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The Importance of Botany and Archival Studies in Modern Society

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Information accumulation:

The evolution of herbaria and botanic gardens in Spain and the United States and their role in modern botany

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Introduction

Throughout history, the natural world has inspired curiosity in humans. In sixteenth century Europe, the field of botany arose as an important branch of natural history. Early botanical efforts consisted of the documentation of plant species encountered and detailed descriptions of many of their characteristics (Ogilvie, 2006). The promising progression of botany convinced more and more European scholars to study plants either in addition to their primary disciplines or as their main field. Their work manifested as manuscripts and live and dried specimens that were brought back to their home countries for display and analysis (Bleichmar, 2012). Consequently, institutions were established across the continent to house those physical materials. Botanic gardens were begun as collections of living plants cultivated for their novelty, economic value, and academic potential. Herbaria were started as groups of dried and pressed plant specimens collected during expeditions or travels that were housed together as the basis of taxonomy.

Over the last five centuries, historical patterns have shaped the uses of herbaria and botanic gardens in Spain and in the United States. While they were established in Spain as collections that showcased the wealth of resources and knowledge of the royal state, botanic gardens and herbaria transformed into symbols of imperial science and were the predecessors to the country's current research institutions (Engstrand, 1997). In the Americas, as several European powers surveyed the western hemisphere, the creation of domestic herbaria was hindered by early explorers sending their specimens back to their home countries (Brendel, 1879). As people living in American colonies became more interested in studying plants, botanic

gardens and herbaria were eventually established to support the study of native flora (Pennell, 1935).

Although the emergence and early functions of these institutions differ between the two areas, herbaria and botanic gardens in both locations have evolved to serve important roles in modern science. The rapid growth and expansion of herbaria in particular during the twentieth century has revolutionized the study of plants across the world and encouraged the development of novel methods of using dried specimens in contemporary research. As a result, herbaria have become a tool for answering a range of research questions and for formulating new research questions. In addition, the trend of convergence between herbaria and botanic gardens has increased the accessibility to and the longevity of the information they preserve. Analysis of herbaria and botanic gardens from their origins to the present yields three insights into their importance to the field of botany. First, cultural and historical patterns of Spain and the U.S. influenced the history and development of herbaria and botanic gardens in each country. Second, differences in the evolution of Spanish and American herbaria and botanic gardens shed light on distinctions in the histories of the two countries, but the expansion of botany has led these institutions in both countries to become more similar over time. Finally, herbaria and botanic gardens have been essential to the success and breadth of that expansion, which maintains their relevance and allows people to continually find new ways to use their materials.

I will illustrate these three points by first outlining the history of herbaria and botanic gardens in Spain and the United States, tracing their expansion and transformation through the twentieth century, and then exploring the ways these institutions are currently used in botanical research.

Imperial Origins

In Europe, herbaria and botanic gardens were created in conjunction with the rise of botany as an academic discipline. Beginning in the fifteenth century, scientific interest was renewed in the European powers, and they invested in building upon previous knowledge in order to widen their intellectual scope of the world (Ogilvie, 2006). The genesis of herbaria and botanic gardens in Spain followed much later, and supported the country's growing study of plants in Spain and interest in gaining economic power.

By the mid-fifteenth century, much of Europe was focused on the revitalization of studying the natural world. This was spurred by the invention of the printing press, which enabled the works of prior naturalists to circulate throughout scientific communities (Egerton, 2012). Translations of Dioscorides' *Materia medica*, Theophrastos' *De causis plantarum* and *Historia plantarum*, and Pliny's *Naturalis historia* were just a few of the works printed at the beginning of the modern era (Egerton, 2012). The Renaissance state of mind had helped renew intellectual curiosity about the natural world, and the desire to expand upon the knowledge of those former works gave rise to the emergence of natural history as a discipline distinct from medicine and philosophy (Ogilvie, 2006).

As access to scholarly material increased and the academic community's interest in plants grew, botany came to be a component of natural history. Italy was the first country to organize lectures in botany at its universities in Padua (1533) and Bologna (1534) (Egerton, 2003). Luca Ghini (1490-1556), professor of medical botany at the University of Bologna, pioneered the establishments of botanic gardens in Pisa and Florence, developed the plant press, and assembled the first herbarium (Egerton, 2003). The purpose of early gardens was to support the collection,

cultivation, and study of plants. During the Renaissance, investigation of plants revolved around description; naturalists sought to improve the "inaccurate or inadequate descriptions of the natural world that had been bequeathed from antiquity" and rectify the inconsistency between the accounts they read and the observations they made (Ogilvie, 2006). Early European herbaria reflected this initiative: they were intended to be central resources for taxonomic study and species discovery, to facilitate species identification, to serve as a comprehensive archive of biodiversity for other academic fields, and to allow a means for the verification and replication of botanical research (Heberling & Isaac, 2017).

