The Brave New World of the Digital Herbarium

Mobilizing the Past to Understand the Future

By CHARLES C. DAVIS AND AARON M. ELLISON

HERE IN THE NORTHEAST OF THE UNITED STATES, spring will soon be upon us, pulling us from the darkness and cold of winter's grip. Spring's exuberance—singing and nesting birds returning from their wintering grounds in more southerly latitudes, flowers bursting from dormant buds, leaves expanding in verdant green—indicate the turning of nature's internal calendar. The timing of these natural events—what biologists call phenology—is deeply tied to climate. And phenological observations are revealing that spring now starts much earlier than it did in the past. Every species responds differently to climate change, but the responses of most species remain unknown.

One of the ways we are beginning to understand the effects of climate change is through the study of botanical collections, whether in the traditional context of museum collections or groundbreaking digital herbaria. These collections represent a new hope of documenting and understanding nature, and how it may be altered irrevocably by climate change. They help us track phenological responses, whether in frosty New England or sweltering Brazil.

PHENOLOGY AS A TOOL FOR UNDERSTANDING SPECIES RESPONSE TO CLIMATE CHANGE

These phenological responses—or the lack thereof—have tangible effects on an individual's ability to reproduce and even the persistence of its species. Flowering of apple and peach trees, for example, is closely tied to winter chilling and spring temperatures; unseasonably warm spring months can trigger earlier flower production. That may be of relatively little consequence if temperatures remain steady and bees emerge to pollinate the flowers. But if hard frost returns after unseasonable February warmth, either the bees won't show up at the right time, or the flower's hidden ovaries will be damaged and fail to produce ripe fruit. These phenological effects of climate change matter to us as well; in the Northeast alone, revenues from apples can exceed one billion dollars.

PHENOLOGY IN THE TROPICS: A MISSING PIECE OF THE CLIMATE-CHANGE PUZZLE

Biologists who study the impacts of climate change have observed consistent changes in phenological events in the lives of many plants, insects and larger animals. But most of these observations have been made only in the last few decades, most frequently for trees, and predominantly in the United States and western Europe. There is much less observational evidence linking phenology and climate change in the tropics, which is home to the lion's share of Earth's biological diversity. For example, there are more than 14,000 species of trees in the rainforests of the Brazilian Amazon, the "lungs" of our planet.

Studying phenology and documenting phenological change in the tropics is remarkably difficult. The extraordinary diversity of tropical forests means that finding enough individuals of a single species can frustrate even the most seasoned field worker. Imagine this: a soccer-field-sized area of the Brazilian rainforest may include more than 650 tree species, which is more than the different kinds of trees than can grow in all of Canada and the United States combined. And in the rainforest, most of those species are likely to be represented by fewer than five individual trees, hardly a large enough

PHOTOS, ABOVE, BY AARON M. ELLISON. OPPOSITE PAGE; TOP PHOTO BY KYLE G. DEXTER. BOTTOM PHOTO BY AARON M. ELLISON.

sample size from which to draw robust conclusions.

Although rainforests get most of the attention of scientists and nonscientists alike, they are only one part of the rich diversity of the tropics. Brazil's Atlantic coastal forests are another biodiversity hotspot, as are the *tepuis*, the table-top mountains bordering Venezuela and the Guayanas that were the inspiration for Sir Arthur Conan Doyle's *Lost World*. And then there are the hot, dry grasslands of the *cerrado* and the southern temperate regions dominated by "southern pines," which are not anything like our northern-hemisphere pines, but are trees in their own family, the Auricariaceae (which includes the familiar monkey-puzzle tree, *Auricaria araucana*).

The origin of Brazil's remarkable diversity remains an open question, but hypotheses include unique ecological dynamics in climatically benign tropical environments, the ancient age of the tropics that has allowed plenty of time for new species to evolve, and the climatic extremes associated with dramatic topography that have allowed different species to evolve in isolation from one another. Sadly, large-scale agriculture and forestry with nonnative species (Photo C), mining and human population growth are destroying this diversity before much of it can even be described.

Finally, physiological linkages between climate and phenology have been little studied in the tropics. Temperature plays a large role in regulating phenological responses of both temperate and tropical plants, but in the frostless tropics, small changes or subtle variation in temperatures may have unexpectedly dramatic effects on phenology. Some evidence also suggests that temperature, precipitation and solar irradiation may interact in particular ways at certain times of the year, or even during previously uncommon El Niño events, to trigger bursts of flowering or fruiting.

