

**REDEFINING THE ROLE OF NATURAL HISTORY
COLLECTIONS AND MUSEUMS IN AN ERA OF GLOBAL
CLIMATE CHANGE**

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ABSTRACT

Natural history collections (NHCs) have accumulated billions of specimens as permanent records of the diversity of the world's natural heritage. For centuries, biological museums have typically supported the goals of taxonomy, systematics, biogeography and public education. In this time of rapid environmental change, herbarium specimens in NHCs have been employed to provide phenological and distributional data that are indicative of rising temperatures and for tracking alien plant introductions. Historical herbarium materials can also provide long-term proxy datasets useful for reconstructing past ecological conditions and which may also be useful for projecting future trends. Changing times require NHCs to re-define their goals so as to remain relevant and sustainable.

KEYWORDS: biogeography, climate change, global change biology, herbaria, taxonomy

The giant task of documenting the world's natural resources has never been so urgent in the face of imminent global environmental changes during the last few decades. This is particularly so with biodiversity worldwide. Efforts to understand and conserve biodiversity have highlighted its importance in all aspects of human life as well as its vulnerability. Many forms of natural and anthropogenic threats serve to undermine their existence and may cause these components of our natural heritage to be eventually lost forever.

Natural history collections (NHCs) maintained in the world's museums have preserved and showcased the diversity and richness of the Earth's natural heritage throughout many generations (Johnson et al. 2011). They form a permanent record of the various life forms and processes, be they biological, paleontological, geological, archaeological or ethnological. Governments and the private sector have long recognized the importance of building and maintaining museums to document the world's natural heritage as well as to celebrate human progress. To date, NHCs all over the world have amassed billions of specimens collected over the past 200 years representing sizeable investments of time, human resource, and infrastructure. Biological specimens in NHCs have since then been used primarily for basic research in taxonomy, systematics and biogeography in an attempt to document and further understand and appreciate biological diversity on our planet (Hoeksema et al. 2011). However, compared to the estimated number

of species to be found around the world, named species represented by those kept in NHCs constitute only a small proportion.

The precursors of today's NHCs mainly arose from human curiosity and the quest for knowledge and fame among the aristocracies and rulers of Renaissance Europe. Among the earliest records of NHCs or their forerunners can be found in Ferrante Imperato's illustrated book *Dell'Historia Naturale* published in 1599 in Naples. During the Age of Exploration of the 16th century, European traders and mercenaries have traveled far and wide and brought back bounties consisting of objects of curiosities from faraway lands. These prized objects and exotica brought honor and fame to their owners. Many of these collections eventually formed the nucleus upon which modern-day museums were founded. For example, The British Museum in London traces its beginnings to the more than 70,000 objects from the collection of Sir Hans Sloane assembled in the 17th century.

The records of the world's known biological diversity are housed in collections maintained by museums where curators perform specialized tasks for preserving, curating and studying them. Each natural history specimen is potentially a witness to and essentially a record of past ecological conditions (Lister and Climate Change Research Group 2011). In the case of biological samples, they are also an irrefutable evidence of historical biogeographic information. The accompanying specimen labels and the samples themselves are useful permanent records if they are properly preserved. Species identification can change according to prevailing taxonomic concepts but specimens and the collecting data themselves are permanent. Specimen data are unambiguous and verifiable records of the occurrence of a taxon at a particular place and time. This alone is one of the most important attributes of specimens and of NHCs as a whole. However, NHCs and museums face a number of challenges such as funding cuts and shortage of personnel and must re-define their roles in order to survive or to continue receiving community support (Pyke and Ehrlich 2010).

Because of the broad scope of natural history, museum workers have found it convenient to divide and categorize these collections into specialized groups. One such specialized group is the herbarium, which is defined as a collection of preserved plant specimens in the broad sense, including fungi, lichens and algae which today are excluded from the strict definition of plants. Within the herbarium, especially in larger ones, further specialized sections may be identified like the xylarium (collection of wood specimens), fungorium (preserved fungal collection), hortorium (collection of preserved cultivated plants) and even preserved seed collections. This brief review will focus mainly on the various uses of herbarium specimens and how those uses are changing in the light of global environmental change.