The development of botany in Spain began several centuries later than in other European powers. In the sixteenth century, the Spanish Renaissance had revolved mostly around the acquisition of new territory in the western hemisphere, the implementation of Catholicism throughout the empire, and the academic exploration of literature and arts (Bleichmar, 2012). The empire's intellectuals began to advocate for state investment in science for its innate importance during the eighteenth century, and the crown responded by incorporating science into its program of royal governance. Exploring scientific inquiry was embraced alongside unifying the Spanish colonies and expanding the empire's economy (Engstrand, 1997). As early as the first half of the eighteenth century, King Felipe V (1700-1749) requested that "all state officials in the Spanish empire…watch for unusual specimens of plants, animals, and minerals and send them to Madrid" (Engstrand, 1997). The Real Academia Médica Matritense had been founded in 1734 to further the studies of medicine and pharmacy, and the institution's naturalists soon advocated for it to embrace the study of plants as well (Armada et al., 2005). This was the first

time that botany was incorporated into Spanish academia, and it was embraced by the crown as a means of securing support for the empire's growing worldly prowess.

With several prominent scholars in support of botany and the need to establish a physical space for materials, the establishment of a botanic garden and herbarium served the academic community as well as the crown. The Real Jardín Botánico or Royal Botanic Garden of Madrid was founded in October of 1755, and its fundamental purpose was to promote dissemination of the study of plants (Armada et al., 2005). The garden was also a symbol that showcased the geographic reach of the Spanish empire with exotic new world species. José Quer, the garden's first director, was a surgeon by training but took interest in plants for their medicinal properties (Armada et al., 2005). As his career in botany evolved, he published the *Flora Española*, or *Flora of Spain*, between 1762 and 1764, which became a gateway for other Spanish scholars to study local plants and necessitated the garden. Quer's *Flora of Spain* was a combination of unfinished work from another collection and analysis of specimens collected during his own travels across the Iberian peninsula that cataloged and described the flora of the Spanish empire (Armada et al., 2005). 2,000 of the physical dried specimens he described initiated the herbarium of the Royal Botanic Garden in 1762. This establishment of botanic gardens and herbaria satisfied the academic community's desire to study plants and appeased the Spanish crown in three ways: both institutions helped the empire keep up with other European states and their development of empirical science, cultivated more scientific minds that could create a physical display of its scientific accomplishments to impress visiting scholars and bureaucrats, and served as a vessel for learning how to exploit plants for economic power.

By the late eighteenth century, emerging botanists of the Iberian peninsula sought to broaden the scope of their work and find ways to use plants to the empire's economic benefit. The establishment of viceroyalties in the New World during the fifteenth and sixteenth centuries presented a plethora of resources to the Spanish empire. It had witnessed other empires successfully maintain powerful monopolies on certain products, such as that of the Dutch on the spice trade, provoking interest in the Spanish crown to create one of its own. In 1770, four viceroyalties comprised the empire. Much of the South American continent was split into the viceroyalties of New Granada, Peru, and Rio de la Plata. The viceroyalty of New Spain consisted of Central America, western North America, and the islands of Cuba, Puerto Rico, and Hispaniola (Bleichmar, 2012). At this point, physicians and surgeons who were interested in plantsl began to steadily approach the monarchs and request funding for their naturalist projects, which tended to involve voyages to the Spanish territories. State officials recognized the potential these voyages held for finding species to exploit and gaining more capital.

In response to these requests, the Spanish Crown invested in three botanical expeditions for the primary purpose of inventorying the flora of the viceroyalties of Peru, New Granada, and New Spain (Bleichmar, 2012). Hipólito Ruiz and José Pavón led the exploration of Peru from 1777-1788. The expedition to the New Kingdom of Granada was piloted by José Celestino Mutis and lasted from 1783-1816. Martín de Sessé and José Mariano Mociño directed the expedition to New Spain from 1787-1803. Casimiro Gómez Ortega, then director of the Royal Botanic Garden, oversaw the organization of these expeditions and employed several naturalists among the three voyages to study and characterize the flora of the Spanish Americas. They recorded

observations, gathered seeds, plants, insects, and animals, shipped collections back to mainland Spain, and portrayed their encounters in thousands of illustrations (Bleichmar, 2012).

José Celestino Mutis, director of the second royal botanical expedition, is representative of the naturalists involved in these endeavors supported by the crown. Mutis had studied medicine and surgery and served as a physician to the royal court, but in the 1750s, he learned of the Royal Botanic Garden and the Cabinet of Natural History in Madrid and became interested in the benefits that economic botany could have for Spain (Ramón Marcaida & Pimentel, 2014). In the early 1760s, Mutis repeatedly proposed a naturalist project to the viceroy of New Granada and to King Charles III, highlighting Spain's lack of advancement with botany and the untapped potential of new world species. Mutis was a self-taught Linnean botanist, "concerned about systematization and nomenclature," but he was far more focused on the commercialization of natural resources and economic success for the peninsula; he recognized the financial boost that exploiting new world species such as quina, cinnamon, cochinilla, and guayacan could have for Spain (Ramón Marcaida & Pimentel, 2014). The funding of his expedition showed that imperial officials believed that their investment in botany was worth the potential economic success that it could bring.

