Examining the spectra of herbarium uses and users

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Abstract

This paper aims to investigate the spectrum of potential uses and users of herbarium collections. Consideration is given to the implications of these for the way in which we look to develop and manage collections. We first present a simplified classification of herbarium uses based on Funk (2004). This framework is then utilised to investigate the spectrum of uses of herbaria by means of a Web of Science survey covering the period 2013-2016. To investigate the user profile of a herbarium, we categorised visitors to the herbarium at the Natural History Museum, London (BM), using the same categories, for the period September 2016-August 2017. The Web of Science survey suggests that the number of papers published across years in all categories, except phylogeny, is broadly consistent and that their importance relative to each other did not change. Taxonomic work was the largest category with identification ranked second across years. Phylogeny was the only category to show a marked increase in the number of Web of Science publications during the study period with a year on year increase evident. The increase in the use of herbarium collections for phylogenetic studies, and indeed molecular analyses more generally that is implied by this finding provides new opportunities for herbarium-based research but also present challenges for herbarium management. The survey of users of the BM herbarium revealed that researchers undertaking taxonomic work account for the vast majority of users. Research focussed on the history of science was the second largest class of users for the study period. The number of users in the history of science reflects recent efforts at BM to engage with researchers in this field and demonstrates how the base of collection users can be

broadened. The high use of the collections by taxonomists is unsurprising but should not be taken for granted. Taxonomists make a significant and essential contribution to herbaria by enhancing the quality of the data that they provide for all users. New developments that allow herbaria to address a broader range of researcher questions should be embraced but in doing so we should not lose sight of the needs of our existing taxonomic users who play a vital role in maintaining and developing the research value of herbaria.

Keywords

Destructive sampling; Herbarium; History of science; Phylogeny; Publications; Taxonomists; Taxonomy; Users

Introduction

Herbaria collectively constitute a vast, distributed global infrastructure for understanding and documenting the world's algal, fungal and plant diversity. Nearly 3000 herbaria are listed in *Index Herbariorum* and collectively they are estimated to house more than 380 million specimens (Thiers 2017).

Herbaria are experiencing rapid changes in the way in which they are both managed and used: mass digitisation initiatives, focussing either on subsets of specimens, such as types, across many different herbaria (e.g. the JStor Global Plants Initiative) or on the digitisation of entire herbaria (e.g. Le Bras et al. 2017) are revolutionising the way in which researchers can, and are, using herbarium collections. Technical innovations such as those in image analysis offer potential new approaches for identification and discovery (Carranza-

Rojas et al. 2017); whilst the development of next generation sequencing techniques (e.g. Staats et al. 2013) and of minimally invasive sampling protocols (e.g. Shepherd 2017) are broadening the scope of collections as a source of genomic data for a wide array of biological questions.

Most herbaria have traditionally been used as a tool for comparative biology; their primary role has been in the discovery, classifying and identifying of diversity. As Bebber et al. (2010) demonstrated, they continue to play a fundamental role in this endeavour. Nevertheless, whilst often idiosyncratic in the way in which they have been assembled (Penn, Cafferty, and Carine 2018) and biased in the sample they provide (Daru et al. 2017), herbaria have been used increasingly and successfully to address a much broader array of scientific questions. Indeed, Funk (2004) identified 72 uses of herbaria and new papers continue to highlight the relevance of herbarium collections across a range of disciplines (e.g. Nualart et al. 2017). The breadth of studies for which herbaria have been utilised, coupled with the impact of studies that have utilised herbarium collections to address key questions have provided powerful support for herbaria at a time of unprecedented threat to the survival of many such collections (Funk 2014).

In this paper, we investigate how the spectrum of *uses* of herbarium collections and of the actual *users* of a herbarium compare, and consider the implications of this for the way in which we look to develop and manage a collection. We focus in particular on the collection for which we are

responsible, namely the herbarium at the Natural History Museum, London (BM).

