoveries, as well as technological innovation and commercial development stemming from those discoveries (i.e., "vertical integration").
- Objects are not in danger of being "orphaned" or discarded when a project is completed or a researcher retires or dies. This longevity helps to ensure that objects will be available if they are needed for rare events such as emerging health crises or natural disasters.
- Discoveries made with collections in one agency can impact activities in other agencies, leading to swift responses to emerging crises at the Federal, state, and local levels.

Wet preserved specimens in the National Museum of Natural History in the early 20th century (Smithsonian)

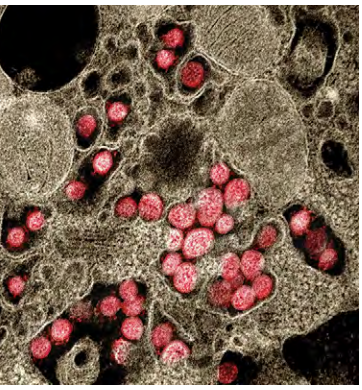
The following sections present 21 vignettes, each focusing on a single Federal scientific collection and how it contributes to the successful pursuit of an agency's mission. In most cases, each vignette describes the collection's support for the agency's mission and its impact in other areas of national importance. For example:

- Vignette 1: The Centers for Disease Control and Prevention (CDC) Biorepository maintains samples of the world's most serious infectious pathogens, such as smallpox, human immunodeficiency viruses (HIV), and Ebola. Recent research using samples from this collection has changed our understanding of how HIV was introduced into the United States and how acquired immunodeficiency syndrome (AIDS) subsequently spread. This new knowledge helped to inform how the United States is responding to COVID-19, one of the most important priorities of the Federal government. This new understanding is an example of scientific discovery, a mission shared by many Federal agencies; it will have widespread impact on responses to future pandemics.
- Vignette 10: The National Oceanic and Atmospheric Administration (NOAA) collection of marine organisms is used primarily to monitor the health of the ocean environment and marine populations. Sea turtles migrate over tremendous distances and are particularly sensitive to environmental quality and water temperature. Changes in their geographic distribution are captured by NOAA's sampling, making the collection and its related data valuable resources for studying global climate change.
- Vignette 15: Biological samples collected and maintained by the U.S. Geological Survey's (USGS) National Water Quality Laboratory are used to monitor the nation's water quality. Local, state, and Federal regulatory agencies rely on the resulting data to identify and respond to emerging threats to the nation's freshwater supply.
- Vignette 19: The National Park Service issues permits for research within parks and has responsibility for maintenance of resulting research objects. Private sector researchers were given access to microbes from the hot springs of Yellowstone National Park, and these were instrumental in the creation of a multibillion dollar biotechnology enterprise. While meeting its mission to preserve national assets on Federal lands for public benefit, the agency has furthered scientific research resulting in discoveries and innovations, some of which have had commercial applications and supported economic growth.

Wet preserved specimens in the National Museum of Natural History today (Smithsonian)

COVID-19 Response and National Health

Defeating COVID-19 is one of the top priorities of the Federal government, and Federal scientific collections are proving critical in this battle. Many of the same collections have been relied on for other outbreaks in the United States, including other infectious diseases (e.g., HIV/AIDS, measles, seasonal influenza), food-borne pathogens, environmental toxins, and others. Very large collections in the Department of Health and Human Services (National Institutes of Health [NIH] and CDC), the U.S. Department of Agriculture (e.g., food-borne bacterial pathogens in the Food and Drug Administration), and the Department of Veterans Affairs (VA) share the mission of protecting and improving national health. The Department of Defense (DoD) has very large collections of biomedical samples taken from members of the armed forces. Collections of non-human samples in the Department of Commerce (National Institute of Standards and Technology [NIST] and NOAA), the Environmental Protection Agency, and the Smithsonian Institution contribute to this mission as sources of samples of disease agents that are present in non-human populations.



(Above) Transmission electron micrograph of SARS-CoV-2 virus particles (red) isolated from a patient. (NIH/NIAD)

The unique role of Federal collections (described above) is apparent in CDC's Biorepository, an enormous ultra-cold storage facility (Vignette 1, described above), as well as the National Health and Nutrition Examination Survey (NHANES, Vignette 2). NHANES collections of human blood and urine are linked to health data obtained through large and statistically representative surveys of the human population that started in the 1960s. Large, long-term surveys like NHANES offer unique information on emerging trends in health and disease. The samples are available to qualified Federal and non-Federal researchers, who use them for fundamental biomedical research and as part of the innovation process leading to new products that serve the public health. VA's Million Veteran Program collection (Vignette 3) plays a role similar to NHANES' collections but with a focus on the armed forces. By taking samples in conjunction with health examinations before and after overseas deployments, DoD can spot emerging threats from infectious diseases and environmental toxins.

Knowing where to look for critical samples can be a challenge for medical researchers, because samples can be housed in unexpected Federal collections. Samples of viruses from the 1918 Spanish flu pandemic were found in the Armed Forces Institute of Pathology (Vignette 4), and these samples are being used to develop antibody-based treatments for COVID-19 patients. The National Cancer Institute's Natural Products Repository (Vignette 5) contains non-human samples (plants, microbes, and marine algae and invertebrates). It is providing molecules that may have potential as anti-cancer treatments. These examples illustrate the distributed nature of Federal collections and the need for an integrated information system that promotes broad visibility and access across disciplinary boundaries.

(Above) CBR stores specimens crygenically in liquid nitrogen freezers. (Smithsonian)

Vignette 1. Hidden History of AIDS Revealed: CDC Biorepository

Acquired immunodeficiency syndrome, or AIDS, is a chronic, potentially life-threatening condition caused by the human immunodeficiency virus (HIV). It affects around 40 million people worldwide and 1.2 million Americans. Since it was first recognized, AIDS is estimated to be responsible for the deaths of 700,000 people in the United States.

The first clinical reports of the disease, before it was even named, were recognized by the Centers for Disease Control and Prevention (CDC) in June 1981. As with all diseases when they first emerge, scientists worked hard to understand where AIDS started and how it spread, information critical for managing the public health response. Based on the clustered occurrence of the first recognized occurrences in New York and California, it was thought that the disease was introduced to the United States by a handful of individuals in the early 1980s.

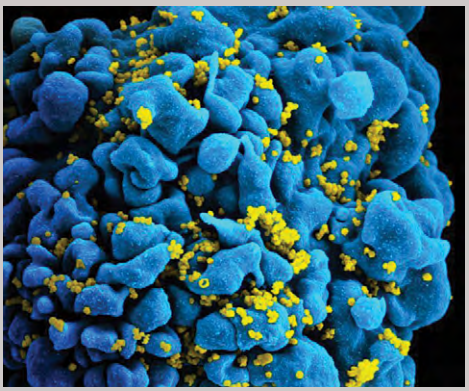
However, in 2016, CDC researchers made a startling discovery that overturned many of the assumptions about the early days of the AIDS epidemic. They applied new genetic sequencing technology to samples dating from 1970s and 1980s archived at the CDC Biorepository (CBR), a centralized facility that houses 6.6 million biological and environmental samples obtained through the CDC's public health surveillance, research, and outbreak response teams. Analysis of the archived materials revealed that the virus strain that caused most U.S. cases was likely spread from Zaire to Haiti in 1967, from there to New York in 1971, and then to California by the mid-1970s. The introduction of HIV to the United States was not shortly before the first cases were detected in 1981. Rather, HIV had been circulating unrecognized in the country for almost a decade!

The discovery entirely changed scientists' views about the origin and spread of AIDS, and more importantly, it changed their understanding of the emergence of diseases with long incubation periods that can circulate for years before symptoms manifest in the wider population. Thanks to the development of effective therapies, AIDS is much less deadly than when it was first recognized, but it continues to affect millions around the world. The discovery that AIDS could remain hidden in plain sight for a decade—information critical to implementing a public health strategy to combat its spread and reduce its cost in lives—was only possible using samples archived in the CDC Biorepository.

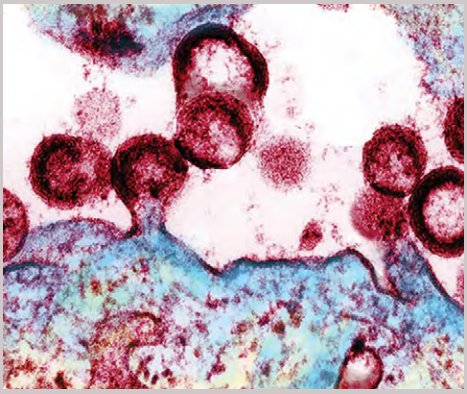
Authorship credit: Marcy Revelez, and Brad Bowzard, HHS/Centers for Disease Control and Prevention

(Below) A scientist analyzes viral DNA to test for HIV drug resistance. (CDC/H. Liu and J. Gathany)

(Below) Scanning electromicrograph of an HIV-infected human cell (NIAID)



(Below) HIV virions (red) budding from an infected cell (blue) (NIAID)



Vignette 2. Monitoring the Health of America: The National Health and Nutrition Examination Survey

Scientists at the Centers for Disease Control and Prevention (CDC) use collections to study how diet, exercise, and environmental factors contribute to human health. Since the 1960s, the National Health and Nutrition Examination Survey (NHANES) has collected biological samples—blood serum, plasma, urine, and DNA—from a nationally representative sample of about 5,000 people each year. Volunteer donors also provide personal information about their health and nutritional history, providing a unique resource to monitor and protect the health of the American people.

The NHANES collection retains more than 1.1 million biological specimens dating back to 1988 that are available to researchers working to address the medical, environmental, and public health issues challenging the nation. Facts about the distribution of health problems and risk factors in the population give researchers important clues about the causes of disease. Collating survey responses and specimens over many years allows health planners to detect the extent to which various health problems and risk factors have changed in the U.S. population over time. For example, NHANES blood lead data were instrumental in developing policy to eliminate lead from gasoline and in food and soft drink cans. Recent survey data indicate the policy has been even more effective than originally envisioned, with a decline in elevated blood lead levels of more than 70% since the 1970s.

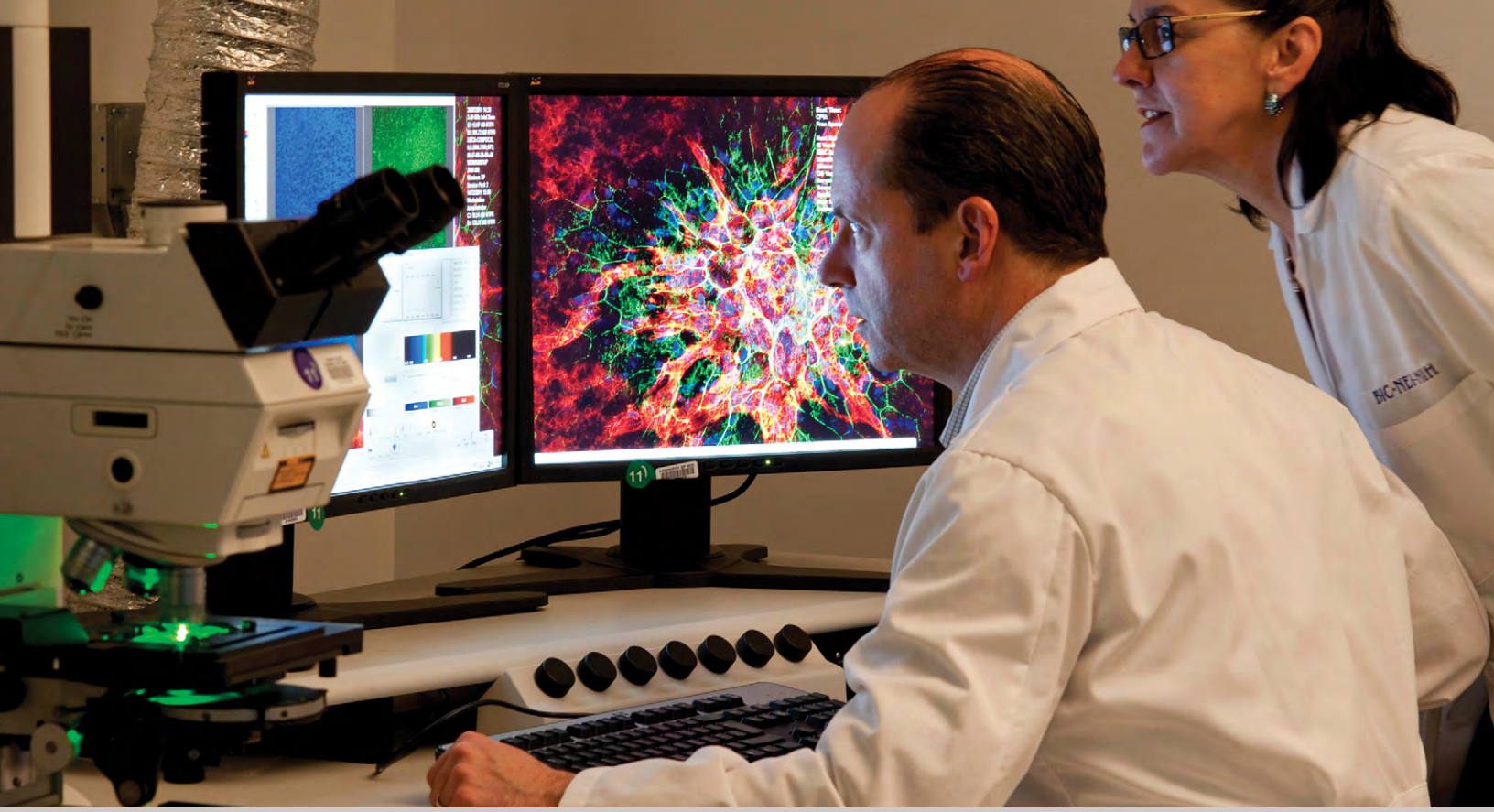
Data from the NHANES collection indicate that undiagnosed diabetes is a significant problem in the United States, providing support for efforts by government agencies and private sector organizations to increase public awareness, especially among minority populations. By tracking changes in the health of the American population over many decades, NHANES has allowed biomedical researchers to inform policy and improve the health of Americans through discoveries of trends in chronic disease, conditions related to aging, environmental contaminants, nutrition, and immunizations.

Authorship credit: Gerry McQuillan, HHS/Centers for Disease Control and Prevention

(Left) Drawing blood from a patient (CDC/Amanda Mills)

(Right) A test tube tray containing vacutainer blood collection tubes (CDC/Amanda Mills)

(Right) CDC microbiologist works to test developed for the Zika virus response (CDC/Sue Partridge)



(Above) Examing tissue samples under a laser scanning microscope (NIH)

(Above) Conducting medical research using collections (NIH)

Vignette 3. Veterans Continue to Serve: The Million Veteran Program

The servicemen and women who make up the armed forces of the United States do difficult jobs far from home, often placing themselves in danger on behalf of the nation and its people. In acknowledgement and thanks for their service, the country's 18 million veterans are eligible for a variety of benefits managed by the Department of Veterans Affairs (VA). As part of its mission to look after the health and well-being of those who served in the U.S. military, the VA's Office of Research and Development supports a wide range of biomedical research to improve the lives of veterans and all Americans, including the Million Veteran Program, a national research program to understand how genes, lifestyle, and military exposures affect health and illness. The program puts VA data to work by asking veterans to voluntarily provide a small sample of blood, fill out a survey on their habits and lifestyle, and permit access to their VA health records.

Since the program's launch in 2011, more than 825,000 veterans across a full scope of ethnicities have participated, creating a unique collection that is helping researchers better understand how genes affect health. Thanks to rapid advances in the analysis of DNA and the health information provided by participating veterans, VA researchers are applying genetic analysis to develop new ways to screen, diagnose, and treat a wide range of illnesses, including cancer, cardiovascular disease, diabetes, Gulf War illness, kidney disease, macular degeneration, mental health, osteoarthritis, Parkinson's disease, post-traumatic stress disorder, substance use disorders, suicide prevention, traumatic brain injury, and tinnitus. The unique biomedical collection created by the Million Veteran Program is the driving force behind scientific discoveries that are transforming health and improving the lives of veterans and all Americans.