Although the efforts of these voyages did not always end with successful monopolies on the trade of target plants, the materials collected were important contributions to the botanic institutions in Spain. The travelling botanists were often under orders from Ortega to "collect species in the form of seeds and dried plant specimens mounted on paper" and "send living plants, bulbs, shoots, and grassy sod back to Spain" for studying the material they encountered (Steele, 1964). As an example of the scope of diversity found in the new world, Mutis returned to

Spain with assembled herbarium sheets and more than 7,000 botanical portraits and illustrations of floral anatomies (Marcaida & Pimentel, 2014). These collected materials were added to the Royal Botanic Garden and herbarium and expanded the breadth of information they held.

At the same time, Ortega and Antonio Palau, a professor of botany, forged relationships with other scholars around the world to supplement the work of the voyaging naturalists (Bleichmar, 2012). By 1794, correspondence was established with a total of 86 men including pharmacists, physicians, priests, and professors who lived in mainland Spain, the Americas, and other European countries. In exchange for acknowledgement as contributors, collaborators supplied the Royal Botanic Garden and its herbarium with seeds, plants, and lists of novel specimens for study and cultivation, which bolstered its repository of knowledge (Bleichmar, 2012).

The importance of botany in Spain was clear in the eighteenth century as a discipline that could elevate the empire's academic and economic status. The prior development of botany and establishment of botanic gardens and herbaia in several European powers reflected their imperial successes, and the Spanish empire sought the same. The formation of these institutions around the world was entangled with pursuits of power, knowledge, and economy. This pattern influenced the rise and early history of herbaria and botanic gardens in Spain, where upon their establishment they were part of the empire's quest for worldwide authority.

Rise in North America

The Americas experienced a different genesis of botanic institutions since the continent was controlled by European powers during much of the early development of botany as a subject

of study. Spanish viceroyalties occupied parts of North America, Central America, and much of South America, and the British empire controlled other parts of North America, but neither power was overtly concerned with improving science for the benefit of its territories. North America represented the colonized perspective as opposed to playing the colonizing role. The relatively late founding of the U.S. and the country's lack of imperial interest are two pieces of its history that strongly influenced the development of its herbaria and botanic gardens. The presence of Europeans on the continent for so long and their subsequent withdrawal left the country without well developed botanic goals and institutions. Collection efforts of early American botanists were much more geographically scattered compared to those of the Spanish, and the institutionalization of botany began as a result of smaller, more niche collections. Later, consolidation and more concerted work with gathering botanic materials created the largest herbaria and botanic gardens of the U.S.

Early records show that the study of American plants was heavily dependent on visiting European scholars and small collectors. *Canadensium Plantarum Historia* was the first European published book that included information about North American flora in addition to accounts of species from Spain and the Eastern hemisphere. It was written in 1635 by the French physician Jacques-Philippe Cornut from his studies of species brought back to Paris (Centre for Canadian Historical Horticultural Studies, 1985). No other substantial literature was published on North American flora until the 1670s, when a few accounts of American flora were given based on voyages to New England (Brendel, 1879).

Throughout the next century and a half, many naturalists hailing from England, France, Sweden, Austria, and more travelled to various parts of North America to collect specimens and

write about the flora they encountered. The plants and information were brought back to the scholars' respective countries so that they could make use of motherland facilities and minds in examining novel species. By the mid-eighteenth century, Carolus Linnaeus' inventory of all known plants was composed of over 8,500 species; 1,075 of them were North American natives that had been brought back to Europe (Brendel, 1879).

In 1730, John Bartram established the first botanic garden on the continent in Philadelphia, Pennsylvania (Middleton, 1925). Bartram was a colonial farmer with no formal education, but plants fascinated him. He started the garden with species he found near his farm, and soon traveled around the area, collecting seeds and plants to expand his collection (Precup, 1976). Herbaria weren't founded in North America until almost a century later (Jones & Meadows, 1948). The oldest institutional herbarium of the U.S. was located at the Academy of Natural Sciences in Philadelphia (now Drexel University), and it formed in 1812 to support the work of American botanists and house their collections. By 1857, its collection consisted of about 46,000 specimens from around the world and over 90,000 particular to North America. The Academy's focus in botany had shifted to the native flora studied by American botanists during their travels around the country, and the herbarium consisted of specimens they brought back with them (Pennell, 1935). Only four more herbaria were established during the first half of the nineteenth century, located at Amherst College (1829), the Boston Society of Natural History (1830, now known as the Museum of Science), the University of Michigan (1838), and the Charleston Museum in South Carolina (1850) (Jones & Meadows, 1948). American plants were the priority of these herbaria at their founding: the majority of their collections were specific to the local flora of their respective regions, with professors and botanists collecting to improve

knowledge of native species (Hitchcock, 1863; Johnson 2004; Allen & Martin, 1922; Sanders & Anderson, 1999).