Opposite page, left: The Amazon rainforest at the 1,158 square-mile Caxiuanã National Forest in Pará, between the Xingu and Anapu Rivers. Established in 1961 and accessible only by boat, Caxiuanã is the oldest National Forest in Brazil, and in addition to its unparalleled biodiversity, it is home to more than 100,000 people. Caxiuanã is managed by the Chico Mendes Institute for Biodiversity Conservation. The Ferreira Penna Scientific Station (Estação Científica Ferreira Penna) is located in the middle of the National Forest and hosts a number of international research projects on rainforest biology, ecology and the effects of climate change on tropical biodiversity and ecosystem processes.

Overcoming these and other challenges requires much more data than are available from individual, idiosyncratic field studies. To bridge this gap, we have partnered with Brazilian colleagues to mine a treasure trove of data that has rarely been explored for this purpose.

HERBARIUM SPECIMENS AS A SOLUTION

It is estimated that nearly 360 million pressed and dried specimens of plants and fungi are secured behind the closed doors of herbaria around the world (Photo D). For example, at the Harvard University Herbaria—the largest university-affiliated herbarium in the world—we care for about 5.5 million herbarium specimens. Botanists have been collecting specimens for herbaria since before the time of Linnaeus, who established in the mid-1700s our system of naming species. Herbarium specimens,

This page: Caxiuanã is one of the last refuges in Brazil of the majestic tauari tree (Couratari guianensis), which has been exploited extensively for its high-quality wood. Like other trees in the Brazil-nut family (Lecythidaceae), flowers of the tauari fruits are pollinated by large bees, and its nuts are eaten by parrots, monkeys and many other canopy-dwelling animals. The hyperdiverse Brazilian cerrado—one of the world's largest producers of livestock and agricultural products—is increasingly threatened by conversion to forest plantations, which often include the planting of nonnative species, such as Eucalyptus (in background). Photograph taken in northern Minas Gerais state(Photo C) The Harvard University Herbaria, with more than 5.5 million specimens, is the largest university-affiliated herbarium in the world. Each of the thousands of compact-shelving cabinets holds thousands of specimens dating back to the early 17th century (Photo D). Charles Davis, Director of the Harvard University Herbaria, uses the herbarium collections to study the evolution of plants and their responses to environmental change. (Photo F) Photograph by Aaron M. Ellison.

and similar mounted specimens of insects, skins of birds, and skeletons of many animals stored in museums such as Harvard's Museum of Comparative Zoology, are essential for describing species and characterizing where they live.

These specimens, and the field data associated with them, are the basis not only for the Linnaean categorization of nature, but also for untangling the intricate details of molecular biology in model plant species like *Arabidopsis thaliana* and reconstructing the evolutionary history of humans. When studying these collections (Photo F) it is hard not to appreciate the efforts of the countless individuals who have scaled mountains, forded rivers (Photo G), been stung by ants (Photo H), preyed on by leeches, and spent long days under tropical suns and rainstorms to help these collections grow and thrive.

TOWARDS A GLOBAL RESEARCH COMMONS

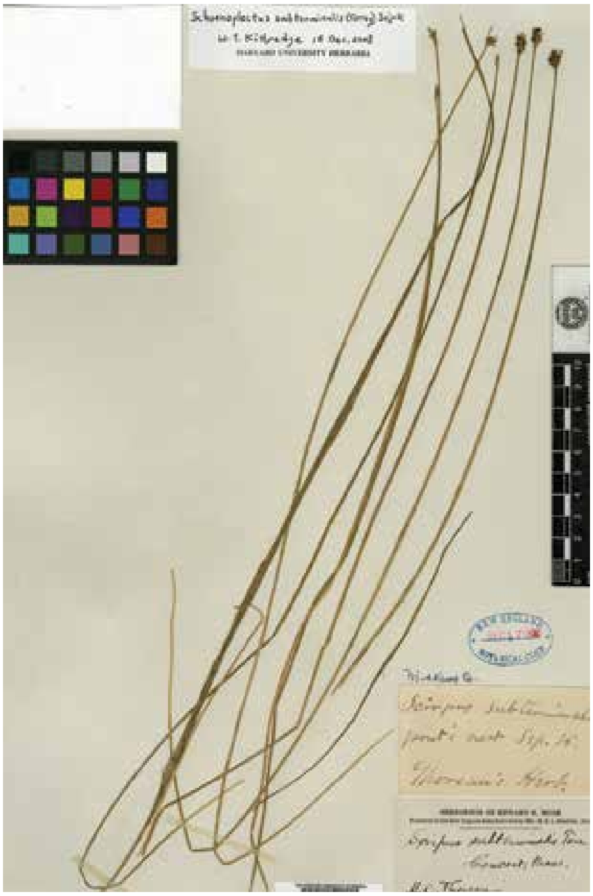
Just as phenology has been studied more in the global north than in the world's tropics, the geographic distribution of herbaria and zoological collections is uneven. Most large, well-curated collections are in the United States and Europe, from where, for centuries, scientists have traveled to tropical countries, collected specimens to document their rich biological diversity, and returned with these materials to their home institutions for cataloging and further study. Documenting and analyzing Brazilian plant diversity, for example, has for decades involved traveling to herbaria in Cambridge, St. Louis, New York or London rather than to Brazil itself. This has been true especially for studies of historical collections from the early days of botanical exploration, which include the first-named "type specimens" and that document diversity in years prior to urbanization and large-scale resource extraction.

