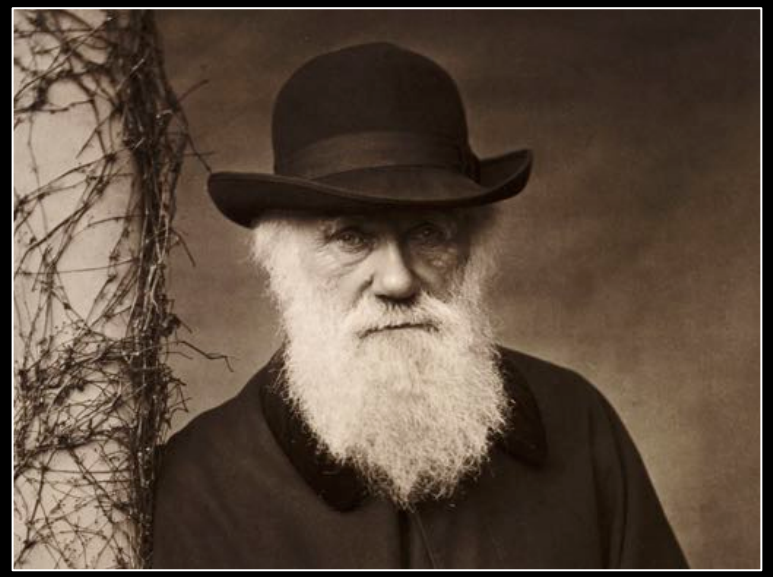
Endless Forms:
Herbarium Digitization of Imperiled Plants with Extreme Morphological Adaptations

California Botanic Garden Herbarium

There is grandeur in this view of life, with its several powers, having been originally breathed into a few forms or into one; and that, whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning endless forms most beautiful and most wonderful are being, evolved.

- Charles Darwin, The Origin of Species



Charles Darwin. English Heritage/
Heritage Images/Getty Images

Overview

Plants with unique morphologies – succulence, epiphytism, and carnivory/insectivory – that permit them to adapt to extreme habitats have fascinated botanists and plant enthusiasts for hundreds of years. Plants with unusual morphologies (e.g., cacti, orchids, agaves) are highly adapted to specific habitats but face serious challenges with changing climate regimes.

Overview

Only 36 areas on earth contain almost half of the world's plant diversity. Biodiversity hotspots occupy only 2.3% of the earth's land surface but harbor a high proportion of endemic species and house most undescribed plant diversity. Plants with unusual morphologies are highly specialized to live in specific environments (arid climates, forested habitats, and wet, low nutrient habitats) and are an important biotic component of biodiversity hotspots. Due to shifts in climate and land use, biodiversity hotspots are experiencing unprecedented species loss. Consequently, these plants face serious threats of changing climate regimes and the potential risk of extinction.

The Project

The Endless Forms Thematic Collections Network (TCN) aimed to build digital resources to document the vascular plants in 15 families that exhibit unique adaptations to extreme environments, and to promote scientific investigation and public understanding of these potentially imperiled plants. Through a recent award made by the National Science Foundation, the Herbarium at California Botanic Garden (RSA) enhanced the Endless Forms TCN by digitizing nearly 80,000 herbarium specimens representing all 18 families, some of which are especially diverse (cacti, agave, spurge) in California, a world biodiversity hotspot.

This online exhibit highlights the Herbarium's unique and project-relevant specimens as well as the efforts to digitize those collections.

Taxonomic Scope

The project focused on digitizing 15 vascular plant families exhibiting such traits as succulence, epiphytism, and carnivory.

SUCCULENCE

Succulent plants are characterized by their thickened plant parts (such as stems and leaves), often have waxy or hairy surfaces, and exhibit CAM (Crassulacean acid metabolism) photosynthesis.

Succulent plants are adapted to arid climates where water is a limiting factor, often for long periods, such as in desert climates.