While these collections are the oldest in the country, they did not become the largest or most cutting-edge institutions for American botany. Founded in 1850, the United States Botanic Garden initially served as a holding place for live plants brought to Washington, D.C. by Charles Wilkes as a result of expeditions to South America, Australia, Asia, the South Pacific, and the Pacific Northwest of America (Shimizu, 2006). Almost half a century later, in 1891, the New York Botanical Garden (NYBG) was founded by Nathaniel Britton, a professor of botany and geology at Columbia University, and Elizabeth Britton, a scholar of mosses. The Brittons modeled NYBG after the Royal Botanic Gardens at Kew, making its focus cultivating landscaped plants, operating as an institution of public education, and participating in international plant exploration and research (Long, 2006).

The herbarium at the NYBG is one of the largest in the world at present (Holmgren et al., 1996). The collection began with 600,000 specimens from Columbia University and grew with the accumulation of other historical, private, and smaller university collections. Throughout the twentieth century, as about 500,000 specimens were added when consolidating smaller collections and NYBG botanists continued collecting specimens for their own research, the NYBG herbarium rose to prominence as an institution that currently houses data from all over the world and represents a large portion of recent work in documenting the world's flora (Holmgren et al., 1996).

The historical context of the U.S. in the early nineteenth century affected the development of botany and the establishment of herbaria and botanic gardens in the country.

European control of the continent delayed American interest in empirical science, but botanists of the early 1800s maintained collections of living and dried plants that were focused on regional flora. Through the middle of the century, these individual collections were distributed throughout the eastern part of the country, and combining many of the dried specimens led to the institutionalization of herbaria. Since then, many American herbaria and botanic gardens have expanded their scopes and experienced tremendous growth.

Modern Status

During the twentieth century, worldwide interest in botany underwent an extreme growth spurt. The systematization of taxonomy was at its peak importance, and the work of herbaria and botanic gardens completely embodied that branch. Herbarium founding occurred in both Spain and the U.S., and botanists continued to build collections as an important part of their work. The increases in the number of collections and the amount of species held by many coincided with the overall evolution of botany, and herbaria played an essential role in the field's resurgence in the latter half of the century.

Modern herbaria and botanic gardens are the culmination of the study of plants over the last several hundred years, through periods of expansion and lull. Time has brought the founding of many herbaria and gardens, closures of some, consolidation into larger facilities, and changes in their accessibility in both countries. The physical persistence of these institutions through the lull and revival of botany in the late twentieth century validates their authority in the field and ensures their livelihood for years to come. The movement away from taxonomic botany during the 1970s toward more experimental branches presented potential problems for the future of

herbaria and botanic gardens. Their ability to adapt to this kind of change had not been explored until their traditional utility was jeopardized by the unknown future directions of botany. In 1969, Stanwyn Shetler, a botanist associated with the National Museum of Natural History, outlined herbaria in particular as institutions afflicted with concerns about the relevance of botany and the maintenance of their physical establishments. He expressed doubt in herbaria as "anachronism[s] in the modern scientific world" that would not survive following the conventions of the past (Shetler, 1969-70).

Shetler reported concerns for the future of herbaria, but they did not lead to the end of these institutions in the long run. It was expected that herbaria would ultimately fall victim to their inability to "[keep] up with the times" and the changing nature of the discipline of biology (Shetler, 1969-70). From the 1930s to the 1970s, the number of herbaria established annually was on a downward trend, and engagement was also expected to decline. However, Shetler did not take into account a number of factors that have since allowed herbaria to thrive.

In the latter half of the twentieth century, biology was parting from the classic divisions of zoology and botany in favor of the systematic approach based on evolutionary relationships. Developments in experimental molecular biology were also receiving more attention than traditional description of species (Shetler, 1969-70). At the time, this drastic change seemed to uproot and overhaul the organization system that herbaria had accomplished as one of their central functions. Not considered is the capability of that information to be successfully repurposed in new branches of botany. The information stored by herbarium specimens—including dates, locations, descriptions, and the species themselves—had the

potential to be exploited in a number of ways and serve as a physical record of the discipline's progression.

In the late 1960s, Shetler proposed consolidating institutions in cities to mitigate the uncertainty of the future role of herbaria with the organizational rearrangement of botany as a discipline and much attention on developing novel research methods. With an average of 1.4 herbaria present per city in 1969, supporting more than one such institution in a single city seemed inefficient and wasteful. The descriptive purpose of their materials might have been strengthened by compiling lots of specimens at one central herbarium per city to provide thorough descriptions of lots of flora, and consolidation could allow them to maximize their financial resources in staffing and maintaining buildings. This outcome was preferable to the potential obsolescence that herbaria faced at the time, but in the long term, it would have limited accessibility to botanic information. As botany is a discipline that thrives when it finds ways to engage the public and show people what it has to offer, having more than one herbarium per city and smaller herbaria in suburban or rural areas only increases the opportunities for encounters and the potential for the spread of the information they cultivate. Having more herbaria could mean the ability to hold more data about plants and the opportunity to train and employ more local experts, which may translate to an increase in the study of species or regions that had previously been overlooked or underrepresented.