Authorship credit: Ron Przygodzki, Department of Veterans Affairs

(Above) Emergency hospital during 1918 Spanish Flu pandemic, Camp Funston, Kansas (National Museum of Health and Medicine)

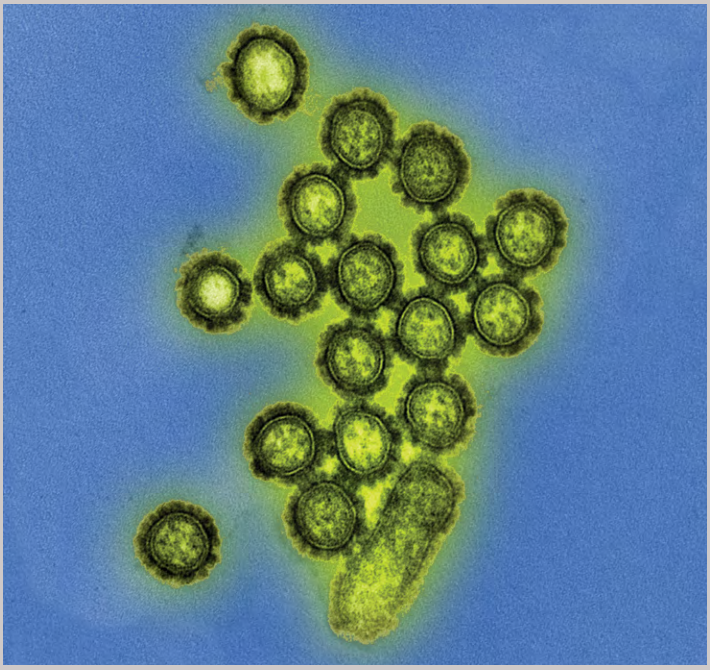
Vignette 4. Fighting Infectious Diseases from Spanish Flu to COVID-19: Armed Forces Tissue Repository

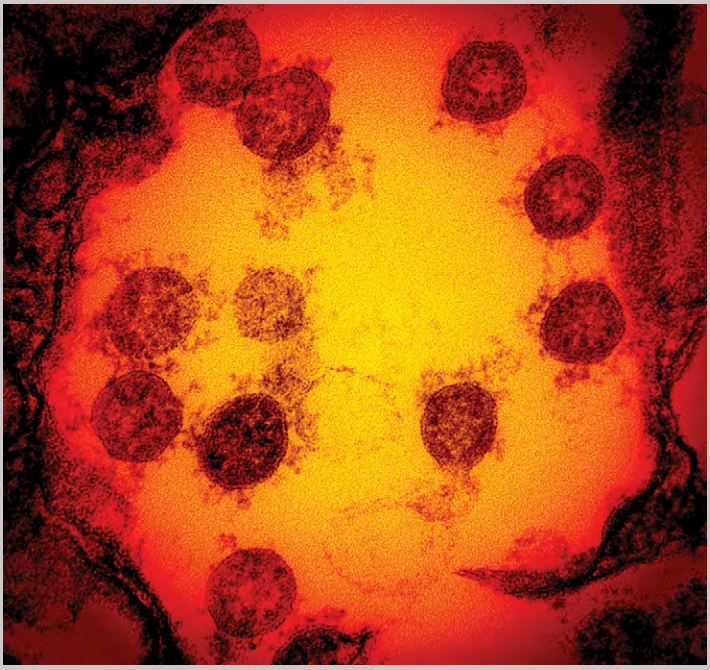
Since it was first recognized in late 2019, COVID-19 has spread to every corner of the globe and taken millions of lives. From the start, the Department of Defense (DoD) has been at the forefront of the effort to find therapies, develop vaccines, and expand medical production. Central to the U.S. military's response to the COVID-19 pandemic has been the DoD's Joint Pathology Institute in Washington, D.C., which houses the nation's oldest collection supporting biomedical research: the Armed Forces Tissue Repository (AFTR). Founded in 1917 to combat the Spanish H1N1 flu pandemic, AFTR now holds 32 million tissue samples and 55 million pathology glass slides. It also houses more than 60,000 bacterial samples collected from patients treated by the Military Health Service, and it receives 500–800 new samples every month from combat support hospitals around the world.

To help fight the COVID-19 pandemic, researchers compared Spanish flu virus obtained from samples preserved in the AFTR with blood samples from still-living survivors of that pandemic. Even after 100 years, survivors still had immune cells that reacted against the Spanish flu, which allowed researchers to identify drugs that could treat or prevent infection. What they learned is that antibody-based treatment can be effective at combating highly infectious diseases like the Spanish H1N1 flu variant, and this discovery paved the way for the antibody treatments that have been used to save lives in the COVID-19 pandemic. Without the commitment to store tissue samples for a century or more, researchers would not have had access to the virus samples they needed to combat COVID-19 and other infectious diseases in the future.

Authorship credit: Diane DiEuliis, DoD/National Defense University

(Below) Transmission electron micrographs of viral particles; H1N1 influenza (left) and SARS-CoV-2 (right) (NIH)





Vignette 5. Searching the Natural World for New Medical Therapies and Treatments: The National Cancer Institute's Natural Products Repository

Cancer claimed the lives of 606,800 Americans in 2019.

Among women, the most common form is breast cancer, which affects 1 in 8 women. In 2019 alone, 268,600 women in the United States were diagnosed with breast cancer, and 41,760 died. Among the more aggressive forms is triple-negative breast cancer, which accounts for 10–20% of all breast cancer diagnoses and affects younger women and Black and Hispanic women at higher rates than other forms. It also has a poorer prognosis, because it is unresponsive to hormonal therapies that are effective against other types of breast cancer.

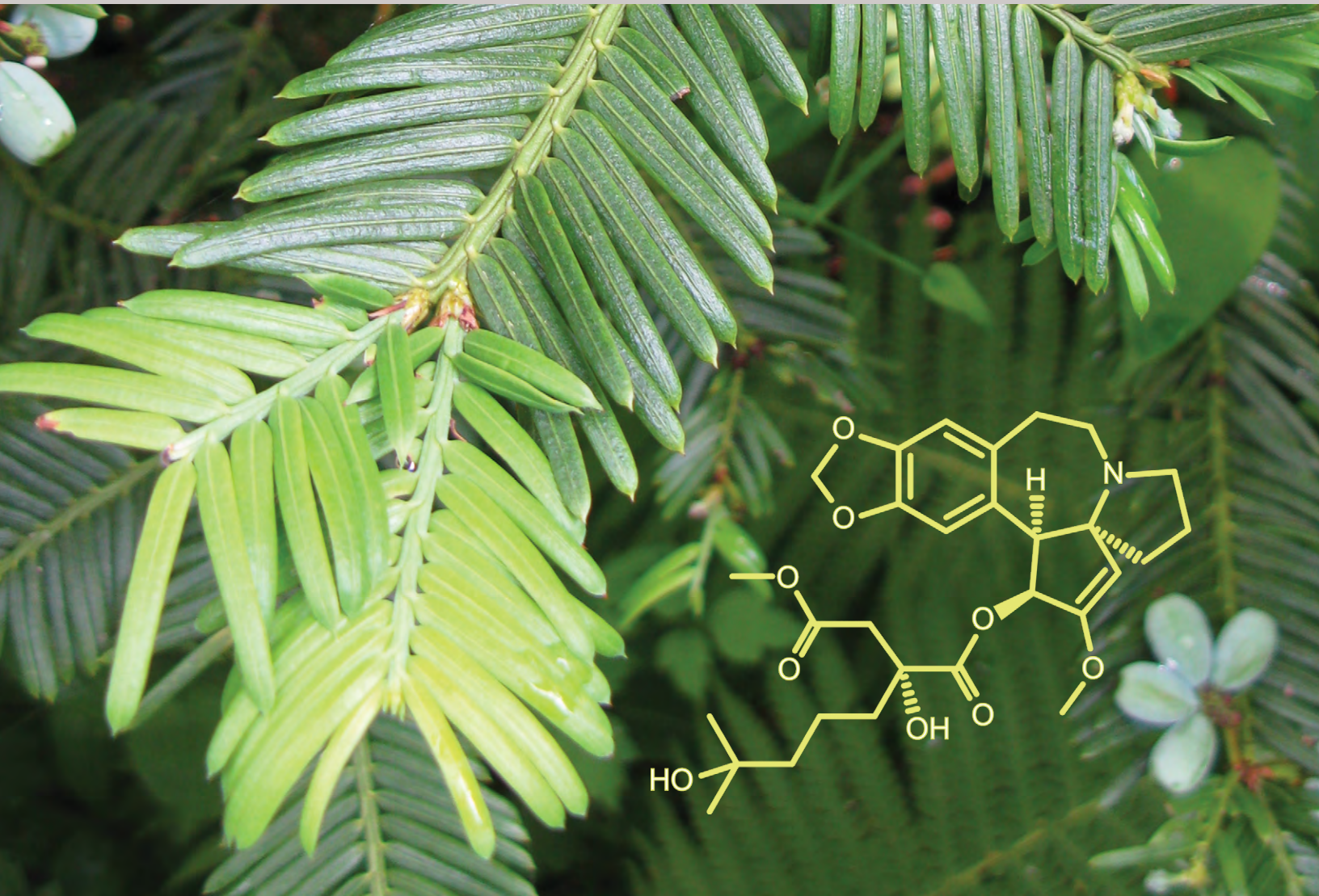
Without access to the usual arsenal of anti-cancer hormonal therapies, other drug leads must be sought, and one rich source of therapeutic compounds is the natural world. More than one-third of all anti-cancer drugs are derived from plants, marine invertebrates, and microbes. As part of its mission to develop new cancer treatments and therapies, the National Cancer Institute maintains the Natural Products Repository, a collection of natural product samples derived from 240,000 extracts of plants, microbes, marine invertebrates, and marine algae from around the world.

These natural product samples are used by researchers in government, universities, and the private sector to search for biologically active molecules to treat cancer. One such molecule is homoharringtonine (HHT), a natural compound derived from *Cephalotaxus*, a coniferous shrub native to northern Burma and China. HHT has been approved by the Food and Drug Administration for chronic myeloid leukemia since 2012, but recently published research suggests that it can also suppress the growth of triple-negative breast cancer cells.

A new treatment for the most challenging form of breast cancer could save the lives of thousands of women in the United States and throughout the world. In addition to cancer, medicines derived from natural products are used to treat many other ailments, including diabetes, Alzheimer's disease, and viral infections. Many of these life-saving compounds were discovered and developed thanks to the collections of the Natural Products Repository.

Authorship credit: Tanja Grkovic and Marianne K. Henderson, HHS/NIH/National Cancer Institute

(Below) *Cephalotaxus*, the coniferous shrub that is the source of the cancer-fighting compound *homoharringtonine*, represented by the chemical diagram (CC/Qwert1234, Anypodetos)



Climate Change

Like defeating the COVID-19 pandemic, tackling climate change at home and abroad is a top priority of the Federal government. The Federal collections that are proving useful for both COVID-19 and climate change research are distributed across departments and agencies, some of which may not be known to most climate researchers. For example, new approaches to reducing greenhouse gases in the atmosphere and developing new green energy technologies have turned to a collection of rock cores maintained by the U.S.Geological Survey (USGS; Vignette 6).

Deep-sea rock cores at the U.S. repository for Scientific Ocean Drilling provide physical evidence of Earth's past geology and climate. (IODP-USIO)

The most direct evidence of human-induced climate change has come from collections of physical samples that record atmospheric and oceanic conditions going back in time, such as the National Science Foundation's Ice Core Facility that document climatic conditions going back hundreds of thousands of years (Vignette 8) and collections of tree ring samples that record growth rates and the frequency of wildfires over centuries (Vignette 9).

Evidence related to climate change can also be indirect, and Federal collections are rich sources of such evidence. Changes in average temperature and precipitation, seasonality, and storm patterns all affect the geographic distribution of plant and animal species. For instance, changes in seasonality can be seen in the timing of flowering plants and the emergence of seasonal insects. The National Ecological Observatory Network, funded by the National Science Foundation (Vignette 9), is building large time series of collections of representative species that are linked to long-term environmental data monitoring. Patterns of environmental change (such as changes in the duration and timing of seasons) will be studied alongside changes in the distribution and biology of different species, offering new insights into the potential impact of climate change on the living world.

Species of sea turtles migrate over tremendous distances, and the conditions they need for reproducing and nesting are very specific. Changes in the environment are reflected in their geographic distributions as well as their reproductive success or failure. Collections of sea turtles and migratory marine mammal species, and their associated data, were established and are managed by NOAA (Vignette 10). These time series collections of migratory species, and many others built and managed by Federal agencies, are increasingly playing a role in documenting climate change and its impacts. An important challenge will be making these collections known and accessible to climate researchers who could benefit from them.

The Smithsonian Institution's National Museum of Natural History is the largest museum of its type in the Western Hemisphere, with more than 125 million biological specimens, as well as frozen tissue and DNA samples. Each object has associated metadata that reflect the date and place it was collected. This trove of information going back 150 years—much longer if fossils are included—could be used to generate maps of species distributions through time, further illuminating patterns driven by environmental changes. The obstacle to achieving this goal is the need to convert analog data records to standardized digital formats that can be used to create maps in a time series.

See "Digital Representation of Objects in Federal Scientific Collections" below for a more detailed discussion on digitization.

(Above) USGS Core Research Center (CRC) storage facility at the Denver Federal Center (USGS)

Vignette 6. Can Fossil Fuel Sites Help Mitigate Climate Change? The USGS Core Research Center

Society's dependence on fossil fuels has resulted in increased levels of greenhouse gases in the atmosphere. In addition, unemployed workers and economically depressed communities remain when the fossil fuels are depleted. Finding new and productive uses for these terrains, often damaged and polluted, is yet another challenge to the nation. In an ironic turn of events, researchers are now exploring two inventive ways to use depleted and even current fossil fuel fields to reverse the damage to the environment. A Federal scientific collection is playing a critical role in both initiatives.

The U.S. Geological Survey (USGS) owns and operates the Core Research Center (CRC) in Denver, Colorado. The CRC contains approximately 10,000 rock cores and 53,000 rock cuttings recovered during drilling operations by USGS and other Federal agencies and from donations by private oil, gas, and coal companies. The CRC collection consists primarily of material from the western United States and is available to qualified users for basic and applied research. The CRC does not charge users for access to the collection, but users must provide the CRC with access to data and other results of research to increase the value of the collection. To learn more about this "virtuous cycle," see the IWGSC's 2020 economic study.[17]

Researchers at the University of Nebraska–Lincoln are exploring ways to sequester carbon dioxide underground after extraction from the atmosphere in order to mitigate its impact on climate. Oil and gas form at depth in Earth's crust, migrate through cracks and open pore space in the rocks, and accumulate in reservoir rocks with lots of connected pore space. The CRC provides researchers with "off-the-shelf" access to information about the characteristics of rock formations in western Nebraska through cores that were once drilled to explore for potential oil and gas reservoirs. The same porosity and permeability that attracts petroleum companies is now attractive as candidate rock formations for CO_2 sequestration after reservoirs have been emptied by commercial fossil fuel extraction. Without the CRC, this research would require prohibitive time and expense to drill new cores.

Coal has historically been mined for use only as a fossil fuel, but coal and surrounding rocks contain varying concentrations of rare earth elements (REE) and critical minerals (CM). These are key ingredients in batteries, magnets, photovoltaic cells, and other critical components of clean, renewable energy systems. The Department of Energy recently announced $19 million to support 13 projects that are exploring ways to extract these valuable resources without mining and burning large quantities of coal.[18] Researchers from the University of Wyoming and the Colorado School of Mines are relying heavily on CRC cores from the Powder River, Wind River, and Greater Green River Basins to assess REE and CM resources and to potentially develop new techniques for locating high concentrations of REE and CM. This capability would enable highly selective recovery of REE and CM while minimizing coal extraction. Other research is underway to find new uses for coal, such as in construction materials.

The impact of these CRC cores and the research projects that depend on them goes beyond new energy sources and climate change mitigation. Thanks in part to the CRC's contributions to this research, jobs and prosperity could return to these areas that have suffered decades of decline.

Authorship credit: Victoria Crystal, Interior/USGS

(Below) Slabbed rock core (USGS/J. Hicks)

(Below) USGS core drilling rig for assessment of natural gas in the Mancos shale formation (USGS)

(Above) NEON terrestrial installations, such as the meteorological flux tower shown above, use a broad variety of platforms and technologies to collect data on life, air, soil, water, and climate at field sites. (NEON)

Vignette 7. Understanding Ecosystems at a Continental Scale: NSF's National Ecological Observatory Network Collections

Human life and civilization have always been dependent on living systems for food, water, and air, but understanding how changes in ecosystems could affect us has a fundamental problem: scientists have never been able to measure the many parts of Earth's ecosystem together. An ambitious initiative funded by the National Science Foundation (NSF), the National Ecological Observatory Network (NEON), aims to overcome this obstacle and transform our understanding of Earth's living systems. And collections play a central role!