The BM herbarium was founded following the death of the prominent naturalist and collector Sir Hans Sloane (1660-1753). His botanical collections, comprising 335 *horti sicci*, more than 12,000 vegetable substances and an extensive botanical library were part of the founding collections of the British Museum that was established based largely on Sloane's personal collections. The collection at BM was significantly expanded by the addition of the herbarium of Sir Joseph Banks (1743-1820) and this led to the botanical collections at BM being separated from the rest of the natural history collections as the 'Banksian branch' in 1835. Continued growth since that time has resulted in a herbarium that today comprises *ca.* six million specimens collected over more than a 400 year time period. The collections were relocated from the British Museum site in Bloomsbury to the Natural History Museum site in South Kensington following the construction of the latter, completed in 1881. The collections are taxonomically diverse and include the following sections: Algae (excl. diatoms); Diatoms; Lichens and Slime Moulds; Bryophytes; Ferns and Lycophytes; British and Irish Seed Plants; European Seed Plants; General Herbarium and Historical Collections. One curator is responsible for each of these sections with the exception of the General Herbarium, for which there are four curators, each with responsibility for a taxonomic subset of the collection.

In this paper, we investigate and contrast the spectra of herbarium uses and of users of the BM herbarium and consider implications for the future development of the collections. We first present a simplified classification of herbarium uses based on Funk (2004). We then investigate trends in the uses of herbaria by means of a Web of Science survey, querying the database to find papers that used herbaria in studies addressing each of the categories we define during the period 2013-16. To investigate users of the BM herbarium, we considered visitors for the period September 2016- August 2017, and classified them using the same categories.

Methods

Categorising uses and users of the herbarium

In order to evaluate the uses and users of the herbarium, we devised a simplified classification of herbarium uses comprising 12 categories that were distilled from the 72 defined by Funk (2004). The categories we defined as follows:

1. Taxonomy - Alpha taxonomic work concerned with documenting, describing and naming taxa, documenting their distributions and generating identification tools. This may have either a geographical or taxonomic focus.

2. Phylogenetics and evolution - Utilising the collections for studying evolutionary patterns. Collections can be used as sources of morphological and molecular characters to generate hypotheses of phylogenetic relationships; they may be used as sources of trait data to be interpreted in a

phylogenetic context; they may provide distribution data for biogeographic analyses.

3. Change - Use of the collections to document extinctions and decline, the spread of invasive taxa, the response of species to climate change (e.g. in flowering times) or the response of plants to increased pollution through time.

4. Conservation - Using the collections for conservation-focussed research and to inform conservation prioritisation and actions (e.g. red-listing).

5. Plant use - Use of the collections to document plant uses (e.g. from label data); also understanding the process and history of plant domestication (crops, ornamentals, etc.)

6. Ecology - Understanding the relationship between plants and the biotic and abiotic environment around them. Using the collections as a source of ecological/chorological information to determine the ecological determinants of plant distributions; sampling collections for associated organisms (both micro- and macro-organisms) to understand their inter-relationships.

7. Identification - Use of the collections to identify plants or plant material. This could be samples from ecological studies or biotic surveys or fragmentary samples, such as from archaeological or forensic studies.

8. Voucher repository - Depositing or consulting vouchers from a published study in a field other than taxonomy (e.g. samples used in an ecological study). Vouchers may also be used in studies falling into other categories; this category is concerned with the creation and use of vouchers that are explicitly created for that purpose.

9. History of Science - Use of the collections as a resource to investigate the generation of botanical and scientific knowledge through time (including the history of science, the sociology of science, etc.)

10. Art and literature - Use of the collections to inspire artistic and literary endeavours.

11. Teaching - Use of the collection as a resource for teaching about plant diversity across all levels

12. Outreach - Use of the collections to engage with and inspire members of the public.

Documenting uses and users.

We first conducted a search in Web of Science to determine the number of publications in each category for the period 2013-2016 (the last four complete years at the time of the study). We conducted searches using the term ‘herbari*’ as the topic to allow for the use of either ‘herbarium’ or ‘herbaria’. This was coupled with the following terms for a total of twelve searches:

1. Taxonom* - Taxonomy

2. Phylogen* - Phylogeny

3. Chang* - Change

4. Conservation - Conservation

5. Plant use – Plant use

6. Ecolog* - Ecology

7. Identifi* - Identification

8. Voucher – Voucher repository

9. History of Science – History of Science

10. Art – Art and literature

11. Teach* - Teaching

12. Outreach - Outreach

Current use of the BM herbarium was determined by categorising each visitor in the period September 2016-August 2017 using the same classification. Where a visit spanned multiple uses, the primary aim of the visit was scored. Multiple visits from the same person each counted as separate visits. The duration of the visit was not considered.