Data from editions of *Index Herbariorum* (*I.H.*) illustrate that there was actually a revival of herbaria that was concurrent with those fundamental changes to the field of botany. Established in 1935, *I.H.* profiles and tracks the presence of herbaria throughout the world. As chronicled by the 1964 edition of *I.H.*, 933 active herbaria existed at the time (Shetler, 1969-70);

as of late 2019, there were 3,324 registered active herbaria in the world that contained over 392,000,000 dried specimens (Thiers, 2020). This tremendous jump in the number of operational institutions reflects the reality that herbaria were able to remain relevant to botanic study through welcoming participation and expanding as a result of it. At least 12,000 staff members are currently employed across all registered herbaria. The U.S. is home to 686 herbaria and almost 79,000,000 specimens, while 56 herbaria containing over 6,000,000 specimens are found throughout Spain (Thiers, 2020).

Botanic gardens faced less criticism in the late twentieth century, resulting in their steadier presence. With their status as public spaces, they were able to consistently bring people in and hold the attention of the public. They had served as living representations of plant taxonomy, but as botany moved away from that focus, their adaptation was smoother. Researchers needing live plants continued to consult botanic gardens, and engagement with their communities kept botanic gardens in the public eye as vital institutions of many cities. A survey given by the International Association of Botanic Gardens in 1967, an estimated 600 botanic gardens existed worldwide (Fletcher, 1967). Only 125 of those 600 reported taxonomic activity with documenting and naming their species. Today, there are over 2,500 botanic gardens worldwide that support collections of living plants (Dodd & Jones, 2010). About 40 are located in Spain, and up to 500 are in the U.S. (GardenSearch).

Today, 35 of the 100 largest herbaria in the world are located in the U.S. The majority belong to universities around the country, but the largest ones tend to be associated with major botanic gardens, natural history museums, or other research institutions. The NYBG houses the largest herbarium in the U.S. and the third largest in the world with some 7,921,000 species, and

it has risen to importance as a major hub of study as a result of its extensive collection effort since its founding. Two of the world's 100 largest herbaria are located in Spain. The country's largest, and the 46th largest in the world, is that of the Royal Botanic Garden, and it contains just over 1,158,000 specimens (Thiers, 2020).

Shetler's concerns were not realized when looking at the history of herbaria post 1970. Data from the summaries of the most recent editions of *I.H.* (2016-2019) reveal that herbarium formation and engagement actually experienced a spike from the 1970s to the present. After several decades of sporadic data collection concerning herbaria in the late twentieth century, *I.H.* resumed as a project organized by the NYBG, and the first contemporary report named 2,962 active herbaria in the world (Thiers, 2017). By three years later, over 300 additional herbaria were added to the list of active organizations (Thiers, 2020). The number of botanic gardens in the world has also greatly increased over the last fifty years. The expansion in the amount of active herbaria around the world is a testament to the role these institutions have played in the evolution of the field of botany, from the creation of new uses for their materials to their ability to draw visitors.

Current Applications in Research

As the discipline of botany has advanced and new directions of study have formed over the last century, the role of herbaria and botanic gardens around the world has morphed to match. Cross-disciplinary branches of science—including ecology, conservation, phenology, biogeography, and more—have repurposed herbarium specimens in their research concerning the natural world, and the materials provided by herbaria have influenced the directions of the

discipline and development of new divisions. These institutions contain extensive materials, and the careful collection, retention, and maintenance of specimens ensures that any research that uses them is verifiable and replicable (Greve et al., 2016). As the field expands and new sections arise, botanists devise ways to make the most of those resources and further their areas of interest. The major types of studies that use herbarium specimens include conservation, climate change, human environmental impact, and genetic analysis.

First, botanic gardens and herbaria have proven quite valuable to plant conservation efforts over the last several decades. With their traditional use in taxonomic research—supporting work surrounding species discovery and confirmation of identity, flora inventories, and botanic gardens and herbaria were not immediately at the forefront of conservation work (Roberts et al., 2005). More recently, however, researchers have turned to the collections of live plants at botanic gardens and descriptive botanical data accumulated by herbaria to inform their assessments of natural areas and target species. Botanic gardens conduct conservation work using their live plant collections both *in situ* and *ex situ*. Threatened or endangered plants may be transferred to gardens in order to study their growing habits, and then researchers can use that information to support those species in their native habitats (Faraji & Karimi, 2020). Conservation work requires knowledge of species' spatial distributions throughout time, and herbarium specimens provide first hand information that aids in that analysis. For example, Roberts et al. (2005) identifies the use of herbarium specimens as a viable alternative or supplement to field work. Field work is a known method used to produce conservation assessments, but lack of resources and its labor, money, and time consumption often prevent sufficient studies from taking place. Specimens contained in herbaria throughout

the world provide primary data on the spatial and temporal distributions of species (Roberts et al., 2005). Research using botanic gardens and herbarium data is valuable to conservation studies, as these institutions' collections provide information about key species and mitigate obstacles that may arise due to lack of resources.