NEON includes 81 field sites across the United States, from the tropics to the tundra. Data collection at each site includes airborne remote sensing, automated ground-based instruments, and sampling of plants, animals, microbes, soils, and water in the field. What makes NEON unique is the integration of all these sources of information. Even more significantly, these measurements will continue over the next 30 years—an unprecedented duration for a study involving so many different sites and ecosystems.

(Below) Some of the myriad life-forms that NEON scientists collect from field sites across the United States (NEON)

Although it is still early days for NEON, it already has collected more than 100,000 biological samples representing more than 700 different types of organisms. As their number and diversity continue to increase, NEON samples will record a long-term archive of each research site, providing the basis to track changes over decades. NEON anticipates more than one million samples curated by the end of 2026 and nearly four million over the 30-year duration of the program. Never before has such an extensive and diverse array of biological and environmental materials, integrated with remotely and automatically collected data at a continental scale, been assembled.

The long-term, comprehensive data collected by NEON will allow ecologists to better understand the impacts of invasive species and forecast the ecological consequences of large-scale climate phenomena like droughts. Reaping the scientific and societal benefits that NEON aims to provide will be founded on the one-of-a-kind collections that will serve as the ultimate legacy of this unprecedented scientific effort.

Authorship credit: Paula Mabee, Batelle Memorial Institute, and Roland Roberts, National Science Foundation

(Above) Inside the NSF Ice Core Facility main archive freezer (NSF)

Vignette 8. New Discoveries from Old Ice: The NSF Ice Core Facility

The Roman Empire arose in the first century BCE, during a time of political unrest and civil war that culminated in the murder of Julius Caesar in 44 BCE. But were raw political ambition and infighting the only reasons for the massive societal upheaval? Written records show the two years after Caesar's murder were characterized by exceptionally cold summers, crop failures, and famine, which contributed to widespread social disruption. In 2020, researchers announced the likely cause of these environmental disasters was the eruption of a massive volcano in Alaska, halfway around the world. The discovery was made thanks to ice cores archived at the National Science Foundation's (NSF) Ice Core Facility in Lakewood, Colorado.

At polar latitudes, snow accumulates year after year, forming the vast ice sheets covering Greenland and Antarctica. As snow falls, it traps minute particles from the atmosphere, which eventually get sealed into the glacier as the snow gets buried and compacted into ice. Analysis of the material trapped in each annual layer of the ice sheet allows scientists to reconstruct how the atmosphere has changed over time. The ice also preserves ash and sulfate released into the atmosphere by large volcanic eruptions. Sulfate aerosols in particular are known to cause Earth's climate to cool by blocking incoming sunlight.

Based in part on minute traces of volcanic ash found in cores collected as part of the Greenland Ice Sheet Project 2 (GISP2), which ran from 1988 to 1993, and now stored at NSF's Ice Core Facility, scientists were able to correlate a spike in atmospheric sulfate particles to a massive eruption of Alaska's Okmok Volcano in early 43 BCE, shortly after the murder of Julius Caesar. Based on the size of the eruption, researchers estimate that parts of Europe and northern Africa were as much as 7°C (45°F) colder than normal, catastrophically shortening the summer growing season and leading to widespread hunger and unrest.[19] Although such eruptions are rare, their impact on people, even on the other side of the world, can be enormous. The ice cores stored at NSF's Ice Core Facility are critical to understanding how major eruptions can affect global climate and preparing to mitigate their impact in the future.

Authorship credit: Lindsay Powers, Interior/U.S. Geological Survey

(Above) Ash and gas plume from the January 12, 2006 eruption of the Augustine Volcano at Cook Inlet, Alaska (USGS/Game McGinsey)

(Above) Extracting cores from an ice sheet (NSF/Doug Clark)

(Above) Ice core from the West Antarctic Ice Sheet project. The dark band is a layer of volcanic ash that settled on the ice sheet about 21,000 years ago. (NSF/Heidi Roop)

(Above) Pueblo Bonito, Chaco Culture National Historical Park, New Mexico (CC/Andrew Kearns)

Vignette 9. Reading the History Written in Tree Rings: Objects Collected from Federal Lands

Between the ninth and thirteenth centuries, the Chacoan community, a Puebloan culture ancestral to many modern Native American groups, flourished in the desert Southwest. The Chacoans' trade network reached as far as Central America; they were expert astronomers who carefully tracked the movements of the Sun, Moon, planets, and stars; and they built large, multistory "Great Houses" using sophisticated masonry techniques. In the center of this widespread and complex culture was Pueblo Bonito in Chaco Canyon, the ruins of which are now protected in Chaco Culture National Historical Park.

In 1924, archeological excavations at Pueblo Bonito uncovered a 20-foot ponderosa pine log that was thought to have grown there and died about 900 years earlier. Trees do not commonly take root in the desert conditions of Chaco Canyon today, making its place of origin a mystery. The size and age of the log, which came to be known as the Plaza Tree, captivated scholars and interpreters for generations and assumed a mythical status as the "life tree" of Pueblo Bonito, a lone survivor from an age before the rise of the Chacoans, when the region was cooler, wetter, and forested. In 1937, the University of Arizona established the Laboratory of Tree-Ring Research (LTRR) as the first-ever scientific collection dedicated to the analysis of annual growth rings in trees. The log from Pueblo Bonito became one of the objects preserved in LTRR.

Several years ago, researchers at LTRR began to have doubts about the Plaza Tree's history. Using the LTRR collection, scientists compared the Plaza Tree with samples of ponderosa pine from possible harvest sites in nearby mountain ranges. They determined that the Plaza Tree had died 400 years before earlier estimates, and that it had not grown at Pueblo Bonito. Comparative studies showed that it had been transported over 50 km in the early twelfth century, at the peak of Chacoan society.[20] Nearly a century after the Plaza Tree was discovered, the new research dispelled the notion that it was living at Pueblo Bonito when the area was populated. As a result, the discovery reinvigorated the question of why it was transported there and what purpose the tree served.

Federal laws and regulations make scientific objects found on Federal lands the property of the agencies that have jurisdiction over those Federal lands. LTRR now manages and maintains an impressive number of objects collected from lands managed by the Department of the Interior's National Park Service, Fish and Wildlife Service, and Bureaus of Indian Affairs, Land Management, and Reclamation; the U.S. Department of Agriculture's Forest Service; and the Department of Defense's military bases on U.S. soil. LTRR's stewardship ensures that the objects will remain available for research on past climate and wildfires, paleovegetation and their environment, and the stories behind wooden artifacts and architectural elements like the Plaza Tree.

Authorship credit: Ryan Polk, Interior/Museum Program

(Below) Cross section from the ponderosa pine known as the Plaza Tree showing dendrochronological interpretation of its annular growth rings (LTRR/Christopher Guiterman)

Vignette 10. Protecting Endangered Marine Species: NOAA's Marine Mammal and Sea Turtle Research Tissue Collection

As its name and place in the Department of Commerce might suggest, the National Oceanic and Atmospheric Administration (NOAA) has a broad-ranging and complex mission, including the protection of endangered marine species. The Marine Mammal and Sea Turtle Research (MMaSTR) tissue collection, located at NOAA's Southwest Fisheries Science Center in La Jolla, CA, serves this mission in many different ways. NOAA's regulatory role often involves close collaboration with foreign governments, as well as the U.S. Fish and Wildlife Service in the Department of the Interior, the lead agency for enforcement under the Endangered Species Act.

The MMaSTR collection holds more than 300,000 frozen tissue and DNA samples from almost all known marine mammal species (whale, dolphin, porpoise, seal, sea lion, and walrus) and all sea turtle species. Within this collection reside 250 samples from 72 individuals of the smallest marine mammal, the vaquita (*Phocoena sinus*), a porpoise found only in the upper reaches of the Gulf of California in Mexico. More than half of these porpoises were found dead, entangled in gillnets or other industrial fishing gear, or stranded with markings of entanglement. The vaquita is now considered the world's most endangered marine mammal with approximately ten individuals left alive. The rapid population decline over recent decades is generally ascribed to "bycatch"—entanglement in fishing gear meant for other species. Extinction is usually considered inevitable when a species reaches this population size, but thanks to frozen tissues in the collection, a recent whole-genome sequence analysis indicates that if gillnet fishing ends immediately in the vaquita's part of the Gulf, inbreeding would probably not interfere with recovery and sustainability of the species.[21]

The collection also holds 170,000 tissue samples from all species of sea turtles, spanning 90 countries. This includes 58,000 leatherback turtle samples from 45 territories that have been used to characterize the genetic signatures of most of the nesting populations around the world. Of these, approximately 40,000 were sampled from live hatchlings as part of an innovative long-term genetic tagging study at a Caribbean nesting site, to determine age of maturity, and 500 came from entangled bycatch in fisheries operating in areas of the Pacific and Atlantic oceans that are far from nesting beaches. Unlike the vaquita porpoise, genetic analysis of leatherback DNA from these samples have revealed the connection between these distant breeding and feeding areas, and confirmed some of the extremely long migration routes documented by satellite tracking. By integrating the population genetic data and the knowledge of foraging behavior, migration and fisheries, the decline in the nesting populations can be connected to bycatch deaths in other parts of the ocean.

Data coming from the MMaSTR collection are helping improve international Recovery Plans and encouraging conservation groups, government agencies, and the fishing industry to implement bycatch mitigation measures that extend to protection of turtle nesting grounds and the distant feeding areas that are now marine reserves. These data are also part of the debate over regulation and sustainability of marine life.

Authorship credit: Alaina Harmon, Commerce/National Oceanic and Atmospheric Administration

(Top) Frozen storage of marine mammal and sea turtle tissue samples held at a constant temperature of –80° Celsius (–112 °Fahrenheit) (NOAA/Paula Olson)

(Below) Loggerhead sea turtle *(Caretta caretta)* (CC/Strombilomyces)

(Below) Hawksbill sea turtle *(Eretmochelys imbricata)* (NOAA)

(Below) Green sea turtle *(Chelonia mydas)* (CC/Brocken Inaglory)

National Food Security

(Above) USDA scientists retrieve seeds stored at 0°F at the National Center for Genetic Resources Preservation in Fort Collins, Colorado. Collections like this one are a critical source of genetic diversity that helps scientists develop new plant and animal varieties for a changing world. (USDA/Stepen Asmus)

Ensuring an adequate food supply for the United States has many facets, and Federal collections play a role in virtually all of them. The U.S. Department of Agriculture's (USDA) National Plant Germplasm System (NPGS) is an important member of a global system for the exchange of plant material for the development of new and more productive crop varieties. NPGS maintains a large collection of seeds and living plants, and it adds new varieties very selectively in order to increase the useful traits in the collection while controlling the cost of maintaining them. NPGS does research on some of them to determine growth characteristics and response to stressors related to climate change (e.g., heat, drought, increasing groundwater salinity and alkalinity) as well as infections and predators. The source of each plant and its characteristics are made available to qualified users who can then request specific plants for additional research, plant breeding, and/or commercial cultivation. NPGS added a peanut variety to its collection in 1950, and 20 years later, it was used to develop new crop varieties that were resistant to a virus that was devastating peanut production (Vignette 11). USDA's Livestock Gene Bank plays a similar role by maintaining the genetic diversity of America's dairy herds (Vignette 12).

(Above) USDA's Agricultural Research Service (ARS) maintains extensive collections of germplasm—living genetic resources maintained for the purpose of animal and plant breeding, preservation, and research. Visitors to historic Mount Vernon can see heritage breeds of many different animals maintained by the ARS, like Hog Island sheep shown here, a rare breed that dates back to the 1600s in Virginia. (USDA/Stephen Ausmus)

Other USDA collections focus on disease agents that attack crop plants or livestock animals. The USDA Agricultural Research Service's (ARS) Culture Collection contains microbial strains that attack crop species, as well as other microbes that are closely related to them. Certain fungi cause significant losses to the global banana production, and research at the ARS Culture Collection is identifying and characterizing fungal strains that may be the ones that attack banana crops (Vignette 13). Like the plant varieties in NPGS and samples in the Livestock Gene Bank, the microbial strains in the ARS Culture Center are the raw materials for R&D leading to a more secure nutritional future for the United States.

USDA's Animal and Plant Health Inspection Service (APHIS), working with Customs and Border Protection Service (CBP), is responsible for keeping threats to American agriculture (insects, fungi, and others) from being introduced by imports and visitors. Border inspectors are able to identify potential crop diseases and pests at ports and airports thanks to identification guides provided by ARS researchers and the collaborating scientists at the Smithsonian Institution's National Museum of Natural History and other research institutions.

None of these identification guides would have been possible without access to comprehensive collections of threatening species, their very similar closest relatives, and more distantly related look-alike species with which they could be confused.[22]

Vignette 11. Working for Peanuts: The U.S. National Plant Germplasm System

Peanuts are the seventh most valuable crop grown in the United States, with an annual farm value of more than $1 billion.[23] The average American consumes more than seven pounds of peanuts every year, and peanuts go into industrial processes that produce a wide variety of non-food products ranging from soap and paint to paper and rayon. Any threat to the U.S. peanut crop not only deprives Americans of a nutritious favorite food, but also has serious implications for several sectors of the nation's economy and the sustainability of American farming.

One widespread threat to peanuts is the tomato spotted wilt virus (TSWV), which is spread by flying insects and infects a variety of other crops, including spinach, lettuce, and beans. The disease was first described in 1919 in Australia and did not appear in the United States until 1974. Within 15 years, it was wiping out entire peanut fields throughout the southeastern United States, destroying $12.3 million worth of peanuts annually in the state of Georgia between 1996 and 2006.[24] Crop agriculture has many approaches to fighting new crop diseases, but developing new plant strains with innate resistance to the disease has many advantages. The challenge is finding an existing plant variety that is resistant to the disease, so plant breeders can develop it into a new, disease-resistant, commercially successful cultivar. Finding a variety with natural resistance to a disease can be more difficult than finding a needle in a haystack. How is it done?

The U.S. Department of Agriculture's (USDA) National Plant Germplasm System (NPGS) is one of the world's largest collections of plant varieties used to breed new crop varieties.[25] The NPGS consists of 25 geographically distributed plant genebanks and support labs that hold more than 600,000 accessions of agriculturally important plants. Each accession, obtained from researchers, plant breeders, companies, and farmers around the world, has different characteristics and genetic makeup, adding to the cumulative diversity available through NPGS. Decisions about acquiring each new accession must weigh the costs of maintaining it long-term against how it could increase the genetic diversity in the collection.

A single NPGS accession was instrumental in developing peanut cultivars resistant to TSVW. Accession "PI 203396" was collected in Brazil by a USDA official and was incorporated into the NPGS collection in 1952. It was used infrequently in breeding new cultivars for more than 20 years, but during that time, its chemical and growth properties, its morphology, and its resistance to leaf spot, a fungal disease, were tested and documented. That information was made readily available through USDA NPGS's online Germplasm Resources Information Network (GRIN).[26]

Thanks to NPGS and its capacity to maintain and study genetic diversity long-term, this particular accession was available and well-documented for peanut breeding when TSVW became a threat to U.S. peanut production. It was rapidly incorporated into the pedigree of several peanut cultivars widely grown in the southeastern United States, and by 2001, the economic value of the TSWV-resistant trait derived from PI 203396 was estimated at $200 million per year.[27]

Authorship credit: Peter Bretting, USDA/Agricultural Research Service

(Below) Each dish holds tiny experimental plants grown from lab-cultured cells. (USDA/Scott Bauer)

(Below) Peanut plants as they are harvested (USDA/David Nance)

(Below) USDA researchers examine peanut plants in the field. (USDA/Peggy Greb)

(Above) Holstein dairy cows (USDA Agricultural Research Service/Scott Bauer)

Vignette 12. Ensuring Genetic Health of U.S. Dairy Herds: USDA Agricultural Research Service's Livestock Gene Bank

To meet America's demand for milk, cheese, yogurt, and ice cream, U.S. dairy farmers produced more than 222.1 billion pounds of milk and received $40.5 billion in 2020.[28] Maintaining the vigor and productivity of the millions of cows making up the U.S. dairy herd requires careful breeding to keep them genetically diverse and healthy, which is one of the reasons that the U.S. Department of Agriculture (USDA) Agricultural Research Service (ARS) maintains the Livestock Gene Bank collection. The Livestock Gene Bank stores more than 1 million samples of germplasm—living genetic resources—from a wide variety of animals ranging from cattle, pigs, sheep, goats, turkeys, and chickens to the more exotic, such as bison, elk, and yak. Included in the Livestock Gene Bank are samples from more than 7,900 dairy cattle that are instrumental in keeping the nation's dairy herd strong and resilient.