For centuries, these collections and their associated data have remained largely off-limits, accessible only to small museum staffers who can accommodate academic visitors or send loans to researchers via global post. But all of this is changing rapidly with the emergence of new technologies and synergies between biologists, computer scientists and engineers. Digitization of museum specimens is creating a global, virtual museum, whose millions of specimens are available online for anyone to view and study.

Digitization involves scanning or photographing specimens in a collection and digitally transcribing the "metadata" associated with them. The specimens themselves are useless without these metadata—information about the specimen, including its scientific name (and changes in its name as understanding of its place on nature's family tree has grown), who collected it, when, where, and why it was collected, and other useful natural history information. Herbarium specimens also are a rich source of data about phenology and climate change. The

Top Photo: An arboreal nest of Azteca *chartifex* at Caxiuanã can contain more than one million aggressive, stinging ants (Photo H). Bottom Photo: Rainforests throughout the world are dissected by rivers and streams, both perennial and seasonal (Photo G).

PHOTOS, ABOVE, BY AARON M. ELLISON.



A specimen of *Scirpus subterminalis* collected on September 15, 1858, at Walden Pond in Concord, Massachusetts, by Henry David Thoreau. Thoreau's Herbarium is part of the Harvard University Herbaria. (Photo 1)

specimens often include the different life stages of plants—buds, flowers, fruits—which, when linked with local climatic data can reveal how species have been affected by past changes in climate.

Because the past is the key to understanding the future, institutions throughout the world are digitizing their collections and mobilizing them online. In northern countries, federal governments are supporting this effort, often in partnership with private donors. In the United States, for example, the Mellon Foundation was instrumental in funding the digitization of type specimens in major herbaria, including those at Harvard. In Brazil, where federal funding for scientific research has been slashed in recent years, the petroleum giant Petrobras and the multinational cosmetics firm L'Oréal, among others, have supported these efforts.

For Brazil, digitization also effectively repatriates its plant biodiversity. Since the early 2000s, the Rio Botanic Garden and its director, Rafaela Forzza, have spearheaded *Reflora*, a global effort, centered in Brazil, to digitize Brazil's botanical biodiversity.

Reflora began with European and American herbaria and was later expanded to Brazilian herbaria, each digitizing and aggregating their own collections. Like many partnering non-Brazilian institutions, the Harvard University Herbaria has virtually repatriated all its Brazilian plant specimens.

NEW TOOLS, NEW DIRECTIONS, NEW UNDERSTANDING

As it nears completion, *Reflora* now includes more than three million images and associated metadata. As an open-access virtual herbarium developed and supported by more than 400 Brazilian botanists and biodiversity specialists, *Reflora* is fast becoming the go-to resource for studying Brazilian plant diversity and its relationship to climate. Our own work has demonstrated that herbarium specimens collected in Massachusetts faithfully capture phenology and its association with climate stretching back nearly 150 years (Photo I). We have also worked with computer scientists to develop *CrowdCurio*, a software platform to engage citizen-scientists in the identification of critical phenological stages on specimens. This large-scale crowd-sourcing of phenological data-collection has demonstrated that non-expert citizen scientists can contribute to scientific research efforts alongside highly trained botanists; the result is datasets on phenology and climate change of incomparable size and global reach.

Just as the 15th- and 16th-century explorers mobilized sailing ships and the resources of kings to document the world's biodiversity, we are mobilizing the virtual resources of *Reflora* and other digital herbaria around the world with Big Data analytical tools to embark on a grand experiment aimed at understanding phenology and phenological change in the tropics. Our first effort is a multi-institutional one, spanning three institutions besides Harvard (Universidade Federal da Bahia, Universidade Estadual de Santa Cruz, and the Jardim Botánico do Rio de Janeiro) and a number of faculty with expertise in computer science, ecology, evolution, and education. And just as the early explorers made new discoveries in the "New World," so too are today's virtual explorers discovering the new patterns and processes of our rapidly changing world.

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