Some plant families exhibiting succulence include:

- Agave family (Agavaceae)
- Milkweed family (Apocynaceae)
- Asphodel family (Asphodelaceae)
- Cactus family (Cactaceae)
- Spurge family (Euphorbiaceae)

EPIPHYTISM

Often called “air plants,” these plants grow with their roots exposed to the air and typically perch on another plant.

Distinguished from parasitic plants, epiphytes do not penetrate the epidermis of the plant that supports them and derives its nutrients and moisture from the air and precipitation.

Some plant families exhibiting epiphytism include:

- Arum family (Araceae)
- Pineapple family (Bromeliaceae)
- Orchid family (Orchidaceae)
- Pepper family (Piperaceae)

CARNIVORY

These plants have modified leaves that enable them to trap insects and other arthropods, which are then digested by the enzymes secreted by the plant.

Carnivory is hypothesized to be a response to nutrient deficient environments. Bogs are one such type of habitat.

Some plant families exhibiting carnivory include:

- Sundew family (Droseraceae)
- Bladderwort family (Lentibulariaceae)
- Tropical Pitcher Plant family (Nepenthaceae)
- Pitcher Plant family (Sarraceniaceae)

Notable Collections

Echinocereus viridiflorus var. *cylindricus*
Benson 15461
El Paso County, Texas

Cactaceae Collection

The Cactaceae collection is among one of the strongest collections held in the RSA Herbarium, owing to important historic and contemporary cacti specialists centered at and affiliated with RSABG. Most prominent are the collections made by the former Chair of the Botany Department and Director of the Herbarium at Pomona College, Lyman D. Benson (1909–1993). An active botanist in California and the western U.S., Benson is best known for his extensive work on Cactaceae. Benson's research on this family resulted in several books, including *The Cacti of Arizona*, *The Native Cacti of California*, and *Cacti of the United States and Canada*. Other historically relevant collections of cacti include those of David Griffiths (1867–1953) whose research centered on *Opuntia*.

Croton suberosus
Jones s.n.
Sinaloa, Mexico

Marcus E. Jones, 1852-1934

Botanist and mining engineer, writer and educator, photographer and traveler, Marcus E. Jones forged his own path over the course of a remarkable career that spanned more than fifty years and covered half of the United States and parts of Mexico. He described over 900 species 53 of which are within five of the 15 families in the Endless Forms TCN . Jones' influence on botany is great, and his works and supporting materials (specimens and archives) are continually sought. California Botanic Garden is the locus of the Marcus E. Jones plant collections and archives. Jones' Herbarium, estimated at ~100,000 specimens, includes his own collections and those of the botanists he traded specimens with. Jones sold his herbarium, library, and archives to Pomona College in 1923 and later the collections became part of the CalBG Herbarium during the formal transfer of that collection.

Asclepias speciosa
Jones s.n.
Utah County, Utah

One important aspect of Jones' work is that, unlike many of his contemporaries, he undertook general collecting, choosing to document the complete flora of areas he explored rather than focusing on one or a few groups of plants or plants likely to be new to science. This collection is of key value in providing a comprehensive picture of species distributions, particularly of many rare, threatened, and sensitive species Jones collected (such as in families Agavaceae, Apocynaceae, Cactaceae, Crassulaceae, and Euphorbiaceae) included in the Endless Forms TCN.

Jones botanizing in 1910 with colleagues

Left: *Dudleya* specimen, collected by Thorne.
Right: Thorne pressing a plant specimen.

Robert F. Thorne Collections

A major contribution to the project is the collections of Taxonomist and Curator Dr. Robert F. Thorne (1920–2015). Thorne's botanical interests and publications were broad and diverse, with notable contributions to our knowledge of the remarkable flora of Southern California. He is best known nationally and internationally, however, for his synoptic work to develop a classification system to accommodate all flowering plants. Thorne's synoptic work on flowering plants was supported by decades of field trips and active collecting, including some of the most botanically significant parts of the world. Thorne's collections number more than 65,000; these have special significance both because many are from areas (New Caledonia, Lord Howe Island, Baja California) and of taxa that are poorly represented in U.S. herbaria in general, and because they provide the factual basis for Thorne's synoptic classification of flowering plants.