One recent example of the value of the Livestock Gene Bank is its role in improving the genetic health of Holstein cows, the iconic black and white cows seen across the American landscape. They are the world's premier breed for milk production, and they comprise more than 85% of the U.S. dairy herd. In 2015, researchers discovered that the 8 million Holsteins in the United States had all descended from only two paternal lines. Lack of genetic diversity is a concern because it leaves animals vulnerable to new diseases and limits the flexibility of livestock breeders to improve the breed. However, a search of the Livestock Gene Bank collection found cryogenically preserved samples dating back to the 1970s that included chromosomes from two additional paternal lines that had been lost from the U.S. Holstein population. These samples were used to generate embryos and impregnate cows. To date, approximately 300 offspring have been generated by industry, thereby increasing genetic diversity and vigor in the nation's Holstein herd.

In addition to improving breeds, the Livestock Gene Bank also serves as a basis for economically valuable innovation. With advances in genome-based technologies, samples from more than 400 bulls in the Livestock Gene Bank's collection (representing 50 years of dairy cattle genetics) have been used to develop new genomic selection techniques that have increased U.S. milk income by $400 million per year.[29] The milk, cheese, and ice cream enjoyed by millions of Americans every day are supplied by millions of cows on thousands of farms across the country. Keeping those cows strong and healthy is made possible by the collections of the Livestock Gene Bank.

Authorship credit: Harvey Blackburn, USDA/Agricultural Research Service

(Below) Semen-containing straws for artificial insemination (USDA/Peggy Greb)

(Below) Holstein cow (USDA/Keith Weller)

Vignette 13. Protecting the World's Most Popular Fruit: USDA Agricultural Research Service's Culture Collection

Naturally occurring pathogens can threaten important food crops and the industries that grow and distribute them. Bananas, the most exported fruit on the planet and the most widely purchased fruit in the United States, is one of those threatened crops. Prior to the 1950s, the "Gros Michel" banana variety became the basis of the global banana export trade. However, starting as early as 1890, a wilt disease was reported in Gros Michel plantations in Panama that was caused by the fungus *Fusarium oxysporum f. sp. cubense* (Foc). Over the following decades, the pathogenic fungus spread throughout Gros Michel plantations in the Americas, almost wiping out the $2 billion global banana industry. In response, the "Cavendish" banana variety was bred to resist the *Fusarium* wilt pathogen, and the industry recovered. A new race of Foc, "Tropical Race 4" (TR4), appeared in Southeast Asia in the early 1990s and was able to overcome the resistance in the Cavendish variety. TR4 has spread from Southeast Asia through banana production regions in Asia, India, and Africa, finally reaching South America in 2019, when it was reported in Colombia for the first time. Its spread has been slowed, but not stopped, by isolating and destroying infected crops, which endangers growers' livelihoods and the global supply of bananas.

The U.S. Department of Agriculture (USDA) Agricultural Research Service's (ARS) Culture Collection[30] in Peoria, Illinois, has archived more than 98,000 isolates of bacteria and fungi over its 80-year history. The collection is comprised of microbes relevant to industry and agriculture, including pathogens that attack crops and close relatives of these pathogens. It now contains one of the world's largest and most genetically diverse collections of *Fusarium*, including more 12,000 strains representing 300 genetically distinct species important to agriculture and human health. DNA data from these isolates and the tools to compare them are available to all stakeholders through a web-accessible database, *Fusarium*-ID.[31] Access to these *Fusarium* strains, their gene sequences, and other characteristics has been critical in finding ways of countering pathogen threats to wheat, corn, barley, soybean, and avocado production, thereby protecting food security for the United States and other countries.

When TR4 was first reported more than 25 years ago, the ARS Culture Collection obtained and studied samples of Foc from around the world from multiple banana species to understand the genetic diversity of Foc and the origin of TR4. Many of the strains used in these studies were already in the collection. Knowing more about the pathogen's close relatives is often useful in developing new diagnostic assays, identifying new sources of host resistance, and finding production methods that control the pathogen. The collection now has approximately 80 isolates of Foc from around the world, making it an important resource for monitoring the spread of TR4 and helping to develop new resistant banana cultivars. As the pathogen gets closer to U.S. borders, pressure will increase to use all available resources to stop it, including the ARS Culture Collection.

Authorship credit: Kirk Broders, USDA/Agricultural Research Service

(Above) A scientist observes growth of *Fusarium oxysporum,* the fungus that causes *Fusarium* wilt. (USDA/Keith Weller)

(Below) Cryogenic tanks filled with liquid nitrogen (Coriell Institute for Medical Research/Courtney Sill)

Environmental Health and Safety

As described above, a unique feature of Federal collections is the ability to collect and maintain long time series of samples that can be used to monitor the status of an environment. These time series establish baselines that will reveal perturbations in the system that reflect natural phenomena (e.g., hurricanes, floods, droughts) or man-made disturbances (e.g., industrial pollutants, changes in land use). To be effective and useful "canaries in the coal mine," Federal collections should be well-documented and linked to analyses of critical environmental parameters.

(Below) Bats collected from 1960s to present for research into white-nose syndromw, named for the white fungus, *Pseudogymnoascus destructans,* that infects skin of the muzzle, ears, and wings of hibernating bats. (USGS)

(Below) Wildlife pathologist conducts necropsy on a little brown bat (*Myotis lucifugus*) at the USGS National Wildlife Health Center, as part of its effort to study the fungus that causes white-nose syndrome in bats. (USGS/Allison Klein)

Vignette 14 describes the collection of marine mammal tissues maintained by the National Institute of Standards and Technology (NIST). The baseline samples and data were critical in assessing the diseases caused by the Deepwater Horizon oil spill. Changes in the diversity of species present are also important indicators of changes in the environment. USGS's National Water Quality Lab is charged with monitoring freshwater quality in American rivers and streams. The invertebrates in each measured water sample are sorted and identified, and an index of stream health can be calculated from the number and relative abundances of the species found in each sample (Vignette 15). The resulting collections constitute an ever-growing reference that can be consulted to look for longer-term trends in environmental quality.

Vignette 16 describes an environmental hazard in the form a destructive feral swine hybrid between domestic pigs and wild European boar. Regulations now prohibit possession and transport of the hybrid, but they can be identified only by DNA analysis. USDA's APHIS collection of wildlife tissue has been amassing an archive of tissue samples that is needed to identify the hybrids and enforce the regulation.

(Above) Fireboats battle the blazing remnants of the Deepwater Horizon oil platform. (U.S. Coast Guard)

Vignette 14. Impacts of Environmental Contaminants on Marine Mammals: A NIST–NOAA Partnership

On April 20, 2010, the Deepwater Horizon (DWH) drilling platform in the Gulf of Mexico exploded, releasing more than 130 million gallons of raw crude oil into the surrounding ocean for 87 days. In the immediate aftermath of the Deepwater Horizon oil spill, researchers at the National Institute of Standards and Technology (NIST) Biorepository[32] at the Hollings Marine Laboratory in Charleston, South Carolina, joined forces with researchers from the National Oceanic and Atmospheric Administration's (NOAA) National Marine Fisheries Service (NMFS) and National Ocean Service (NOS) to preserve samples that would record the impact on Gulf of Mexico coastal and offshore marine mammals due to this environmental disaster as it unfolded.

NIST has partnered with NMFS since the 1980s in managing and preserving tissues from marine mammals in Alaska harvested for food by Alaskan Natives or beached for unexplained causes throughout the coastal United States to study levels of environmental contaminants. It was through this partnership that NIST developed standardized protocols for collecting, processing, and cryogenically preserving marine mammal tissues, stabilizing the anthropogenic and natural chemical constituents residing in samples for future analysis. The Marine Mammal Health and Stranding Response Act of 1992 authorized the creation of a National Marine Mammal Tissue Bank (NMMTB) that would preserve marine mammal samples for future analyses.[33] Through this partnership, NOAA researchers, state and local government institutions, non-profit organizations, and academic institutions that were authorized to collect samples for the Marine Mammal Health and Stranding Response Program could provide samples to the NMMTB. NIST would be responsible for developing protocols on collecting and preserving these samples and their associated data, providing training to the permitted researchers and ensuring access to samples by scientists that meet the policy requirements approved through the NMMTB Tissue Request Access Policy. The NIST Biorepository contains more than 150,000 biospecimens that are preserved at cryogenic temperatures (≤ –150°C/ –238°F), including the NMMTB collection, which contains biospecimens from more than 50 species of marine mammals from the coastal United States, including Alaska and U.S. Pacific territories.

(Above) NIST Biorepository freezers (NIST/A. Holt)

Protocols used at the NIST Biorepository provided an "off-the-shelf" starting point for sampling and preserving the marine mammal samples collected from animals exposed to the DWH oil spill. These protocols were refined for this assessment, and an updated chain-of-custody protocol for marine mammal specimens was added, as these samples and the data generated from them were part of the Natural Resource Damage Assessment (NRDA).[34] Intensive field research conducted by NOAA researchers and their partners uncovered serious health problems among bottlenose dolphins in Louisiana's Barataria Bay, one of the most heavily oiled stretches of coastline. These dolphins exhibited lung disease, compromised immune function, adrenal functional abnormalities, reduced survival, and poor reproductive success as compared to dolphins not exposed to the DWH oil. Tissue samples sent to NIST were used to determine contaminant levels in the affected dolphins and archived samples remain available to address potential future examinations. These high rates have persisted much longer than expected, leading to chronic health effects in dolphins exposed during the spill.

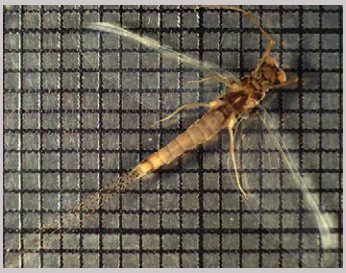
Like canaries in a coal mine, dolphins reflect the health of the marine environment and can warn of dangers to human health. Through the long-term preservation of high-quality samples, we have the potential to see long-term effects on marine ecosystems and the marine mammals and humans that rely on them. Over the decades, the NIST–NOAA collaboration, and the scientific collection it established, allows us to understand and react to unprecedented environmental disasters like oil spills while also providing samples and data to monitor long-term trends in our changing oceans.

Authorship credit: Rebecca Pugh, Commerce/National Institute of Standards and Technology

(Above) NWQL hydrologist measuring streamflow, Moran, Wyoming (USGS/Rob Hood)

(Above Inset) NWQL Aquatic Invertebrate Collection (USGS/Rob Hood)

(Above Inset) *Ecdyonurus dorsal* (USGS/Rob Hood)



(Above Inset) *Ephemerella ventral* (USGS/Rob Hood)

(Above Inset) *Paragnetina Dor Ent* (USGS/Rob Hood)

Vignette 15. Protecting the Nation's Critical Water Resources: USGS's National Water Quality Laboratory

Pure, clean water is necessary for life. We drink it, we use it to grow food, we play in it, and we need it to make almost every kind of manufactured good, but it is a finite resource that is easily degraded. Aquatic invertebrates are very sensitive to pollution in the environment, making them excellent indicators of water quality. For this reason, the Aquatic Invertebrate Collection is a critical resource in the National Water Quality Laboratory (NWQL) of the U.S. Geological Survey (USGS).[35]

The NWQL has played a central role in monitoring the quality of water across the United States through the National Water Quality and Assessment Program (NAWQA).[36] NAWQA includes many different periodic sampling surveys of rivers and streams throughout the nation. Scientists at the lab characterize water samples by measuring properties like acidity, oxygen level, turbidity, and dissolved chemicals. As important as measurements of these properties are, they fluctuate over time, so a sample provides only a snapshot of water quality at the moment it was collected. To fully understand the health of a body of water, it is also necessary to examine the life in the aquatic ecosystem, which reflects water quality over a period of days, weeks, or longer. The NWQL has maintained the Aquatic Invertebrate Collection in Lakewood, Colorado, for more than 25 years, using it to standardize the documentation based on bioassessment of environmental quality and its history over decades.

Although often overlooked by casual observers, a wide diversity of small, bottom-dwelling invertebrate animals, such as aquatic insects, mollusks, worms, and crayfish, thrives in unpolluted freshwater bodies. Aquatic invertebrates cannot migrate away from sources of water pollution, so they reflect the local water quality over time. The primary use of the Aquatic Invertebrate Collection is as a reference for specimen identifications, which ensures that the number of specimens per species in a sample is counted accurately. Some species are more sensitive to pollution than others, and some species may react to each type of pollution differently. The species found in each sample are linked to the hydrological, environmental, and chemical data from that sample, which builds our understanding of how the distribution of each species reflects water quality.

Bioassessment using aquatic invertebrates was an essential tool for annual NAWQA surveys of rivers and streams that began in the early 1990s and continued for more than 25 years. The survey sometimes sampled broadly across the country and focused on specific regional watersheds at other times. Each annual survey would typically involve hundreds of sampling sites, ranging from rivers to small streams. Monitoring water quality across a country as large and complex as the United States is a monumental challenge that demands both accuracy and cost-effectiveness. By combining physical and chemical testing with surveys of aquatic invertebrate life, NWQL is squeezing as much useful information as possible out of every drop of water.

Authorship credit: Rob Hood, Interior/U.S. Geological Survey

Vignette 16. Rooting Out Information on Feral Swine: USDA's Wildlife Tissue Archives

The U.S. Department of Agriculture's (USDA) Animal and Plant Health Inspection Service (APHIS) has the critical mission to protect the health and security of the nation's agricultural enterprise and the food, feed, and fabric it produces, and also to protect our agriculture and natural resources from damage inflicted by wildlife. Wildlife Services is a branch of APHIS that helps people and wildlife coexist by resolving conflicts between free-ranging animals and human society.

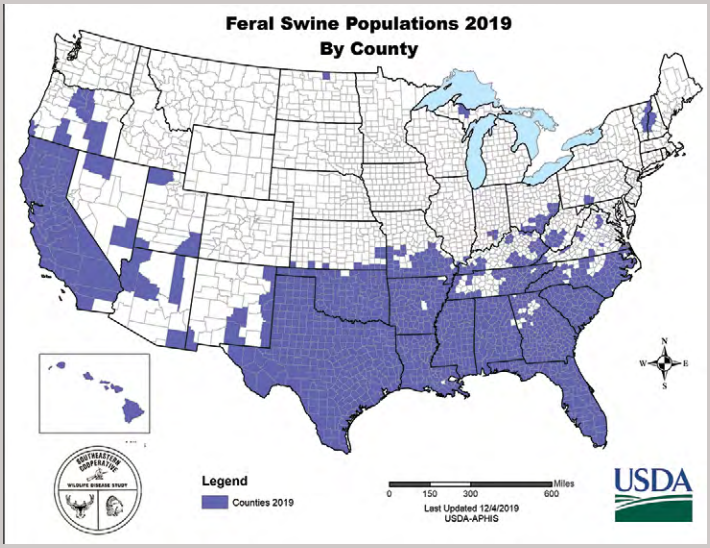
Domestic pigs were originally imported from Europe in the 1500s and managed for food; wild boar were brought to the United States in the late 1800s and early 1900s for sport hunting and the exotic meat trade. Feral swine belong to *Sus scrofa*, the same species as domestic pigs, but interbreeding between domestic pigs that have escaped the farm and European wild boar (sometimes referred to as Eurasian or Russian) has created the invasive, destructive feral variety. Millions of feral swine inhabit the United States with damage management efforts ongoing in 37 states and three U.S. territories. In addition to causing significant damage to crops, livestock, private property, public parklands, historic sites, and natural ecosystems, they are involved in collisions with vehicles and aircraft and can attack humans. Feral swine also carry a variety of viral and bacterial diseases (e.g., brucellosis, tularemia, and leptospirosis) that can infect other animal species and even spread to humans. Estimates of the annual damage they cause exceed $1.5 billion.[37]

Within APHIS, the National Feral Swine Damage Management Program (NFSDMP) was initiated in 2014 and works in partnership with Federal, state, and territorial partner organizations. The program removes approximately 100,000 animals per year, and these operations created opportunities to collect samples that help design more effective control measures. Wildlife Services began collecting blood and serum samples in 2006 to identify disease agents in these wild populations and began collecting tissue samples for genetic analysis in 2015. The Wildlife Tissue Archives, located in the USDA National Wildlife Research Center in Fort Collins, Colorado, now holds approximately 30,000 frozen samples, to which 6,000 samples are being added each year. High-density SNP (single nucleotide polymorphism) genetic analysis of 20,000 of these samples has demonstrated feral swine are genetically distinct from domestic pigs and that populations of feral swine are distinct from one another.[38] Understanding the geographic limits and sizes of distinct feral populations has given rise to a two-pronged approach to control efforts. Some lineages are local and insular, and these can be eliminated through removal, leaving those areas free of feral swine. More widespread and growing populations are the result of well-established historic populations on the landscape, as well as transport and introduction of feral swine into new areas with the goal of establishing hunting areas. Wildlife Services works with law enforcement to stop the translocation of feral swine, illegal hunting, and further spread of invasive populations. Investigating and prosecuting suspected traffickers rely on the genetic information from confiscated animals, analyzed in the context of the global dataset generated from the Wildlife Tissue Archives.