Second, herbaria and botanic gardens provide research materials to studies examining plant responses to climate change. In particular, emergent research analyzes material from these institutions to understand the impact climate has on plant phenology (Lavoie, 2013; Primack & Miller-Rushing, 2009). Herbarium collections invite retrospective analysis of plant morphology and phenology that can be compared to living specimens, and botanic gardens house those living specimens and may keep records that supplement collections-based research related to climate change. Everill et al. (2014) demonstrated that herbarium specimens could be used to analyze the timing of spring leaf-out in 27 common New England trees. This study accurately showed that higher temperatures lead to earlier leaf-out times. Without the historical herbarium specimens, Everill et al. (2014) would have had to rely on written records from botanic gardens or other institutions of leaf-out times of trees; such information may have been scarce if no studies on leaf-out times or the relationship between plants and climate change were performed historically. Botanic gardens can supplement the data that herbarium specimens present for phenological research: they may keep records of anomalous flowering or leaf-out events of their species, and staff may dedicate long-term projects to studying changes in certain species' phenologies over time (Primack et al., 2004). The reliable historical record that herbarium specimens contain is key to this kind of work: analyzing changes to species over time is an effective way of studying the past and using that work to anticipate the future.

Third, studies of human environmental impact utilize herbarium specimens: analyzing plant material for chemical concentrations provides insight on the biogeochemistry of study areas. For example, researchers in Spain and the U.S. have analyzed the heavy metal concentrations of preserved specimens collected at different times. Peñuelas and Filella (2002) examined concentrations of 23 elements in herbarium specimen samples as a proxy for their sites of collection in northeastern Spain throughout the twentieth century. Findings showed that three of the elements—vanadium, cadmium, and zinc—exhibited increased concentrations in the specimens studied from the 1920s until 1995, which can be attributed to human industrial activity throughout the study region (Peñuelas & Filella, 2002). This study's use of herbarium specimens is a demonstration of their reliability in such analyses, and the timeline of species collected in different periods provides insight into the past that otherwise might not be easily accessed.

In the U.S., a study conducted by Rudin et al. (2017) examined copper, lead, and zinc contamination at three industrial sites in Providence, Rhode Island, and a nonindustrial site on Block Island based on historical herbarium specimens and specimens collected in 2015. This study confirms the value of herbaceous vascular plant specimens in this kind of research and their effectiveness in evaluating levels of pollution over time. In the past, similar studies analyzed tree foliage from herbarium specimens and modern trees, and herbarium specimens of mosses were compared to modern mosses to examine temporal differences in heavy metal concentration (Rodríguez Martín et al., 2014; Weiss et al., 1999). Rudin et al. (2017) successfully used herbaceous vascular plants in this kind of research, and they used the quasi-control of consulting a specimen of the genus *Plantago* L. for each sample, which are

known metal accumulators and frequently occur in herbarium collections and current environments. With this development, this study eliminated variation that may occur between species of different genuses for heavy metal bioaccumulation due to perennial vs. annual life cycles and genetic predispositions. Rudin et al. (2017) demonstrates the key role herbarium specimens play in developing botanic research about human environmental impact by providing reliable information and physical samples that can be analyzed.

Last, herbarium specimens provide physical plant material for studies in developing branches of botany that entail genetic analysis. Recently, a DNA fragment of *Phaulopsis talbotii* from the Linnean period was successfully amplified, which opens the door to performing genetic analysis of historical plants and using it in contemporary research (Andreasen et al., 2009). Comparing genetic fragments of old and new species may provide insight into evolutionary lineages and relationships. This division of botanical research is extremely young, and its development employs herbarium specimens as essential elements. In one study that does this, Saltonstall (2002) uses historical herbarium specimens and present-day populations of *Phragmites* in Europe and North America to analyze the spread of the species. Genetic analysis of herbarium and fresh plant material was used to differentiate between native and nonnative haplotypes, providing insight on temporal changes in *Phragmites* populations. This study successfully incorporates herbarium specimens into contemporary research and proves that they can be used to inform the understanding of current plant populations. The development of branches of botany that involve studying plants' spatial and temporal distributions takes advantage of herbarium specimens as a source of historical botanists to find ways to use herbarium resources in achieving their study goals.

The development of these four recent branches of plant research and the many uses of dried and living plants have brought herbaria and botanic gardens into the present as impactful resources for modern botany. In assessing the history of herbarium specimen use in research, Heberling and Isaac (2017) call the documents exaptations. This term, coined by Gould and Vrba in 1982, is a biological trait that was naturally selected for its original function, but was eventually co-opted to a new role that increases the fitness of a species. Herbarium specimens and botanic garden plants are exactly that to the world of botanical research. While they continue to serve their original purposes of describing flora and supporting systematic classification, they also became a fundamental constituent of the expansion of the field by providing materials that botanists repurpose and manipulate to achieve new objectives.

Ensuring Persistence

Looking forward, three factors are key for ensuring that herbaria and botanic gardens continue to exist in modern society. Their extensive history and adaptation prove that they are capable and deserving of preservation, and there is no shortage of specimens or lack of need for botanic research in sight. First, formally linking herbaria to botanic gardens strengthens the staying power of both institutions and increases the audiences of both. Second, the international community encourages botanic gardens to participate in the evolution of conservation strategies, and their involvement is key for the future. Finally, recent advancements in technology have facilitated the digital protection of botanic data from these collections and led to more people physically visiting herbaria and botanic gardens. These actions are crucial for allowing the relationship between herbaria and botany to exist and continue to evolve.