Much evidence has accumulated in recent years suggesting global environmental change as seen in studies reporting rising annual mean temperatures, increasing CO₂ levels in the atmosphere, ocean acidification, erratic climatic patterns among other evidences. Specimens kept in NHCs represent a

recently tapped resource to document environmental conditions in the past as specimen physical features indicative of prevailing conditions at the time of material collection may be obtainable from them (Lister and Climate Change Research Group 2011). As such, plant specimens deposited in NHCs can be a good source of proxy data to reconstruct past climatic conditions by way of a retroactive time series that can also be helpful in future projections that can probably be useful in modeling future trends and patterns of plant distribution. While herbaria are traditionally sources of static data obtained from the direct examination of preserved plant samples, they have assumed an exciting new role in characterizing environmental change over the years. From its traditional support role for the study of taxonomy, systematics and phytogeography, herbaria can potentially play an important role in emerging climate research and global change biology.

Owing to the physical integrity of most preserved botanical samples over time, the use of herbarium materials as a useful indicator of phenological responses to past climate conditions and as a predictor of future climate change represents a promising and exciting role (e.g., Lavoie and Lachance 2006, Miller-Rushing et al. 2006). Such physical integrity can be informative for the most part granting proper preservation techniques are followed and optimum storage conditions are provided. For instance, many researchers have studied flowering times of plants as gleaned from herbarium records and associated their observed changes with annual temperature change. Primack et al. (2004) examined 372 herbarium records representing 37 genera of flowering plants collected between 1885 and 2002 from areas in and around Boston. They found a general trend of progressively advancing flowering times, with plants flowering at an average of eight days earlier than usual among plants collected from 1980 to 2002. Throughout the period surveyed, meteorological records in Boston revealed a 1.5°C increase in mean annual temperature. In another study using the southern European terrestrial orchid, *Ophrys sphegodes*, Robbirt et al. (2011) recorded a similar pattern. Using a combination of herbarium records obtained between 1848 and 1958 and annual field data collected between 1975 and 2006, they observed that flowering dates were advanced by warmer spring temperatures, that for every 1°C rise in average spring temperature, flowering was advanced by six days! Furthermore, both herbarium records and annual field observations of the flowering in *O. sphegodes* exhibited striking parallel trends. It has also been shown by other researchers that herbarium data do correlate well with field phenology data sets (e.g., Bolmgren and Lönnberg 2005). However, there are obviously factors other than temperature that affect flowering and other physiological traits. Changes in rainfall have also been linked with phenological changes in some plants (Penuelas et al. 2004).

Different plants can display different responses to a similar set of environmental factors. Neil et al. (2010) studied 87 species of Sonoran Desert plants collected between 1902 and 2006 and kept in herbarium collections. About 19% of all desert plants examined showed either advanced or delayed flowering times throughout this time frame. Comparing flowering times of plants inside urbanized areas versus those outside, they also noted that 24% of

plants in urban areas flowered earlier while 5% were delayed. Their study argued that these altered flowering times resulting from urbanization may affect native biological diversity and ecosystem services through potential changes in population and community functions. In a study of the trophic interaction between the winter moth *Operophtera brumata* and its associated tree, the common oak *Quercus robur*, the synchronization of moth egg hatching and oak bud burst in the spring seemed affected by changing mean temperatures, thus potentially altering ecosystem interactions in the long run (Visser and Holleman 2001).

The study of phenological responses has also extended into organisms other than flowering plants. Using historical herbarium specimens, Diez et al. (2013) studied fungal responses to climatic variations and found that most of autumn-fruiting fungal species from Michigan showed delayed fruiting in warmer and drier years. Kauserud et al. (2008) found the same pattern of fruiting delay among mushrooms in Norway upon examination of 34,500 dated herbarium specimens collected between 1940 and 2006. An average delay of 12.9 days since 1980 has been observed among their samples. In the same manner, Coleman and Brawley (2005) attempted to correlate reproductive maturity of the intertidal brown alga *Fucus distichus* species complex collected from 1905 to 2003 with interannual air and water temperature fluctuations. However, the results showed inconclusive overlaps that were attributed to suspected collection bias for reproductive materials and the complex reproductive traits among these species. A similar warning on shifting collector biases in the study of herbarium and other long-term records was issued by Feeley (2012) when oftentimes sampling efforts leaned towards more populated and easily accessible areas (Aikio et al. 2010). On the other hand, the use of proportion curve analysis that reduces the effect of collecting effort may serve to cut down on some biases presented in herbarium data (e.g., Delisle et al. 2003, Fuentes et al. 2008, Crawford and Hoagland 2009).