The Wildlife Tissue Archives added new technological capabilities for USDA's mission to protect American agriculture. It is generating a growing reference database that benefits Federal, state, and local partners working at the interface between society and natural ecosystems. The use of these new technologies and data is proving cost-effective in generating benefits to our society, far beyond the cost to the taxpayer of these Federal government operations.

Authorship credit: Vienna Brown and Tim Smyser, USDA/ Animal and Plant Health Inspection Service

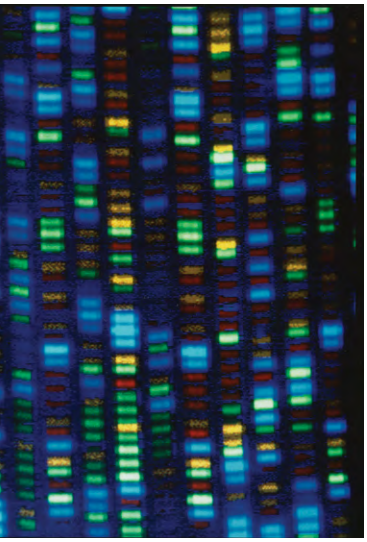
(Below) Distribution of feral swine in the U.S. by county in 2019 (USDA)



(Below) Wild hogs captured by motion-sensor camera in Big South Fork National River and Recreation Area, Tennessee (NPS)

Scientific Discovery

Scientific discovery as a national priority may be the best example of the valuable and special characteristics of Federal scientific collections. Federal collections made for basic scientific research are among the largest in terms of the numbers and variety of objects they contain and the spans of time they record. These collections can also be extremely narrow and deep in their focus on particular phenomena. In either case, the stability of the departments and agencies within which collections are managed is ensured for decades, even centuries, as are the security, preservation, and accessibility of the objects in their collections.



(Above) Output from a DNA sequencer used in the Human Genome Project (NIH National Human Genome Research Institute)

Genomics has become a prominent tool in biology, biomedicine, agriculture, and other fields, and analytical technology may no longer be the principal challenge to research. Access to the necessary biological samples may now be one of the primary rate-limiting factors. The Earth BioGenome Project (Vignette 17) is building an unprecedented global library of genomes that represents the diversity of microbes, plants, and animals. Scientific collections that preserve frozen tissues and the genetic material they contain offer "off-the-shelf" access for representatives of most major groups of organisms. In many cases, new collecting activities will be needed for poorly sampled taxonomic groups. Existing collections distributed across diverse Federal agencies are positioned to incorporate the resulting objects, capture their metadata and genome data, and make them available to the research community. Either way, the Earth BioGenome Project serves this critical function: finding samples that are widely distributed, obtaining important data from them, and distributing these data as if the samples came from a single collection, broadly speaking.

The collection whose objects have been obtained by *Okeanos Explorer*, a 224-foot NOAA research vessel, represents the other end of the spectrum (Vignette 18). It is the only Federal ship dedicated to sampling life in the deep ocean, and the more than 1,500 nearly impossible-to-obtain specimens representing many diverse groups are documented and preserved in the Smithsonian Institution's National Museum of Natural History. They are accessible to the global community of qualified researchers, and 12,000 digital images of these objects are accessible online. This long-term collaboration between NOAA and the Smithsonian makes it possible to obtain extremely rare and inaccessible objects, preserve them for diverse uses, and make them accessible from a single, stable source.

History has shown that serendipity can also play a role in scientific discoveries based on Federal collections. For example, the collections in the Armed Forces Institute of Pathology (AFIP) were created and are maintained to protect the health of members of the United States' armed forces. Owing to the long time spans recorded in these collections, dating back to the Civil War, the objects in these collections enable fundamental research on the evolution of infectious diseases (see Vignette 4). Archeological collections of objects located on Federal lands are providing data to climate scientists (see Vignette 9). The varied nature and diversity of their primary uses is an added strength of Federal scientific collections. Whether they are broad and distributed or narrow and centralized, collected for one purpose but found useful in others, their potential for scientific discovery is valuable to the nation. These discoveries are sometimes evident immediately, while others take longer to discover and occasionally appear in ways that were impossible to predict or even imagine

Vignette 17. Looking Deeper into the Living World: USDA's Ag100Pest Initiative and the Earth BioGenome Project

Gene sequence data and the rapid advances in biotechnology that revealed them are revolutionizing research in all branches of life science research, from microbiology to biomedicine to the diversity and conservation of life on Earth. The Earth Bio-Genome Project (EBP)[39] is an international initiative that has catalyzed ambitious and forward-looking genome sequencing projects. These projects are united by high scores on sequence quality metrics, adherence to EBP's consensus quality standards, and use of protocols for meeting those standards. EBP was registered as an Umbrella Comparative Genomics project by the National Center for Biotechnology Information (NCBI, host organization for GenBank) in April 2019.[40] Since then, EBP has grown to include more than 50 affiliate project networks and hundreds of individual projects. These have collectively submitted approximately 8.5 million sequence records to NCBI as of this writing.[41]

USDA's Ag100Pest Initiative[42] is one of the EBP affiliate project networks, catalyzed by EBP and the U.S. Department of Agriculture's (USDA) understanding of the potential in genomic research. Ag100Pest's original goal was to generate genome assemblies for 100 arthropod species, selected through proposal review to be the most important pests on a wide diversity of agricultural crops. The original goal expanded to more than 150 based on review of proposals and early successes of the project. Insects are at the core of the initiative because of their harmful and beneficial relationships with plants, other animals including livestock, and human society. Analysis of whole-genome assemblies may transform our understanding of these relationships and reveal new mechanisms for controlling the most dangerous ones—those causing disease transmission and destruction of agricultural crops.

Control of insect pests on crop plants is a never-ending arms race. A prime example is the ongoing struggle between domesticated corn (*Zea mays*) and corn rootworm (three species of the beetle genus *Diabrotica*). For example, farmers use crop rotation and field management techniques to limit outbreaks and damage caused by these pests; agrotechnology has developed new insecticides that target these beetles; and genetic engineering has inserted genes into crop plants that produce proteins that are toxic to the pest but will not harm beneficial insects (e.g., "Bt corn"). The rootworm has diverged into variants that make them more successful, including those that are resistant to crop rotations, new insecticides, or transgenic corn.

The western corn rootworm (WCR), *Diabrotica virgifera virgifera*, is one of the Ag100Pest's targets, and the rootworm genomics project demonstrates the potential benefits that can be generated by applying new analytical technologies like genomics to Federal collections. The USDA Agricultural Research Service's Corn Insects and Crop Genetics Research Unit in Ames, Iowa, has isolated populations of the beetle that are susceptible to particular types of Bt corn or insecticides and populations that are resistant to either of them as well as different variants of Bt corn. Using EBP protocols, Ag100Pest has produced a genome assembly for WCR and DNA sequences from different WCR populations. This research is providing growing insight into how genetic differences translate into insect resistance or susceptibility to the control measures used by farmers.

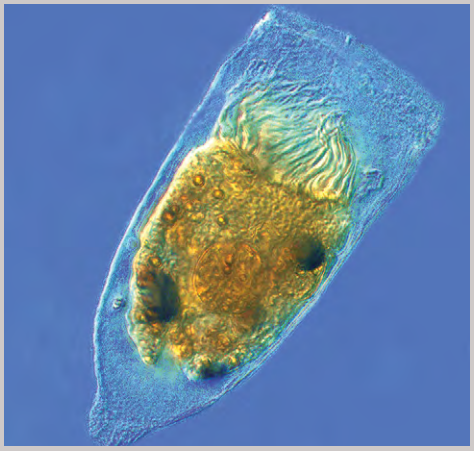
By narrowing the focus on which insect genes for resistance have been successful, researchers will be able to explore the proteins that result and the metabolic pathways they turn on or off. These new insights may reveal new ways to block resistant pathways and make control measures more effective.

The genomic revolution has a place alongside other new technologies (e.g., electron microscopes, radio telescopes, particle accelerators) that have opened new universes of scientific knowledge. Federal collections cover the full range of variation in the life sciences, from microbes to humans, all available for mission-driven research using the approach that EBP has created.

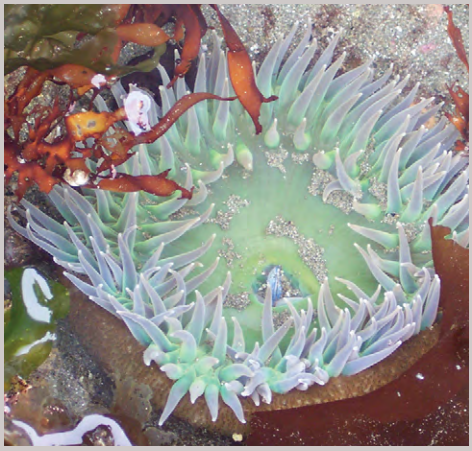
Authorship credit: Anna Childers and Brad Coates, USDA/Agricultural Research Service

(Below) *Macrocystis pyrifera,* giant kelp (NPS/Susanna Persham)

(Below) *Favella* sp., a single-celled eukaryote (CC/Tintinnidguy)



(Below) *Anthopleura xanthogrammica,* Giant green sea anemone (NPS)



(Above) The 224-foot NOAA ship *Okeanos Explorer* (NOAA)

Vignette 18. Documenting Deep Sea Life: NOAA–Smithsonian Partnership

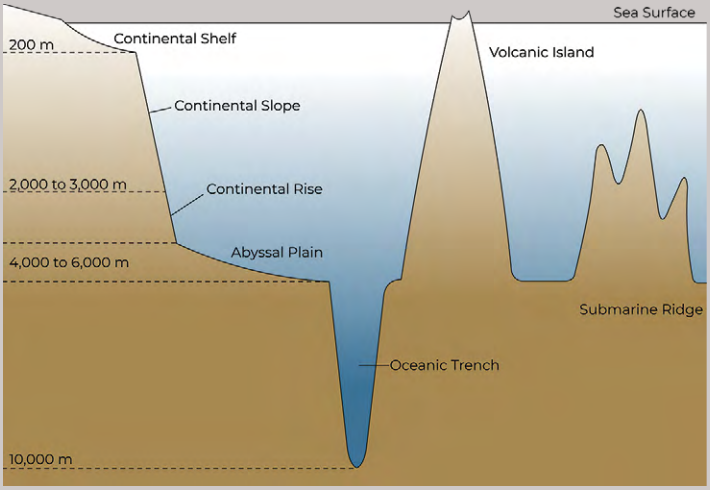
The impulse to explore is part of what makes us human. It compels us to walk over the next rise simply to see what's there and to send people to the Moon and Mars. It may seem that we've been everywhere on our own planet—after all, we've visited the highest mountain peaks and reached both poles. However, a substantial part of our world remains largely unexplored and full of wonders to be discovered: the Ocean. The ocean covers more than 70% of Earth's surface and represents more than 95% of the livable space on our planet. To fill this gap in our understanding of our world, the National Oceanic and Atmospheric Administration (NOAA) operates the *Okeanos Explorer*, the only Federal vessel dedicated to discovery and the advancement of knowledge about the deep ocean.

In more than a decade of expeditions, the 224-foot vessel has visited all the world's oceans and even the Great Lakes. Everywhere it goes, it encounters many species that are new to science. Off the Northern Mariana Islands and Guam, at depths greater than 3 miles, the ship discovered an ecosystem with carnivorous sponges that survive by capturing and eating crustaceans. Closer to home, about 100 miles off the coast of Florida and Georgia, the ship mapped a landscape of coral mounds thriving 2,000 feet below the ocean surface. In the Caribbean, between Cuba and Jamaica, the crew discovered a field of deep-sea hydrothermal vents—features that previously were thought to occur only at more volcanically active sites like the Mid-Atlantic Ridge—supporting a thriving ecosystem of shrimp, tubeworms, and other awe-inspiring creatures.

Planning and carrying out deep-sea exploration isn't easy or cheap, so everything the *Okeanos Explorer* finds is carefully documented and saved in the collections of the Smithsonian Institution's National Museum of Natural History. The collection has grown to 1,563 specimens of deep-sea creatures documented by nearly 12,000 publicly accessible images. In addition to preserving a record of discovery, the collection is an important resource for documenting the diversity of life on Earth and how it is responding to a changing climate. The collection also provides information helpful for: managing and protecting deep-sea ecosystems that support valuable fisheries, discovering new biological compounds with potential for medical breakthroughs, and ensuring that increasing interest in deep-sea mineral extraction is managed responsibly. Without the collection, we would know even less than we do about the least-known part of our planet.

Authorship credit: Allen Collins, Commerce/National Oceanic and Atmospheric Administration

(Below) Diagram of ocean floor features (CC/Chris_huh)



(Above) Remotely operated vehicles *Deep Discoverer* and *Seirios* on the deck of the *Okeanos Explorer* (NOAA/Art Howard)

(Above) Coral habitat approximately 440 meters deep in Norfolk Canyon, 80 miles off the coast of Virginia (NOAA)

Innovation and Commerce

Federal departments and agencies are involved in the full range of commercial activities, from supporting the innovation process, to ensuring regulatory compliance, to overseeing legal and ethical trade agreements. As Vignettes 19 and 20 illustrate, Federal scientific collections play a part in many aspects of the Federal role in the marketplace.

The Manhattan Project was the first major demonstration that the Federal government could catalyze breakthroughs in R&D. This led to the creation of Federal research agencies, facilities, laboratories, and support mechanisms following World War II. Many Federal collections were launched during this period, while older ones accelerated their growth and expanded their scope of activities.

Collections made on national park system lands were considered Federal property before World War II, and by the time DNA was understood and biotechnology became a rapidly expanding field, critical microbes from Yellowstone's hot springs were already accessible in a collection. Researchers working on DNA sequencing technologies knew of these microbes and their physiologies from academic publications. They were available for private R&D, which led to a discovery, a Nobel Prize, and a multibillion dollar per year commercial application (Vignette 19).

The regulation of international trade and the enforcement of trade agreements are responsibilities shared by several Federal departments and agencies. Enforcement of laws and trade agreements by the Department of the Interior, Department of Commerce, Department of State, Department of Justice, or Department of Homeland Security will frequently depend on scientific specialists and collections in the Department of the Interior, USDA, HHS, and the Smithsonian Institution. Vignette 20 provides an illustration of how enforcement of global trade regulations and laws can depend on objects in Federal scientific collections.

(Below) NPS and USGS partners discuss seasonal drought experiments in a living field collection. (USGS/Erika Geiger)

Vignette 19. Yellowstone Microbe Revolutionizes Genomics: National Park Service

The ability to characterize DNA sequences for all genes in an organism—its genome—is one of the most revolutionary discoveries of the twentieth century. Genomics has facilitated advances in almost all biological sciences, contributing to biomedicine and species discovery, and linking genealogy to heritage for millions of people. Many are unaware, however, that an organism from Yellowstone National Park contributed to this genomics revolution. In 1966, while studying micro-organisms living in Yellowstone National Park's thermal pools, American microbiologist Dr. Thomas D. Brock discovered a new bacterium, which he named *Thermus aquaticus*. He cultured *T. aquaticus* in the laboratory and deposited, on behalf of Yellowstone National Park, a living strain (YT-1) at the American Type Culture Collection (ATCC) in what is now the National Park Service Special Collection. Its potential for use in genomics was not discovered until two decades later.