Results

Published uses of the herbarium

The results of the Web of Science querying are presented in Figure 1. As can be seen, the survey revealed a broadly consistent pattern across years. For

all years, the combination ‘herbari*’ and ‘taxonom*’ retrieved the maximum number of hits. Identification was the second most important category of use. Plant use, conservation, ecology, history of science and vouchering were all broadly consistent in the number of papers published across years and their importance relative to each other and to taxonomy and identification did not change. Across all years, there were very few publications relating to art (maximum of five in 2015) outreach (one in 2016) or teaching (a maximum of three in 2014). Phylogeny was the only use category to show a marked change in the number of Web of Science publications listed during the study period: the number of papers published in 2016 (116) was almost double the number published in 2013 (65) and there was a year on year increase.

Users of the BM herbarium

There were 486 external visitors to the BM herbarium in the period September 2016-August 2017. Categorising those visits by the primary reason for the visit revealed that most visitors (337) are using the collections for taxonomic work (Figure 2). History of Science was the second largest category for this period with 57 visitors. There were a small number of users whose visits were primarily concerned with identification (18), phylogeny (12), change (9), conservation (3), plant use (5), ecology (4) and vouchering (2). There were 19 external visitors concerned with art and 21 concerned with teaching (primarily participants in a taxonomy course for external participants organised by our department). There were no visitors recorded in the ‘outreach’ category but this reflects the way in which visitors in this category are hosted and recorded

which is separate from our main visitor recording system and consequently they are not recorded here.

Discussion

In this study, we have presented a simplified classification of herbarium uses that is based on earlier accounts of the uses of herbaria (Funk 2004). The classification broadly captures the uses of herbaria for various types of research, for education and for outreach and we have used it to examine both trends in the uses of herbaria, through a survey of publications relating to herbaria in Web of Science and to investigate the current users of a herbarium, through a survey of users of BM during 2016-2017.

The number of publications for each category in the Web of Science search are limited and are likely to be a significant under-estimate of the total number of papers published in the categories considered. For example, with respect to taxonomy, Bebber et al. (2010) noted that in the order of 2000 species of angiosperm species alone are described each year and these will all refer to herbaria since all will have type specimens. The 150-200 papers referring to taxonomy and herbaria in the Web of Science search is thus likely a significant under-estimate of the actual number of papers describing new species. We suspect that other categories will be similarly under-estimated in this analysis given that many publications using herbaria will either be in journals that are not listed in Web of Science or, if they are listed, then reference to herbaria will not be detectable with WoS searches (i.e. the term ‘herbari’ or the additional search terms used do not appear in the title, abstract

or key words). These limitations notwithstanding, the results suggest that the use of herbaria across all categories except phylogeny are broadly consistent through time, with taxonomy the main use of herbarium collections. Furthermore, a trend that is apparent from the analysis is the increasing number of publications relating to phylogeny and herbaria across the period of the survey. This likely reflects the increasing utility of herbarium collections as a source of genomic data, a trend that has been facilitated by technological advances. Whilst herbaria have long served as a source of DNA for molecular studies (e.g. Williams et al. 2014), next generation sequencing approaches offer an even greater chance of success with archival DNA given that they work with highly fragmented DNA, which is a characteristic of archival material (e.g. Bakker 2017). Our survey suggests that this is a field that is continuing to grow. The increasing utility of herbarium material for genetic analyses represents an additional use for herbaria rather than a change in use, since publication numbers in other categories remain broadly consistent. The growth of this area opens up new opportunities for herbarium-based research but at the same time presents challenges for the curators concerned with the preservation and management of those collections: it is an additional time commitment, it presents potential issues relating to compliance with permits and international conventions; conservation issues need to be considered as well; and in a world of fast moving technological developments, being able to determine when sampling is appropriate can be difficult to assess.