Leaf structural and chemical components as observed in herbarium materials are useful indicators for atmospheric CO₂ level changes. Woodward (1987) examined the stomata of eight temperate arboreal species using historical herbarium materials collected over a 200 year period from the midlands of England. Stomatal density showed a 40% decline over this time period when global atmospheric CO₂ level has increased by about 60 μmol mol⁻¹ as revealed by ice core measurements. His results were corroborated with greenhouse experiments wherein herbaceous species were exposed to a range of CO₂ mole fractions. Penuelas and Matamala (1990) found a similar decrease in stomatal density with increasing atmospheric CO₂ among herbarium samples representing 14 species. Likewise, leaf N content showed a similar decrease in the same samples. Penuelas and Azcon-Bieto (1992) and Bonal et al. (2011) found a significant decrease of δ¹³C in leaf herbarium materials with increasing atmospheric CO₂ levels. Among Amazonian tree species preserved in the herbarium, Bonal et al. (2011) found a 1.7% decrease of δ¹³C since 1950 as measured from leaf cellulose.

The use of herbarium specimens has helped reconstruct flora of the immediate past within smaller geographic areas. In doing so, the information can also reveal species invasions and introductions. This information is then related to changing environmental conditions of both natural and anthropogenic causes, but mainly the latter. Aikio et al. (2010) searched through herbarium records and reconstructed the invasive history of alien plants in New Zealand. From the herbarium records, they found that alien species have different spread rates or variable spatial patterns in this isolated group of islands. In an urbanized setting that saw a recent shift from agricultural into urban/suburban land use, Dolan et al. (2011) noted a non-random loss of species starting with high quality wetland species. In addition, they found from herbarium records that urbanization impacted on the numbers of both introduced and native species. Non-native species increased by 1.4 species per year while a higher decrease was recorded among native species at an annual rate of 2.4 species paving the way for an invasive scenario. The invasion chronology of South American weeds in East Africa was similarly elucidated. Stadler et al. (1998) observed a rapid colonization of alien weeds during the 1960s to 1980s as gleaned from herbarium records that coincided with significant changes in the agricultural systems in Kenya. More herbarium collections of alien weeds from the lowlands were recorded as agricultural and irrigation activities increased in arid lands which were otherwise inhospitable for colonization. In the same manner, Fuentes et al. (2008) examined more than 71,000 herbarium records of Chilean alien plants. They were able to identify various chronological waves of invasion with the aid of extrapolated invasion and proportion curves.

One of the well documented historical cases of invasive plants based on herbarium records is that involving the common ragweed *Ambrosia artemisiifolia* L. An examination of more than 700 herbarium specimens suggested its occurrence in Quebec for the last 200 years (Lavoie et al. 2007). Its spread into pockets of Quebec as gleaned from the herbarium records has been linked to the development of road networks that further contributed to its wide distribution suggesting an anthropogenic cause. This North American native species was also traced across the Atlantic Ocean to France by Chauvel et al. (2006) who examined more than 1,200 specimens deposited in various herbaria and dating back to 1863. Earlier introductions of the common ragweed were attributed to seed crops brought from America that apparently came with viable ragweed seeds. The more widespread and recent introductions were traced to commercial trade and horse feed that came along with American troops in the first half of the 20th century.

Individual species help define, constitute or direct the development of ecological landscapes. The presence or absence of species as gleaned through herbarium records can help reconstruct past conditions as depicted by species composition data. Lienert et al. (2002) tracked the disappearance of species that have presumably suffered local extinctions. They used herbarium records to relocate 63 sites around Switzerland where the wetland species *Swertia perennis* L. used to thrive. They also found that local extinctions increased as habitat

altitude decreases in addition to the effects brought by ecological stressors like habitat fragmentation and intensified agriculture.