First, associations between herbaria and botanic gardens are essential to encouraging collaboration and correspondence between and within the public and scientific communities. Although their basic identities and goals differ, the work of both institutions is inherently linked. The goals of herbaria concern a mostly scientific audience and involve academic and research oriented motives, while botanic gardens have expanded to engage a broader audience and serve as organizations for the use of the public (Rogers, 1995). Linking these institutions eliminates competition that could arise between them, inviting people to supplement their work or interest with materials from both instead. In Madrid, the Complutense University possesses both an *Herbario* and a *Jardín Botánico* that cater to overlapping audiences. Each operates as its own institution, but their association with the University allows students and scholars to use the two resources to their advantage and visitors to learn more if desired. Botanic gardens and herbaria support each other in three main ways: first, the botanic garden provides fresh research materials to professors and students who also use herbarium specimens in their work. Second, the exchange of curatorial knowledge of the garden's staff and taxonomic expertise of the herbarium's staff keeps both institutions up to date and ensures that their growth caters to their collective audience. Third, the botanic garden serves as the public face of the discipline of botany, which piques visitors' interest in plants and provokes interaction with the subject (Rogers, 1995).

Academic settings in particular use botanic gardens and herbaria to promote continued botanical awareness. Academic institutions in the U.S. own about 78% of the country's herbaria (Barkworth & Murrell, 2012). Facilities large and small are valuable resources for student and faculty research, establishing relationships with similar institutions at other universities, training

future experts, and communicating findings across public and academic settings (Snow, 2005). While some university herbaria, including that of the Complutense University, possess over 100,000 specimens in their collections, the majority operate with fewer than 50,000. Such small facilities are important elements in the study of many areas' local flora: they may possess archives of rare, threatened, and endemic species or unique specimens not found in any other herbarium (Snow, 2005). These collections provide important information about regional flora, and they encourage relationships between community members and the plants around them. The incorporation of this information into university curricula produces a community knowledgeable about its flora.

Second, the formation of Botanic Gardens Conservation International (BCGI) was key to connecting botanic gardens across the world, and it urges them to participate in conservation. Prior to its formation in 1987, the International Association of Botanic Gardens was the only networking organization for the world's gardens that provided conferences and a published list of institutions (Blackmore, Gibby & Rae, 2011). BCGI revamped the nature of communication between gardens, encouraging proactive engagement with each other, their publications, and their conferences. The organization is also dedicated to accomplishing the objectives of the Global Strategy for Plant Conservation (GSPC). Adopted in 2002, the GSPC is an international agreement whose primary goal is to combat the decline of plant biodiversity (Convention on Biological Diversity, 2012). BCGI coordinates botanic gardens all over the world and urges them to take advantage of their resources and support the GSPC.

The GSPC has effectively engaged botanic gardens and herbaria in its intentions to raise worldwide awareness of threatened plants. The international agreement provided a framework

for botanic gardens to take action and contribute toward its goal. Much of the success of the GSPC is owed to gardens aligning their own priorities with the agreement's objectives and redistributing their resources to accomplish them (Blackmore, Gibby & Rae, 2011). The current adoption of the GSPC outlines sixteen targets as benchmarks for the improvement of the understanding of worldwide biodiversity, and botanic gardens are unique and important contributors to these goals (Convention on Biological Diversity, 2012). Many gardens choose to engage with five or six targets, but it has been suggested that they can directly contribute to twelve by documenting flora, conserving plants *in situ* and *ex situ*, training experts, and more (Convention on Biological Diversity, 2012). The range of skills possessed by botanic garden staff—the research, cultivation and communication of plants—coupled with their international network and public engagement afford them unique opportunities to support accomplishing the GSPC's goals (Blackmore, Gibby & Rae, 2011). Although not directly overseen by BGCI, herbaria also support the GSPC by providing historical data on species distributions that can be used by researchers and botanic gardens alike.

Spain has adopted the goals of the GSPC in its pursuit of conservation; the country also adopted a strategic plan (*Estrategia española de conservación vegetal 2014-2020*) in which it defines ten objectives with the conservation of domestic plant biodiversity as its ultimate goal (Conferencia Sectorial de Medio Ambiente, 2014). The coordination unit that oversees the accomplishment of its objectives is supported and advised by the Royal Botanic Garden of Madrid. This role makes the work of the garden essential for achieving the plan's targets. The U.S. has not formally ratified the GSPC, but it recognizes that the framework enables the sharing of information and materials on an international scale, so many American botanic gardens and

research institutions have adopted versions of the GSPC in order to maximize their global accessibility and contribute to the agreement's overall goals (Blackwell, 2012). The effectiveness of this strategy depends on the engagement level of botanic gardens and their experts with the agreement's objectives. For example, the NYBG developed its own Center for Conservation Strategy that derives from the GSPC in order to contribute to global biodiversity and conservation goals (New York Botanical Garden). In this case, the scope of NYBG's Center for Conservation Strategy determines its ability to make contributions toward the GSPC's objectives. Since NYBG is a prominent garden, it has the resources to allocate staff to their goals and support related research. This particular work of NYBG is significant because it allows the U.S. as a whole to support the GSPC, and not all of the country's gardens have the personnel or financial resources needed to develop such centers.