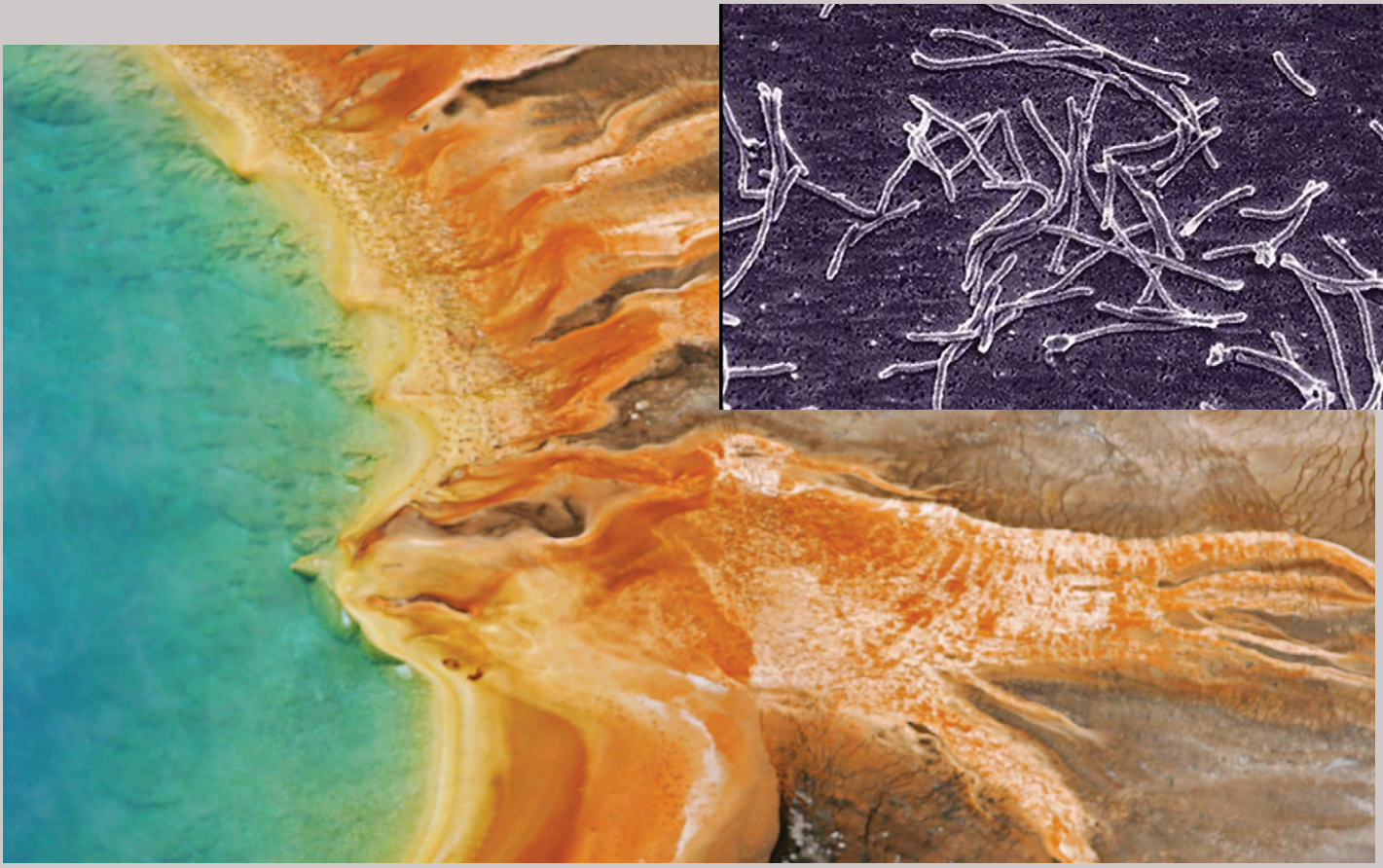
DNA sequencing requires billions of exact copies of the original sequence, and without an efficient way to generate these copies, early sequencing was time consuming and expensive. The general approach to producing copies (termed "amplification") that was being explored was thermal cycling, which involves repeated heating and cooling of a solution of the original sequence and raw materials for building DNA strands. In principle, heating the mixture causes the complementary strands in the DNA's double helix to separate, like a zipper being opened. When cooled, an enzyme that promotes growth of the DNA chain (a polymerase) uses the raw materials to form the complementary DNA strands, like closing a zipper. Each cycle thus has the potential to double the number of complete double DNA strands, providing enough copies for DNA sequencing. The challenge was to find an enzyme that could survive the heating phase, so it could help grow the new complementary strand during the cooling phase without requiring replenishment after each cycle. Recognizing the thermo-tolerant properties of the YT-1 strain of *T. aquaticus*, researchers at Cetus Corporation obtained the strain from ATCC and isolated a new enzyme—Taq polymerase—that could remain active through repeated cycles of heating and cooling. This discovery led to the Polymerase Chain Reaction (PCR) becoming economical and a cornerstone of a critical multibillion dollar global biotechnology enterprise.

As with all Federal property, the National Park Service preserves its specimens in accessible collections making them available to all to study and use. The *T. aquaticus* strain deposited in the ATCC fundamentally revolutionized genomics. Who knows what other unanticipated discoveries and innovations might come from specimens collected on Federal lands that are safely stored long-term in scientific collections and accessible to future researchers?

Authorship credit: Interior/National Park Service

(Below) Color gradations in Grand Prismatic Spring, Yellowstone National Park, correspond to various types of heat-tolerant microbes adapted to different water temperatures. (NPS/Jim Peaco)

(Below) Bacterium *Thermus aquaticus* YT-1 strain (NPS and Indiana University/Thomas Brock)



(Above) Timber being transported on the Ucayali River in Peru (USDA/Tom Moreland, IWGSC representative for USDA Forest Service)

Vignette 20. Fighting Illegal Trade in Endangered Species: USDA's Forest Products Laboratory Wood Collection

The illegal harvest, transportation, purchase, and sale of timber is a pervasive problem around the world that degrades the environment, impedes economic development, and contributes to crime and corruption. The International Criminal Police Organization (INTERPOL) estimates that the global trade in illegally harvested timber is between $51 billion and $152 billion annually. The United Nations Convention on International Trade of Endangered Species (CITES) is the forum for decisions concerning endangered status, and several Federal agencies are involved in meeting the U.S. obligations as CITES members. For example, the Customs and Border Protection Service (CBP) in the Department of Homeland Security is the front-line agency that enforces U.S. laws prohibiting the illegal import of regulated timber species. International shipments of lumber have declarations of the species of origin that are checked against CITES.

In December 2015, CBP seized 24 pallets of timber being imported from Peru through the Port of Houston. The shipment included component bundles that were labeled *Manilkara*, a widely distributed genus of fruit-bearing trees that is not protected under CITES. CBP inspectors had reason to believe that the wood was incorrectly labeled and that it came from an endangered species, in violation of Peruvian law. If correct, it would mean that import into the United States would violate the U.S. Lacey Act, which prohibits U.S. trade in natural products that were obtained in violation of foreign laws. Peruvian authorities also alleged that application to harvest the trees did not correctly identify the species, so they were harvested without proper authorization. CBP doesn't have experts capable of validating the accuracy of the species identification, so they rely on experts in the Forest Products Laboratory (FPL) of the U.S. Department of Agriculture's (USDA) Forest Service in Madison, Wisconsin.

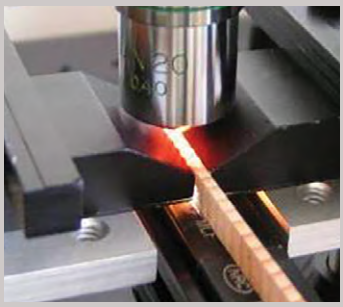
(Below) The U.S. Forest Service Wood Products Laboratory Collection (USDA/Tom Moreland, IWGSC representative for USDA Forest Service)

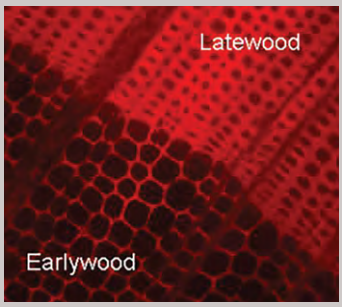
The standard protocol for identifying tree species from processed wood is by going through the features in a sequential identification key, examining the cell structure on a polished surface of the item being identified, and comparing the feature with images of different species in atlases of wood anatomy. Rather than comparing samples from the Peruvian timber with printed images, FPL's experts could use the FPL Wood Collection, originally established in 1910, which contains more than 100,000 wood specimens representing more than 14,000 tree species from every corner of the world. The experts concluded that the bundles labeled *Manilkara* included *Brosimum* cf. *rubescens* (bloodwood), *Peltogyne* (purpleheart), and *Platymiscium* (macawood). The FPL collection had provided the critical evidence needed by the Department of Justice to block the illegally harvested timber from entering the U.S. marketplace, which would have undercut the sale of lawfully obtained products.

In addition to being experts on all types and aspects of wood, the researchers at FPL have developed digital image-based methodologies for automated identification of wood products.[43] A system using this methodology would integrate an electronic on-screen identification key with images of the sample being identified side-by-side with images of reference samples from the FPL Wood Collection. The system would accelerate identification, improve reliability, and would not need physical access to the FPL wood samples. Digitization of the collection and development of the computer software would generate diverse benefits by improving international trade relations, weakening organized crime, and protecting endangered species.

Authorship credit: USDA/National Forest Service

(Below left) Ring profiler used to examine fiber structure and growth characteristics of a wood sample; (Below right) Ring profiler image of normal cell wall growth for earlywood and latewood fibers (USDA/David Vahey and C. Tim Smith)





STEM Education

(Above) *Cardiospermum coloradensis* fossil leaf from the Eocene epoch (48.5–53.5 million years ago), Green River Formation, Colorado (Smithsonian/CC)

Science and math education became a national priority following the Soviet Union's launch of Sputnik in 1957, and it has since evolved into STEM (Science, Technology, Engineering, and Mathematics) education. The "hands-on" science movement accelerated in the early 1990s as an attempt to engage students through experiential learning, as a complement to book-based teaching.[44] Hands-on instructional material, including kits of equipment and supplies for classroom use, proliferated across the range of physical, life, and earth sciences, soon reaching all age groups in K–12 classrooms. There is little doubt that teaching can be more effective if it combines physical contact and direct engagement of scientific phenomena with printed or digital descriptions of them.

Objects in Federal scientific collections offer agencies the opportunity to be a part of experiential learning in K–12 classrooms, but there are also limitations. The objects in these collections, strictly speaking, are Federal property that agencies manage accordingly, to ensure their preservation and security for future use. In contrast, the equipment and supplies used in classroom science kits are considered consumables that can be replaced, and commonly are after a class is finished with an activity. There are circumstances under which an agency may deaccession objects that are no longer fit for their purposes, often donating them to museums, science centers, or schools for educational use. For example, objects that were accessioned into a Federal collection and later found to have unreliable provenance data or were separated from their original data records can't be used for research, but they remain objects of interest for students and teachers. Replicas of research objects may also be used in ways that might lead to deterioration.

Vignette 21 provides an example of how objects in Federal collections are having substantial impact through hands-on experiences. The Smithsonian Institution's National Museum of Natural History is among the most visited museums in the world, and it has a hands-on education center that has few equals anywhere.

(Below) Visitors interact with the collections and equipment in the National Museum of Natural History's science education center, Q?rius, in Washington, DC. (Smithsonian/James DiLoreto)

Vignette 21. Inspiring Q?rius-ity through Collections: A Science Education Center in the Smithsonian Institution's National Museum of Natural History

Q?rius, the Coralyn W. Whitney Science Education Center, provides the public with an exceptional opportunity to experience specimen-based scientific discovery. Consider the American West, an awe-inspiring landscape of sculpted deserts, endless plains, and majestic mountains. Thanks to generations of painstaking fieldwork and careful curation of enormous scientific collections, we now know that 50 million years ago, during the Eocene epoch, things were very different. Dense, humid forests extended across North America, from the Gulf Coast to above the Arctic Circle. *Hyracotherium*, an early relative of horses, ran through the underbrush, and *Smilodectes*, a forerunner of primates, lived in the high branches. Enormous lakes covered what are now parts of Wyoming, Colorado, and Utah, harboring abundant fish, freshwater sting rays, and crocodiles. The Eocene fossil plants and animals in the Smithsonian Institution's National Museum of Natural History are a small part of one of the world's great natural history collections, and Q?rius makes a portion of the collection accessible. Q?rius offers the visitor something unique: learning and experiencing science through direct contact with rare objects, guided by specialists they might otherwise never encounter.

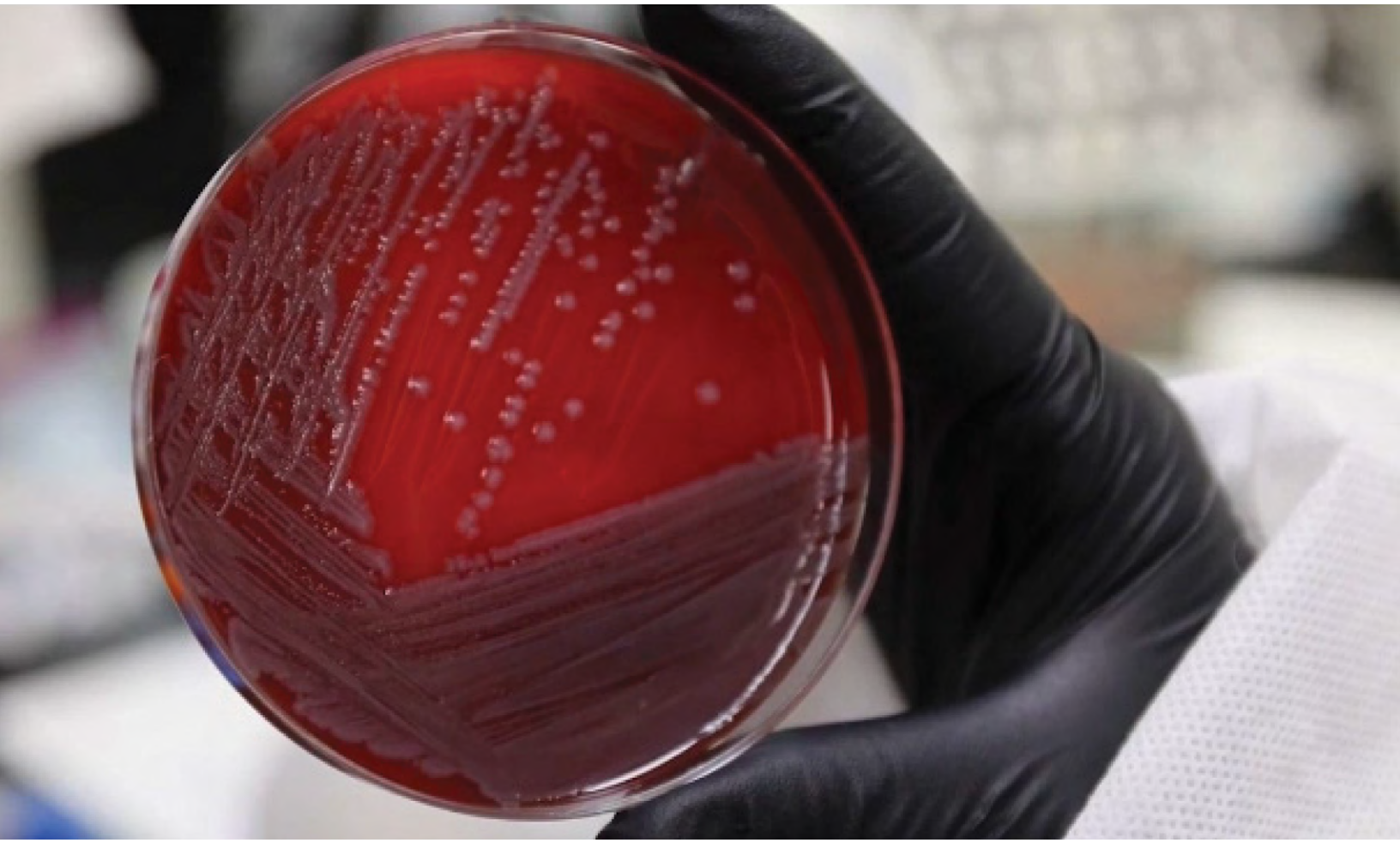
Q?rius is a place where 200,000 visitors each year come to examine and touch museum specimens, and interact with science experts. The Q?rius collection includes a piece of the Canyon Diablo meteorite, which created Meteor Crater when it crashed to Earth in Arizona, giving people a chance to touch an object dating to the origin of the solar system.

Visitors can also examine an exact replica of the Killer Whale clan crest hat and appreciate the cultural significance of an object sacred to the Native American Tlingit Dakl'aweidi clan.