The survey of users of the BM herbarium (Figure 2) reveals two main findings: first that researchers undertaking taxonomic work account for the vast

majority of users during the period September 2016-August 2017 and second, that users in other categories constituted much smaller proportions of the total user base, with research focussed on the history of science being the second largest class of herbarium users. The survey does not capture all uses of the herbarium since it does not adequately include the use of the collections for outreach. It is also incomplete since it does not include virtual enquiries (via email or the web) that relate to the collections, nor loans. We expect that including these would not significantly alter the broad findings we present and this is supported by our on-going use of the classification to record visitor and enquiry activity that reveals a consistent pattern.

The BM herbarium has been used in studies across the full range of categories reflected in the classification. In addition to taxonomic work, the herbarium has contributed to phylogenetic, biogeographic and evolutionary studies (e.g. Mitchell et al. 2016) and it has played a prominent role in studies examining change over decadal timescales in response to anthropogenic impacts. For example, the pioneering study of Robbirt et al. (2011) used BM collections to investigate flowering times in early spider orchids (*Ophrys sphegodes* Mill.*)* and demonstrated that the species flowers earlier in response to warmer temperatures (Figure 3). More recently, Jungblut and Hawes (2017) used next generation sequencing to investigate change in cyanobacterial communities in Antarctica over the past century by comparing assemblages in herbarium specimens collected during Scott's 1902 Discovery Expedition with those collected today (Figure 4). Specimens at BM have been used in red listing of taxa (e.g. Brummitt et al. 2016) and in a range of studies

of plant use, from the modelling of the distributions of crop wild relatives to facilitate the assessment of their representation in genebanks (Syfert et al. 2016), to examining the relationship between cultivation history and pre-Columbian human migration across the Pacific (Roullier et al. 2013; Figure 5). BM herbarium specimens have been used as a source of precise distribution data for studies of the climatic preferences of species (e.g. Yesson et al. 2015) and have also been used to study ecological impact of species, for example in studies of cyanobacterial toxins (e.g. Metcalf et al. 2012). The collections are regularly used for identification – particularly for taxa and regions that are well represented – and the herbarium continues to act as a voucher repository for researchers both at BM and elsewhere (e.g. Wang et al. 2014). Historians of science have utilised the collections (e.g. Rose 2017) as have artists. The collection is used for teaching at a range of levels and tours for specialist societies are regularly hosted.

Broadening the base of herbarium users and developing new areas of research activity around herbaria often involves engaging with different communities to those with which we have traditionally interacted. In this regard, the prominence of historians of science among users of the BM herbarium is notable. Whilst the historic nature of the BM collections means that they have always attracted the attention of historians, a concerted effort in recent years has seen much greater engagement with humanities scholars. As a consequence, BM has been actively participating in grants awarded by the Arts and Humanities Research Council and hosting PhD students in the

History of Science. Active engagement with different communities can be successful in expanding the usage of the collections.

The dominance of taxonomists among herbarium users is perhaps unsurprising. The BM collection has been used extensively for both monographic studies (e.g. Robson 2012; Knapp et al. 2017) and floristic works (Davidse, Sánchez, and Knapp 1994; Press and Short 1994; John, Whitton, and Brook 2002) across a wide range of groups and geographical regions and by a wide range of researchers. The survey suggests that this is still the case. The importance of taxonomic research on herbarium collections for discovering and documenting plant diversity is well known and the fundamental role of herbaria in the discovery of new species was highlighted, for example, by Bebber et al. (2010). They demonstrated that there may be a substantial time lag between the collection and description of new species such that many ‘new' species have already been collected and are awaiting discovery in the world’s herbaria by relevant experts. The long time-lag in the description of new taxa is true across groups as evidenced by research on the BM collections that have revealed new taxa many years after their initial collection, across a range of taxa (e.g. Aptroot 2014; Ellis 2016).

Taxonomic research on collections is essential to enhance their value through refining the quality of the data they provide. Goodwin et al. (2015) estimated that more than 50% of records in the Global Biodiversity Information Facility may have the incorrect name and they showed that in the groups they examined, a similar proportion of specimens in herbaria were incorrectly

identified prior to recent taxonomic work. Continuing taxonomic work on collections enhances herbarium collections for users across all categories. In the context of Amazonian plant diversity, Cardoso et al. (2017) recently demonstrated that using critically examined herbarium collections to study diversity patterns in the Amazon basin not only provided falsifiable data based on specimens, but also resulted in estimates that differ markedly from those based on some modelling approaches with potential implications for macroecological and evolutionary research.