Aleurites moluccana
Wheeler 12613
Sri Lanka

Euphorbiaceae Collection

Among RSA's noteworthy collections is that of the large and diverse family Euphorbiaceae, with 6,745 species worldwide. RSA's holdings total nearly 16,000 specimens, with nearly global representation. Important collectors who have made significant contributions to the Euphotbiaceae collection include Marcus E. Jones, Robert F. Thorne, and Louis Cutter Wheeler. Botanist and professor at the University of Southern California, Louis C. Wheeler (1910–1980) is best known for his work on Euphorbiaceae. His publications include a revision of the *Euphorbia polycarpa* group of the southwestern U.S. and Mexico and revision of *Euphorbia* subgenus *Chamaesyce* in Canada and the U.S. He also provided treatments on taxa in Euphorbiaceae for the Flora of Ceylon project. Wheeler's collection includes specimens from throughout the U.S., with emphasis on Euphorbiaceae from Sri Lanka.

Yucca capensis
Lenz 9310
Baja California Sur, Mexico

Agavaceae Collection

Agavaceae, a family of nine genera and ~300 species found in arid to semiarid habitats primarily in southwestern U.S., Mexico, Central and South America, is an excellent model system to address hypotheses of diversification, hybridization, and morphological adaptation. Many species of Agavaceae have exceedingly narrow geographic ranges, often endemic to a particular region. RSA's collection is especially noteworthy, due in large part to important collections made by several botanists and specialists who worked on Agavaceae, including Marcus E. Jones, Howard S. Gentry, Philip A. Munz, and Lee W. Lenz, among others. Lenz documented for the first time naturally occurring hybridization between baccate-fruited and capsular-fruited species (*Yuccca elata* x *Y. madrensis*, *Y. baccata* x *Y. madrensis*). Lenz also examined seed dispersal and distribution of the iconic Mohave Desert species, the Joshua tree (*Yucca brevifolia*).

Left: Carlquist among Silversword collections in Hawaii.
Right: Specimen of Drosera cistiflora collected by Carlquist from South Africa.

Sherwin Carlquist Collection

Dr. Sherwin Carlquist (1930–2021) contributed a great deal to the geographic breadth and taxonomic diversity of RSA over the course of his distinguished career. Carlquistis best known for significant contributions in systematic, phylogenetic, and ecological plant anatomy and structure, and studies of island plant diversity, and has published prolifically on these subjects. Because of his systematically based research goals, Carlquist collected voucher specimens from some of the most biodiverse and undercollected parts of the world, many of which are otherwise not well represented in herbaria. Especially noteworthy are his voucher collections and research on several Endless Forms families, including many endemic taxa in Araceae, Droseraceae, Nepenthaceae, and Orchidaceae. With colleague Allen Lowrie, Carlquist described nine new taxa of *Drosera* from Australia, the type specimens of which are housed at RSA

Digitization

Applying a barcode to a specimen

Barcoding

Barcoding, where a barcode is adhered to each specimen, is the essential first step in the digitization workflow.

Over the three-year duration of the project, interns, staff, and students from California Polytechnic University, Pomona barcoded 78,231 specimens.

Curation

Some specimens require curation prior to digitization, including adhering archival fragment packets for specimen material and for rehousing photographs accompanying some specimens.

Intern Garrett Goodrich, glues archival packets to specimens to rehouse photographs accompanying specimen material.

Intern Maheen Khan images specimens for the Endless Forms project

Imaging

Once specimens have been barcoded, they can then be imaged. Specimens are placed into a lightbox and a high resolution image is captured using an overhead digital camera. Skeletal data is captured from the specimen during the imaging process, including taxon name and geography.

Images of specimens are checked for quality, color aberrations, and focus, then imported to the Herbarium's live managed database through the Consortium of California Herbaria 2 portal (CCH2; https://cch2.org/portal/) where they can then be transcribed.