And among all the specimens and materials for people to explore at Q?rius, there is a fossil leaf excavated from Eocene rocks in Colorado. Its scientific name is *Cardiospermum coloradensis*, and it is closely related to modern balloon vines, a group of plants native to tropical forests like those of Central America. Seeing and examining such a delicate object from so long ago helps visitors imagine the long-vanished Eocene jungles of North America. And this is what makes the Q?rius experience different from all other areas in the museum: it allows visitors to experience the joyful surprise of making scientific discoveries through the tangible exploration of specimens and collections, inspiring them to learn more about the world around them and maybe even become scientists themselves.

Authorship credit: Carol Butler, Smithsonian Institution/ National Museum of Natural History

(Below) Visitors explore the National Museum of Natural History's education center, Q?rius, in Washington, DC. (Smithsonian/Donald Hurlbert)



(Above) Typical antibiotic-resistant pathogen cultured in Petri dish containing blood agar medium (Defense/WRAIR/Tyra Breaux)

(Below) Computer-controlled analysis of multidrug-resistant organisms at the Walter Reed Army Institute of Research (WRAIR), Bacterial Diseases Branch, Multidrug Resistant Organism Repository and Surveillance Network (MRSN) (Defense/WRAIR/Tyra Breaux)

National Security and Defending against Biological Attacks

Scientific collections play an important role in keeping the United States secure, particularly in the face of potential attacks using biological agents. The same rapid advances in genetic engineering and synthetic biology that have opened new opportunities in biomedicine and the bioeconomy have also created the dual use potential for weaponized, engineered pathogens that could be used against Americans by military adversaries or terrorists.

Detecting whether a pathogen is bioengineered requires comparing it with naturally occurring variants. Although public digital databases of sequences are the first line of investigation to determine the provenance of a suspected bioengineered agent, comparison with actual biological materials remains necessary for several reasons.[45]

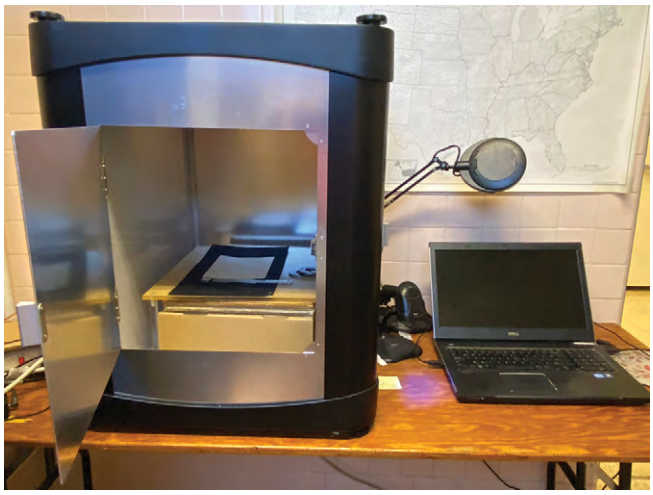
First, although digital archives are large and growing rapidly, they are not comprehensive, particularly with respect to microbial genomes. Second, although the tools for analyzing genomes continue to advance at a rapid pace, different models and generations of analytical equipment and laboratory protocols produce results of differing yields and fidelity. Finally, original pathogen specimens provide the greatest understanding of how genetic information is expressed in the transmissibility and severity of disease.

Keeping pathogens sampled from infected people provides the best way to understand how infectious agents affect their hosts under natural conditions, without the danger and ethical violation of deliberately infecting people. Storing primary biological material in secure, centralized collections ensures that it will be readily accessible when needed, and that comparisons with suspected engineered pathogens will be accurate and consistent.

Examples of Federal collections supporting a biosecurity mission include the DoD's Multidrug-Resistant Organism Repository and Surveillance Network, which houses more than 60,000 bacterial samples used to monitor antibiotic-resistant "superbugs" collected from around the world, and the Unified Culture Collection maintained by the United States Army Medical Research Institute of Infectious Diseases, a repository of pathogenic bacterial and viral agents whose purpose is to "protect the Warfighter from biological threats and to be prepared to investigate disease outbreaks or threats to public health." Other pathogen collections supporting a biosecurity mission and driving research aimed toward protecting the U.S. civilian population from biothreats are maintained by the HHS at NIH, CDC, and the Food and Drug Administration. Unlike the collections represented in the preceding vignettes, access to the samples in some of these collections is highly restricted and controlled to protect public safety and national security. Specifically, access is restricted for those that are considered the most dangerous and lethal pathogens and that may not have adequate countermeasures to protect human, plant, or animal health should they be used for harm.

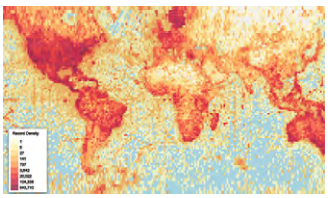
(Above) Apparatus for scanning large quantities of mounted botanical specimens at the National Museum of Natural History (NMNH)

(Below) Scanning apparatus at the Herbarium COLO, Natural History Museum, University of Colorado at Boulder, which in partnership with the USGS has integrated a Federal collection of botanical specimens. (Herbarium COLO/ Dina Clark)



Digital Representation of Objects in Federal Scientific Collections

The billions of objects in Federal scientific collections would be worthless without their associated data and metadata. Knowing where, when, and by whom it was collected is the bare minimum for an object's subsequent use in analysis, research, and scientific publication. Just as crime scene evidence must be carefully collected, tagged, and documented for use in courtrooms, scientific objects without provenance data are inadmissible in the courtroom of science. The earliest objects that were accessioned into a Federal scientific collection may have only had a handwritten label and a pen-and-ink entry in a leather-bound registry, used primarily as the bookkeeping system for inventory control. Like libraries before the dawn of computers, these registries allowed the loan and return of borrowed objects to be audited. As the number of objects in a collection grew (along with demands to access and use them), paper-based systems became more cumbersome to maintain and less useful for finding objects of interest.



(Above) Red coloring on world map indicates distribution of scientific collections. iDigBio, with support from the National Science Foundation, contains more than 130 million collection-based specimen records from every corner of the world. (iDigBio)

The conversion from paper-based analog information in Federal scientific collections to computer-based digital form paralleled the process in commerce and libraries, and eventually to media, entertainment, and other sectors of society. The entries in paper documents were reentered as digital records, and the need for data standards became quickly apparent. The Darwin Core standard gained rapid acceptance among natural history collections, creating opportunities for computerized searches and the exchange of data records among institutions.[46] Digital latitude and longitude data began to replace narrative description of collecting localities, which made it possible to create distribution maps directly from collection catalogs. Growth of the Internet brought with it online searchable collection catalogs, and many of these quickly began attaching high-resolution digital images to catalog records. The enthusiastic use of online searches by researchers was parallel to the rise of online shopping as an alternative to brick-and-mortar stores.[47]

The growth of digitized, standardized collection data and online access to them led to innovative new research directions. "Aggregators" such as the Global Biodiversity Information Facility[48] and the Paleobiology Database emerged as centralized hubs, through which the previously distributed contents of collections in the same field could be searched simultaneously.[49] New curricula and classroom activities were developed for K–12 and undergraduate classrooms.[50] "Ecological Niche Modelling" emerged as the byproduct of having enormous numbers of aggregated, standardized, digital collection records with GPS coordinates.[51] The objects represented by these records were collected over decades and centuries, which allowed researchers to document changes in the geographic ranges of species over time. The ability to visualize these temporal changes has opened new opportunities for research in population and community ecology, ecosystem behavior, and the effects of climate change and changing land use patterns.

(Above) National Museum of Natural History digital scan of a mounted dried specimen of *Buddleia racemosa*, collected in 1849 by Charles Wright, during an expedition from Western Texas to El Paso, New Mexico (Smithsonian)

Federal agencies have been leaders in supporting the rapid growth of digitization efforts, both on the collections they manage and through funding of non-Federal collections in universities, colleges, museums, and research institutions. NSF grants to digitize non-Federal natural history collections began in the 1970s under its program for improving the physical infrastructure of biological collections. Specify, a widely adopted collection database system, and VertNet, an aggregator of distributed collection databases, illustrate the broad impact that NSF support has had in helping the research community to efficiently achieve large-scale implementation and interoperability.[52] Research using digitized collection data quickly became a mainstream component in NSF's portfolio, along with support for development of software and tools related to the digitization processes needed for different types of collections (e.g., 2- and 3-D imaging technologies, and CAT scan images.

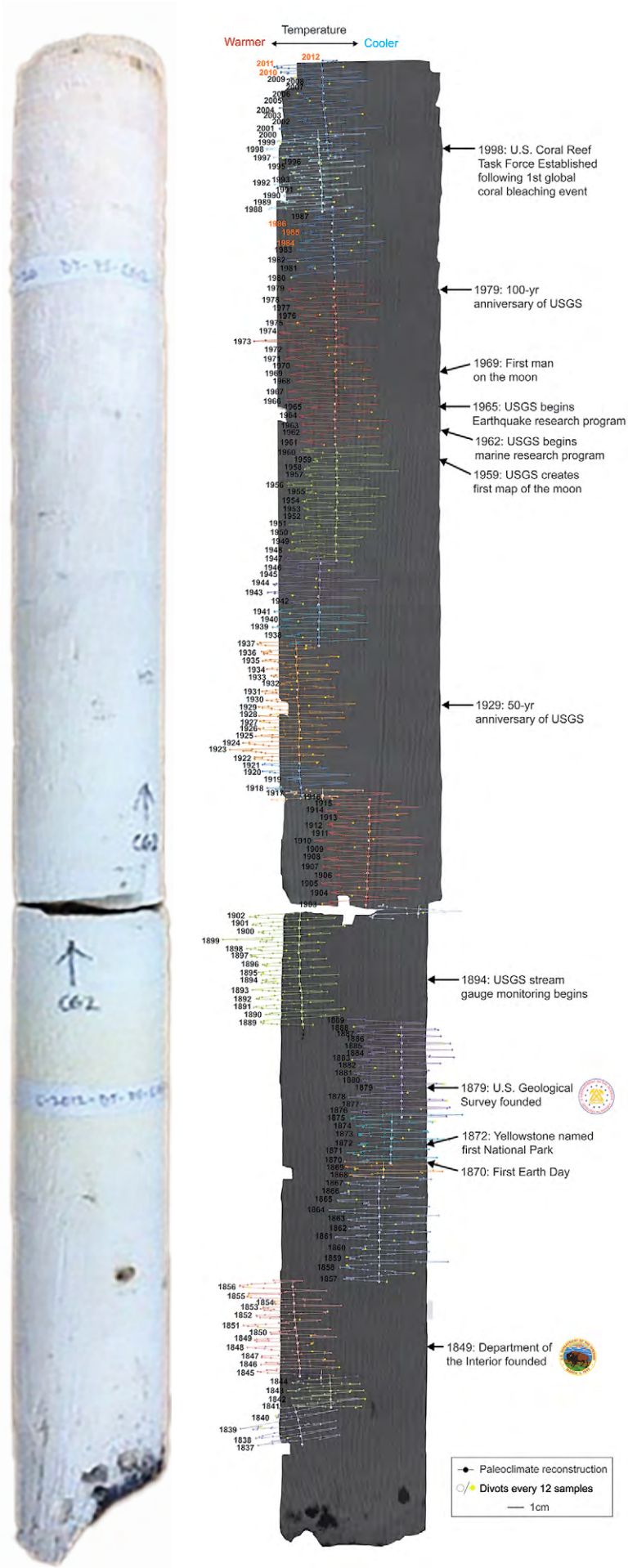
Longer-term planning and coordination have been necessary components because interoperability has been an ongoing challenge in efforts to integrate systems and data. In 2010, NSF launched Advancing the Digitization of Biological Collections (ADBC), a 10-year initiative that has created a network of dozens of thematic networks of digitization projects as well as a national hub and data aggregator.[53]

USGS is at the forefront of digitizing its own collections and is a lead organizer of EarthCube, a global initiative to standardize and accelerate the digitization of earth science samples.[54] The Smithsonian Institution has active programs in digitization of collection records and scanning of scientific literature.

IWGSC's 2020 report on the economic analysis of collections[55] considered digitization and data curation two separate services provided by agencies that manage object-based scientific collections, though they are clearly related. As described in that report, the digitization process served the goal of increasing access to objects in a collection, alongside loan and visitor programs. Online digital collection catalogs have enabled more researchers to find objects relevant to their research. As more collections attach digital images and other media (e.g., CAT scans, x-radiographs) to the digital records of their objects, researchers will be able to examine and use them for their research. Data curation complements digitization by expanding user access to the published results of prior research on objects. These results range from publications that cited the use of a specimen, a DNA sequence, or a chemical analysis from an object in a public database (e.g., GenBank), to new physical objects that have been derived from original objects in a collection (e.g., DNA extracts, cryogenically preserved tissue samples, or thin sections from a rock sample). By linking the diverse and often distributed information and byproducts, data curation makes it easier for researchers to discover the original object and to design new uses for it based on prior results.

The evolution of collections from analog to digital representation has brought with it a range of cultural challenges. IWGSC has been, and will continue to be the forum for Federal agencies with scientific collections to learn about, discuss, and develop best practices that will meet these challenges:

- Many institutions resisted the trend toward open data sharing, preferring to safeguard access to ensure that they will be given full and clear credit for the benefits derived from the contents of their collections. This is an ongoing issue for Federal collections, though some must remain inaccessible for reasons of public health and national security.
- As data standards and software systems developed in different scientific communities for their respective collections, they became less and less connected to each other. Enthusiasm for digitization within each discipline has contributed to divergence among standards, so researchers in different fields cannot find their way to collections and objects that could be valuable to their work.
- As the commercial value and wider impact of increasingly accessible scientific collections grew, countries became more concerned with sharing in the benefits derived from the objects collected and used by researchers from other countries. These are critical issues for several international treaties and United Nations Conventions.[56]
- Concern about sharing the benefits of access to genetic resources expanded from access to physical objects (e.g., biological specimens, tissue subsamples, DNA extracts) to access to their digital representations, in the form of published DNA sequences. Data curation and digitization are both areas of activity that must consider these concerns if they are to continue as global enterprises.



(Above) USGS resercher extracts a core sample from a coral (Interior/USGS)

(Left) Core from a starlet coral, *Siderastrea siderea,* and x-ray of the core. By counting the annual growth bands and seasonal cycles of temperature, USGS researchers estimate that this coral grew for almost 200 years. (USGS/Lauren Toth)

Conclusions

The IWGSC has learned important lessons and helped agencies improve their performance in three areas: transparency, accessibility, and accountability. These are the three goals that were set in the 2009 Green Report, identified by OSTP as priorities, and passed into law as part of the America COMPETES Reauthorization Act of 2010. In the area of transparency, IWGSC agencies have developed policies that govern their scientific collections, and they have made them publicly available online through the IWGSC Clearinghouse. Policy documents continue to be added or updated. Accessibility to information about the collections, their contents, and their access and use policies has been improved through the GRSciColl, except for those Federal collections whose contents are classified for reasons of public safety or national security. IWGSC will continue its work to maintain and improve transparency and accessibility through these online resources for stakeholders.

IWGSC's exploration of accountability has deepened over the past decade. Agency collections are tied closely to agency missions, and to regulatory standards and legislative mandates in some cases, as the preceding vignettes illustrate. For these reasons, collections are accountable for generating results in more tangible ways while improving accessibility, preserving objects, and managing long-term operating costs. IWGSC member agencies have gained new insight into how the costs of providing users with access to collections and other user services are linked to the benefits that are most important to their missions. For example:

- Potential users of objects in Federal collections will have specific uses in mind, but if objects have been degraded by poor storage conditions, they may not remain fit for those uses, foreclosing any potential benefits.
- Adding objects to a collection is a long-term commitment of resources to ensure the security of those objects, but simply maintaining them will generate few, if any, benefits unless users can learn of their availability and have access to them.
- Digitization of collections will improve the visibility and accessibility of the objects in Federal collections, which expands the pool of potential users and potential benefits. However, like collection security, proper environmental control, and other user services, digitization will add to operating costs.
- Charging user fees for access to objects in a collection may help to offset operating costs, but it may also present obstacles to use of the collection, especially for students, teachers, and researchers at resource-poor institutions. Users can add value to collections in other ways that may be more valuable than user fees, such as returning value added subsamples, analytical results, and copies of publications in which the use of objects from that collection are cited.