Technology is the third major factor that has allowed and will continue to allow herbaria to adapt to the evolution of botany. With the rise of computers, herbaria have adapted to maintain their accessibility and make dissemination of their information smoother. Over their 250 year history, they have already undergone major transformations concerning their role in society and the field of botany; having started as private collections that were kept to satisfy personal curiosities, herbaria experienced institutionalization during the eighteenth century to keep up with the pace of scientific advancement (Shetler, 1969). Further expansion of botany through the twentieth century gave rise to the establishment of more herbaria and diversified their potential contributions. Over the last twenty years, computers and the Internet have been the key instruments for enabling this history to survive in one common place and be accessed from a variety of places.

Digitization of herbaria has most recently revolutionized their future. The development of digital databases reinstitutionalized herbaria as accessible repositories of specimen information that reinforce their physical counterparts. At the Complutense University of Madrid, steady effort is made to digitize herbarium vouchers. Information found on each specimen's label—species common and scientific names, location and date of collection, name of collector, name of identifier, and assigned record number—are entered into a database constructed by Spanish botanists. Specimens can be searched for in the database, and the information found in their entries, such as its location or date of collection and photographs of the specimen itself, can aid in locating them in the archive.

Herbaria may experience a range of limitations when digitizing their records. For example, digitization does not always coincide with mobilization. Using the Internet to create online databases mobilizes a herbarium's records by allowing access to them regardless of geographic constraints. The database maintained by the Complutense University is only accessible from two computers on the entire campus, which limits the amount of people able to readily obtain its records. Effectively transferring records online also comes at a high cost: over 15 years, some 130,000 hours of staff labor at the Herbarium at NYBG resulted in 1.3 million species entered in its online database. In 2012, nearly 6 million specimens remained unentered, showing how slowly the process initially developed (Tulig et al., 2012).

Facing these limitations has forced herbaria to adapt to and use technology to their advantage. Although the Complutense University's herbarium is not mobilized, it has a website that provides information about how to access its specimens. NYBG also has a website with comprehensive information about its collection with a searchable public database. In spite of

limited personnel and financial resources, it has effectively expedited its data entry process and provided digital images of specimens online (Tulig et al., 2012). As a result, 4 million of NYBG's 7.8 million total specimens have been mobilized into the C.V. Starr Virtual Herbarium (sweetgum.nybg.org/science/vh/). These efforts have ultimately benefited herbaria through increasing their exposure through the Internet by inviting scholars to take advantage of their online and physical resources.

In 2008, a new initiative for the digitization of American herbaria called the U.S. Virtual Herbarium project was started. Its overall goal is to digitize all specimens in U.S. herbaria to create a national resource for the study of plants (Barkworth & Murrell, 2012). In 2012, there were an estimated 800 active herbaria in the U.S. that housed some 90 million specimens, and a survey of 287 active responding herbaria (of 601 contacted) returned that 33% of those institutions' 50,583,000 specimens were databased and 3% were imaged (Barkworth & Murrell, 2012). With the continued development of strategies for accelerating database entry and bringing the cost of imaging down, U.S. herbaria are making strides to ensure that their specimens are accessible and that they remain a critical part of the study of the natural world.

The abundance of adaptations that herbaria and botanic gardens have accomplished with regards to technological advancement will ultimately help them remain as key institutions for the future of botany. Connecting herbaria and botanic gardens, encouraging academic affiliations, supporting legal objectives, and embracing technology have created a dynamic that intertwines these institutions with botany and assures that they will be vital to the inevitable and continual development of the field.

Conclusion

Overall, the history and development of herbaria and botanic gardens is a significant element of botany. In Spain and the U.S., the distinct historical patterns of each country influenced the genesis of these institutions. Spanish botanic gardens and herbaria were founded in conjunction with a number of imperial motives in order to support the empire's economic and scientific progress, while U.S. botanic gardens and herbaria rose as reflections of the young country's early interest in plants. The differences between the evolutions of Spanish and American botanic gardens and herbaria point to contrasts in each country's society and goals for them, but with the expansion of botany that occurred through the late twentieth century and into the present, these institutions have taken on similar purposes in both countries. That expansion could not have occurred successfully without botanic and herbaria in each country, which provide valuable resources that researchers continually repurpose in current studies.

Today's uses of herbaria and botanic gardens indicate that these institutions will continue to exist into the future. Both provide engagement opportunities that cater to an extremely wide audience from children to professionals. Positive experiences at these institutions that expose people to plants and the study of botany encourage continued patronage and community support. The scientific opportunity that herbaria and botanic gardens offer through their relationship with botany shows no sign of dwindling with the constant repurposing of the plant material they contain. Continued development of the discipline suggests that herbaria and botanic gardens will be vital to studies for years to come.

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