The use of floristic lists supplemented with herbarium records is also a useful yet underutilized tool for documenting environmental change. This approach is especially feasible in regions that are floristically well documented for which a good set of herbarium specimens collected through time is available. Oliveira and Qi (2003) took advantage of comprehensive seaweed surveys of Santos Bay in Brazil published in 1957 and 1978 and compared such historical data with their own survey of the same region conducted in 1997 and 1998 in what came to be known as a decadal study approach. Starting with 105 seaweed species in 1957, only 69 species were found in the 1978 survey with a noticeable decline of brown algal species that was attributed to increased pollution level inside the bay. They hinted that the return of brown algal species during the 1997-1998 survey was possible after government efforts to cut down on pollution were put in place with the building of a submarine sewage terminal. The appearance/disappearance of brown algae pointed to their potential value as biological indicators of marine pollution, particularly heavy metals.

In another elegant decadal study focusing on marine green algae, Titlyanov et al. (2011) made good use of a combination of historical checklists, herbarium specimens and recent collections from Hainan Island in the northern South China Sea. Comparing herbarium collections of marine green algae from the 1930s, 1950s, 1990s and 2008/2009, a picture of marked floristic change through time became evident. This remarkable transition has been attributed largely to episodes of anthropogenic environmental changes such as unabated coral reef destruction, conversion of foreshore areas for aquaculture, rapid tourism infrastructure development, etc. on the island. Interestingly, the changing environmental scenario within this 80-year time span has also seen the displacement of less hardy green algal groups such as species of the Codiaceae, Caulerpaceae and Udoteaceae by species that prefer nutrient-enriched or degraded habitats such as the notorious green tide-forming members of the Ulvaceae and Cladophoraceae which showed an increase of 1.6- and 1.7-fold, respectively, in the 1990s.

Many coralline algae form thick crusts on sea bottoms through complex biomineralization pathways contributing towards their growth by calcareous accretion. Halfar et al. (2011) studied recent collections of *Clathromorphum nereostratum* in an attempt to understand marine paleoenvironmental conditions. An important feature of crustose coralline algae including *C. nereostratum* that is useful for reconstructing past environmental events is the regular annual growth-increment patterns exhibited by these organisms. The width of these annual increments as shown in digitally imaged thick sections and estimated to be 370 μm per year in *C. nereostratum*, plus the degree of cell wall calcification provided reliable proxy records of changing climate patterns in the Bering Sea region which have long-term implications for Alaskan salmon abundance. Because calcification is affected by solar radiation reaching the sea, coralline algae also provide information about historic marine cloud cover patterns representing a valuable proxy dataset of long-term light dynamics (Burdette et al.

2011). It is conceivable that similar annual increments can be studied using coralline algae stored in herbaria.

Historical herbarium seaweed samples have also been subjected to retrospective ecological analysis by employing information from species life history and meteorological records as performed by Tomizuka et al. (2012). Using herbarium materials collected between 1914 and 2009 from Tateyama Bay on the Pacific coast of Japan, they observed a direct correlation of mean winter surface seawater temperature with species diversity employing a new floristic index emphasizing the presence or absence of alternation of generations in seaweeds (Tomizuka et al. 2011). A higher floristic index value indicates a marine flora with more warm-water seaweed representatives.

The use of herbarium materials for documenting temporal and spatial changes in biodiversity represents an exciting tool for scientists in this period of rapid environmental change. Historical materials deposited in NHCs can be tapped as proxy long-term datasets for researches in biodiversity and climate change studies, among some of the many relevant possibilities. However, extreme caution must be exercised in the use of such datasets. Magurran et al. (2010) opined that while changes inevitably occur among species and indeed all the way up to the community level, a more pressing question than identifying change is to distinguish change attributable to external factors like anthropogenic activities from underlying natural change. The use of descriptive statistics and diversity indices in attempting to assess change, although generating numerical values, may suffer from the pitfalls of interpretation and subjectivity.

The role of NHCs in conveying information about global and environmental change is only starting to be appreciated. Still largely underexplored and underexploited, NHCs will become increasingly important in the coming years by providing baseline data useful as archives for historical ecological research (Hoeksema et al. 2011). The data will gain more relevance particularly when vulnerable ecosystems are involved. With this redefinition of NHC goals and relevance, the scope of NHCs can be expanded beyond their traditional domain into supporting researches on environmental and climate change and even palaeoecology. NHC administrators can use these as leverage for more funding support and increased community involvement through the concept of citizen science as espoused by Magurran et al. (2010). Following the maxim of 'change being the only permanent thing in this world' NHCs must re-invent themselves in response to evolving challenges in this era of rapid global change for their survival so as not to go the 'way of the dodo.'

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