Over the past decade, several broad challenges have confronted U.S. administrations, resulting in calls for "all-of-government" responses. Federal scientific collections have had important roles to play in responding to many of these challenges. Global climate change, the COVID-19 pandemic, and the Russian invasion of Ukraine have elicited all-of-government responses from many IWGSC member agencies. These government-wide priorities present very specific challenges to agencies with scientific collections:

- How can agencies make their collections more visible and accessible to non-traditional users, like those involved in all-of-government responses? Agencies will need to develop ways to make their collections visible more generally, not just to traditional users within a scientific discipline.
- Digitization is a critical mechanism for facilitating searches and use by those who have discovered the collection exists. Agencies are at widely varying stages of digitizing their collections, primarily due to funding limitations. Increasing visibility and access will require either new funding specifically for digitization or reduction of support for other user services (e.g., accessioning new objects, loan and visitor programs, education, and outreach).
- Data standards and digitization programs are designed by and for specific scientific disciplines, reflecting the terminology and knowledge frameworks of those communities. New and creative cross-over approaches to digitization will be needed to facilitate search and use of collections by professionals from other fields, such as those involved in all-of-government responses.

These and other issues will be topics considered by IWGSC in the near future. The results of those discussions will produce a Decadal Program of Work for IWGSC with associated goals, timelines, and implications for stakeholders of Federal scientific collections.

(Above) A kioea (*Chaetoptila angustipluma*), an extinct bird from Hawaii known from only four museum specimens in the world. This example from the National Museum of Natural History was collected during the U.S. Exploring Expedition (1838–1842). The thousands of ethnographic and natural history specimens brought back from the South Pacific and Pacific Northwest by the expedition formed the founding collections of the Smithsonian Institution. (Smithsonian)

References

[1] Original 2006 charter, https://iwgsc.nal.usda.gov/sites/default/files/IWGSC_Charter(signed)_2006_06_07.pdf. Information about the Interagency Working Group (IWGSC) can be found at the IWGSC Clearinghouse, http://iwgsc.nal.usda.gov

[2] IWGSC (2009), Scientific Collections: Mission-Critical Infrastructure for Federal Science Agencies, Report of the Interagency Working Group on Scientific Collections, https://usfsc.nal.usda.gov/sites/usfsc.nal.usda.gov/files/IWGSC_GreenReport_FINAL_2009.pdf

[3] IWGSC (2009) defined "object-based scientific collections" as follows: consist of physical objects that are preserved, cataloged, and managed by Federal agencies and other organizations for research and other purposes. In general, the contents of these scientific collections are documented and publicized with the goal of making the specimens available to other members of the research community for study.

[4] IWGSC distinguishes "institutional" from "project" object-based scientific collections. Institutional collections are generally managed by professional collections staff and preserved long-term for use by any qualified researcher. Objects in institutional collections are generally not consumed entirely by destructive sampling and analysis. In contrast, project collections are managed for near-term use by a defined set of researchers involved in specific research projects. Objects in project collections may be consumed entirely by destructive sampling and analysis.

[5] America COMPETES Reauthorization Act of 2020, 42 USC 6624, Public Law 111–358—January 4, 2011, https://www.congress.gov/111/plaws/publ358/PLAW-111publ358.pdf

[6] https://www.gbif.org/grscicoll

[7] Interagency Working Group on Scientific Collections (2013), Recommendations for Departmental Collections Policies, https://iwgsc.nal.usda.gov/sites/default/files/IWGSC_Recommend_Collxns_Policies_2013_01_28.pdf

[8] IWGSC Clearinghouse, http://iwgsc.nal.usda.gov

[9] Report published in 2020: D.E. Schindel and the Economic Study Group of the Interagency Working Group on Scientific Collections (2020), Federal Scientific Collections: Methods for Documenting Costs and Benefits (Washington, DC: Smithsonian Institution Scholarly Press), be https://www.dailybreeze.com/2008/09/09/house-panel-knocks-va-over-destroyed-lab-specimens/

[10] Scientific Collections International (SciColl; www.scicoll.org) was an initiative organized through the Global Science Forum of the Organization for Economic Co-operation and Development (https://www.oecd.org/sti/inno/global-science-forum.htm). SciColl's Secretariat Office was hosted by the Smithsonian Institution's National Museum of Natural History from 2013 to 2016.

[11] D. DiEuliis, K.R. Johnson, S. Morse, and D.E. Schindel (2016), Opinion: Scientific Collections Should Play a Much Larger Role in Infectious Disease Research and Response, Proceedings of the National Academy of Sciences 113(1):4–7, http://www.pnas.org/cgi/doi/10.1073/pnas.1522680112

[12] Associated Press (2008), House Panel Knocks VA over Destroyed Lab Specimens," Daily Breeze, September 9, 2008 (updated September 6, 2017), https://www.dailybreeze.com/2008/09/09/house-panel-knocks-va-over-destroyed-lab-specimens/.

[13] Office of Science and Technology Policy (2006), National Science and Technology Council, Committee on Science, Interagency Working Group on Scientific Collections Charter (Washington, DC: National Science and Technology Council), https://iwgsc.nal.usda.gov/sites/default/files/IWGSC_Charter(signed)_2006_06_07.pdf.

[14] National Research Council (2015), Preparing the Workforce for Digital Curation (Washington, DC: National Academies Press), https://doi.org/10.17226/18590.

[15] See Summary of the 2019 White House Summit on America's Bioeconomy, https://trumpwhitehouse.archives.gov/wp-content/uploads/2019/10/Summary-of-White-House-Summit-on-Americas-Bioeconomy-October-2019.pdf

[16] Schindel and the Economic Study Group of the IWGSC (2020).

[17] Schindel and the Economic Study Group of the IWGSC (2020), p. 21, Box 7.

[18] DOE Awards $19 Million for Initiatives to Produce Rare Earth Elements and Critical Minerals, Energy.gov (April 29, 2021), https://www.energy.gov/articles/doe-awards-19-million-initiatives-produce-rare-earth-elements-and-critical-minerals https://files.eric.ed.gov/fulltext/EJ1057153.pdf

[19] J.R. McConnell, M. Sigl, G. Plunkett, and J.P. Steffensen (2020), Extreme Climate after Massive Eruption of Alaska's Okmok Volcano in 43 BCE and Effects on the Late Roman Republic and Ptolemaic Kingdom, Proceedings of the National Academy of Sciences 117(27):15443–15449 (first published June 22, 2020), https://doi.org/10.1073/pnas.2002722117

[20] C. Guiterman, C. Baisan, N.B. English, J. Quade, J. Dean, and T. Swetnam (2020), Convergence of Evidence Supports a Chuska Mountains Origin for the Plaza Tree of Pueblo Bonito, Chaco Canyon, American Antiquity 85(2):331–346, https://doi.org/10.1017/aaq.2020.6

[21] J.A. Robinson, C.C. Kyriazis, S.F. Nigenda-Morales, A.C. Beichman, L. Rojas-Bracho, K.M. Robertson, M.C. Fontaine, R.K. Wayne, K.E. Lohmueller, B.L. Taylor, and P.A. Morin (2022), The Critically Endangered Vaquita Is Not Doomed to Extinction by Inbreeding Depression, Science 376(6593):635–639, https://doi.org/10.1126/science.abm1742

[22] The economic benefits derived from collections that are used in agricultural inspection are described in Schindel and the Economic Study Group of the IWGSC (2020), p. 24, Box 8.

[23] National Agricultural Statistics Service/U.S. Department of Agriculture, Orange Production Up Less Than 1 Percent from March Forecast, Crop Production (April 2022):6, https://www.nass.usda.gov/Publications/Todays_Reports/reports/crop0422.pdf

[24] USDA Ramp Project, https://tswv.caes.uga.edu/usda-ramp-project/history-and-economic-impact.html

[25] https://www.ars-grin.gov/Pages/Collections

[26] https://www.ars-grin.gov/

[27] T.G. Isleib, C.C. Holbrook, and D.W. Gorbet (2001), Use of Plant Introductions in Peanut Cultivar Development, Peanut Science 28(2):96–113, https://doi.org/10.3146/i0095-3679-28-2-11

[28] National Agricultural Statistics Service/U.S. Department of Agriculture, Milk Production, Disposition, and Income: 2020 Summary (April 2021), https://www.nass.usda.gov/Publications/Todays_Reports/reports/mlkpdi21.pdf

[29] C. Rexroad, J. Vallet, L.K. Matukumalli, J. Reecy, D. Bickhart, H. Blackburn, M. Boggess, H. Cheng, A. Clutter, N. Cockett, C. Ernst, J.E. Fulton, J. Liu, J. Lunney, H. Neilbergs, C. Purcell, T.P.L. Smith, T. Sonstegard, J. Taylor, B. Telugu, A. Van Eenennaam, C.P. Van Tassell, and K. Wells (2019), Frontiers in Genetics 10, art. 327, Genome to Phenome: Improving Animal Health, Production, and Well-Being—A New USDA Blueprint for Animal Genome Research 2018–2027 https://doi.org/10.3389/fgene.2019.00327

[30] Welcome to the ARS Culture Collection (NRRL) https://nrrl.ncaur.usda.gov/

[31] T.J. Torres-Cruz, B.K. Whitaker, R.H. Proctor, K. Broders, I. Laraba, H.-S. Kim, D.W. Brown, K. O'Donnell, T.L. Estrada-Rodríguez, Y.-H. Lee, K. Cheong, E.C. Wallace, C.T. McGee, S. Kang, and D.M. Geiser (2022), *FUSARIUM*-ID v.3.0: An Updated, Downloadable Resource for *Fusarium* Species Identification, Plant Disease 106(6), https://doi.org/10.1094/PDIS-09-21-2105-SR; databases available for download at https://github.com/fusariumid/fusariumid

[32] https://www.nist.gov/programs-projects/nist-biorepository

[33] https://www.fisheries.noaa.gov/national/marine-mammal-protection/national-marine-mammal-tissue-bank

[34] https://darrp.noaa.gov/oil-spills/deepwater-horizon

[35] National Water Quality Laboratory https://www.usgs.gov/labs/nwql

[36] National Water-Quality Assessment (NAWQA) https://www.usgs.gov/mission-areas/water-resources/science/national-water-quality-assessment-nawqa

[37] For additional information on feral swine, visit USDA APHIS Wildlife Damage Technical Series, History of Feral Swine in the Americas, https://www.aphis.usda.gov/aphis/resources/pests-diseases/feral-swine/sa-fs-history

[38] T.J. Smyser, M.A. Tabak, C. Slootmaker, M.S. Robeson II, R.S. Miller, M. Bosse, H.-J. Megens, M.A.M. Groenen, S.R. Paiva, D.A. Faria, H.D. Blackburn, B.S. Schmit, and A.J. Piaggio (2020), Mixed Ancestry from Wild and Domestic Lineages Contributes to the Rapid Expansion of Invasive Feral Swine, Molecular Ecology 29(6):1103–1119, https://doi.org/10.1111/mec.15392

[39] Earth BioGenome Project, https://earthbiogenome.org; H.A. Lewin, S. Richards, E.L. Aiden, and G. Zhang (2022), The Earth BioGenome Project 2020: Starting the Clock, Proceedings of the National Academy of Sciences 119(4) e2115635118, https://doi.org/10.1073/pnas.2115635118

[40] https://www.ncbi.nlm.nih.gov/bioproject/533106

[41] https://www.ncbi.nlm.nih.gov/nuccore?term=533106%5BBioProject%5D

[42] The USDA-ARS Ag100Pest Initiative: High-Quality Genome Assemblies for Agricultural Pest Arthropod Research https://www.mdpi.com/2075-4450/12/7/626/htm;
USDA Agricultural Research Service's Ag100Pest Initiative
https://www.ncbi.nlm.nih.gov/bioproject/555319

[43] P. Ravindran, A. Costa, R. Soares, and A.C. Wiedenhoeft (2018), Classification of CITES Listed and Other Neotropical Meliaceae Wood Images Using Convolutional Neural Networks. Plant Methods 14, art. 25, https://doi.org/10.1186/s13007-018-0292-9

[44] D.L. Haury and P. Rillero (1994), Perspectives of Hands-On Science Teaching (Columbus, Ohio: ERIC Clearinghouse for Science, Mathematics, and Environmental Education), https://files.eric.ed.gov/fulltext/ED372926.pdf

[45] D. DiEuliis, N. Bajema, and N. Winstead (2019), Biospecimens and the Information Landscape for Biodefense: Workshop Report (Washington, DC: Center for the Study of Weapons of Mass Destruction, National Defense University), https://wmdcenter.ndu.edu/Publications/Publication-View/Article/1941393/biospecimens-and-the-information-landscape-for-biodefense/; a product of the Interagency Working Group on Scientific Collections

[46] https://dwc.tdwg.org/

[47] C. Marshall (2018), Digitizing the Vast 'Dark Data' in Museum Fossil Collections, https://phys.org/news/2018-09-digitizing-vast-dark-museum-fossil.html#google_vignette

[48] https://www.gbif.org

[49] J.A. Cook, S.V. Edwards, E.A. Lacey, R.P. Guralnick, P.S. Soltis, D.E. Soltis, C.K. Welch, K.C. Bell, K.E. Galbreath, C. Himes, J.M. Allen, T.A. Heath, A.C. Carnaval, K.L. Cooper, M. Liu, J. Hanken, and S. Ickert-Bond (2014), Natural History Collections as Emerging Resources for Innovative Education, BioScience 64(8):725–734, https://doi.org/10.1093/biosci/biu096;
Biodiversity Literacy Undergraduate Education Network (BLUE), https://www.biodiversityliteracy.com

[50] Cook et al. (2014); BLUE, https://www.biodiversityliteracy.com; K.E. Powers, L.A. Prather, J.A. Cook, J. Woolley, J.L. Bart Jr., A.K. Monfils, and P. Sierwald (2014), Revolutionizing the Use of Natural History Collections in Education, Science Education Review 13:24–33; National Research Council (2015), Identifying and Supporting Productive STEM Programs in Out-of-School Settings (Washington, DC: National Academies Press), https://doi.org/10.17226/21740

[51] A.T. Peterson (2001), Predicting Species' Geographic Distributions Based on Ecological Niche Modeling, The Condor 103(3):599–605, https://doi.org/10.1093/condor/103.3.599

[52] Specify Collections Consortium, https://www.specifysoftware.org/
VertNet, http://vertnet.org/

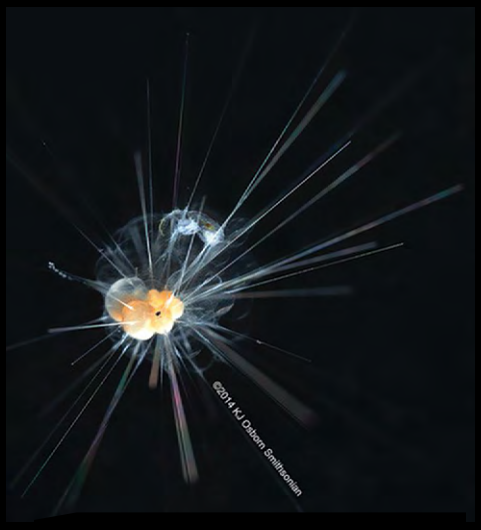
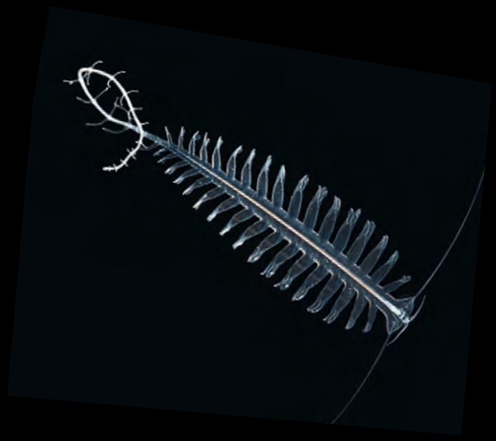
[53] For information about Advancing Digitization of Biodiversity Collections (ADBC), see https://www.idigbio.org/content/nsf-adbc-program-information

[54] EarthCube, Transforming Geosciences Research, https://www.earthcube.org/

[55] Schindel and the Economic Study Group of the IWGSC (2020).

[56] Examples are the Convention on Biological Diversity, the Nagoya Protocol on Access and Benefit Sharing, and the Convention on International Trade of Endangered Species.





©2014 KJ Osborn Smithsonian


©2012 KJ Osborn Smithsonian




©2014 KJ Osborn Smithsonian

©2015 KJ Osborn Smithsonian

©2015 KJ Osborn Smithsonian

Midwater animals collected and photographed using a remotely operated vehicle or Bluewater SCUBA by Department of Invertebrate Zoology curator Karen Osborn. The animals shown here range in size from a few tenths of an inch to over a foot in length. (Smithsonian/Karen Osborn)

Smithsonian
Scholarly Press