Interns, staff, and graduate students imaged 79,139 specimens.

Intern Ivy Jordan transcribes specimen data from the image into the specimen record on the Herbarium's live-managed database

Data Transcription

Images of specimens are retrieved from the CCH2 portal by performing a simple query on taxon name and geography and specimen data is entered into the record from the image.

64,509 specimens were transcribed by interns, graduate students, and staff.

Intern Amanda Aguilar georeferences specimen records.

Georeferencing

Georeferencing – translating a location description from the specimen label into a mappable representation by assigning latitude and longitude coordinates – was the final step in the digitization process.

Interns, graduate students, and staff georeferenced 31,293 project specimens.

Student Participation

Interns working on the Endless Forms Project, clockwise from top left: Ray Vilchis, Amanda Aguilar, Maheen Khan, Garrett Goodrich

Integral to the project were the activities that involve student participation, which formed about 90% of the workforce. The project provided training for a total of two graduate students and six undergraduate interns. Several Herbarium Curatorial Assistants also participated in digitization steps. All participants learned various aspects of collections management and digitization techniques, as well as opportunities to participate in several presentation-style workshops geared toward connecting students and recent college graduates to collections, digitization, and the plant sciences.

Students from Mt. San Antonio Community College barcode specimens in exchange for herbarium tours

Interactive Tours

The Herbarium routinely provides behind the scenes tours of the collection to undergraduate institutions in the Greater Los Angeles Metropolitan area. One option we provide is the opportunity for classes to waive their tour fee in exchange for volunteering their time to barcode specimens. Tours that provide hands-on experiential learning shift the dynamics of a passive tour into an active one, where students can work directly with specimens and gain an increased appreciation for the value of natural history collections.

Staff Picks

Staff Picks was created to highlight a noteworthy specimen in the Herbarium from the viewpoint of one of the curatorial staff. The specimen selected may have been chosen for it's aesthetics, history or science behind the specimen, or intriguing story.

I found this specimen while adding barcodes to the Yucca specimens in our collection for the Endless forms TCN grant and was immediately overwhelmed with curiosity. It wasn't clear when this specimen was collected, who collected it, why they collected it, or why it was filed under Yucca brevifolia. How could this flat sheet amount to a Joshua Tree herbarium specimen? There were two specimens like this, and their brief labels describe them as "wrappers" to protect young citrus trees from both sun damage and frost. After a quick and relatively unhelpful google search for "Joshua Tree Wrappers" it was clear that this was a matter for the archives, and I reached out to find a time to visit CalBG's library. Thankfully my searching there was much more fruitful and, with Irene Holiman's help, I was able to piece together a much clearer picture of how these odd specimens found their way into our collection.

--Garrett Goodrich, intern 2022

Availability of specimen data through digitization facilitates research to further explore morphological adaptations, patterns of diversification and endemism, and ecological niche evolution of these highly unusual plants. The digitization of Endless Forms plant specimens enables researchers to study contemporary patterns of distribution and predict future environmental change, as well as help to mitigate negative impacts such as climate change and shifts in land use, and importantly, to implement conservation measures on these imperiled plants.

Acknowledgements

Interns spring 2022. Left to right: Ixchel Maston, Ivy Jordan, Stephanie Quintanilla, Maheen Khan, Karrie Chung

This project was made possible by the following participants:

Mare Nazaire, Administrative Curator
Carrie Baldwin, Digitization Manager
Erin Berkowitz, Workroom Manager
Rhay Flores, Workroom Manager
Bryana Olmeda, Curatorial Assistant
Sydney Kaye, Curatorial Assistant
Maheen Khan, Curatorial Assistant
Lauren Wright, Intern
Ray Vilchis, Intern
Garrett Goodrich, Intern
Amanda Aguilar, Intern
Christian Caro, Intern
Robert Comito, Grad RA
Nina House, Grad RA
Cal Poly Pomona students, Form & Function in Plants

This work was supported by the National Science Foundation, Advancing Digitization of Biodiversity Collections Program, DBI 2001358