Conclusion

The results of the classifications of uses and users that we present here highlight three main points. Firstly, a survey of Web of Science-listed publications suggests a year-on-year increase in the number of studies using herbaria for phylogenetic studies during the period. This does not reflect a shift away from other uses since publications in the other categories examined remained broadly consistent. The development of this field provides significant opportunities to use herbarium collections in novel ways to address significant scientific questions, but it does present challenges for collection managers. Secondly, the profile of users of the BM herbarium and in particular, the number of users in the history of science suggests that herbaria can attract new users. Finally, the survey of users also demonstrates that taxonomists are the largest user group of the BM herbarium. Their use of the collections is essential since it represents a major contribution towards improving the quality of the data that herbaria provide for all users. A large number of taxonomists actively working on a collection is to be welcomed and

the contribution that they make to enhancing the global infrastructure of herbarium collections should be acknowledged and supported.

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Disclosure statement

No potential conflict of interest was reported. The authors are the curators responsible for the collection on which the visitor information reported in this paper is based.

Note on contributors

The authors of this paper constitute the curatorial team responsible for managing the Natural History Museum's collection of six million botanical specimens.

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Figure 1. Number of publications retrieved from a Web of Science search designed to establish the number of publications dealing with herbaria and each use category defined in the methods for the years 2013-2016.

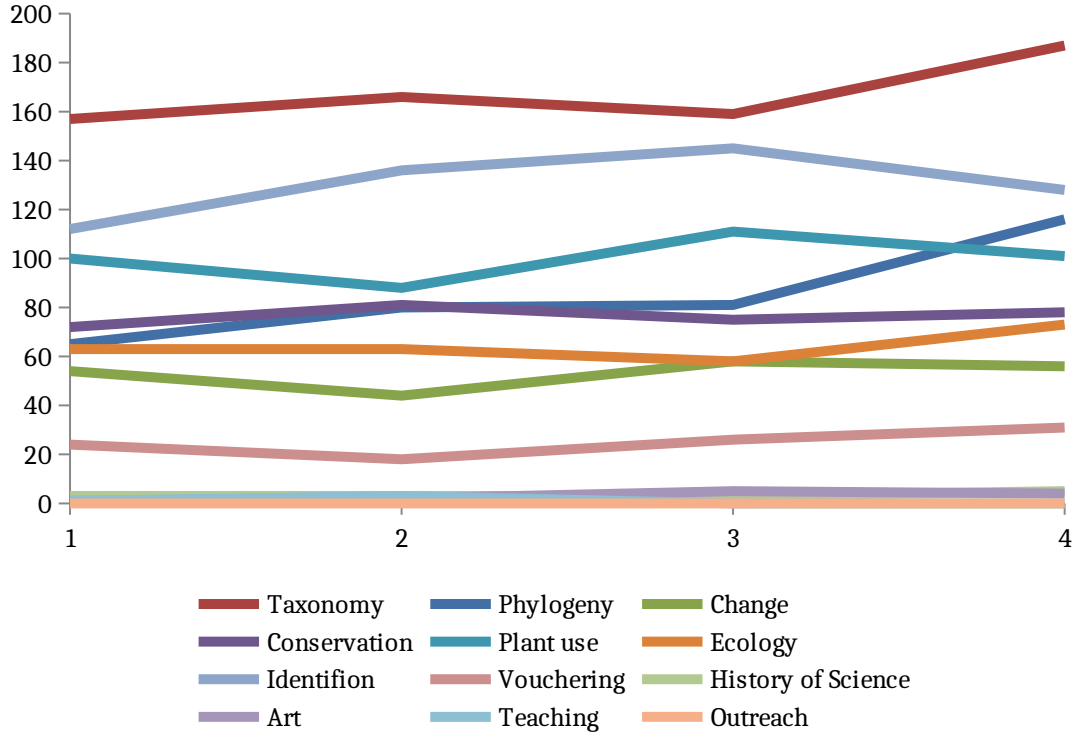

Figure 2. Categories of visitors to the BM herbarium between September 2016 and August 2017. For an explanation of the categories used, see methods

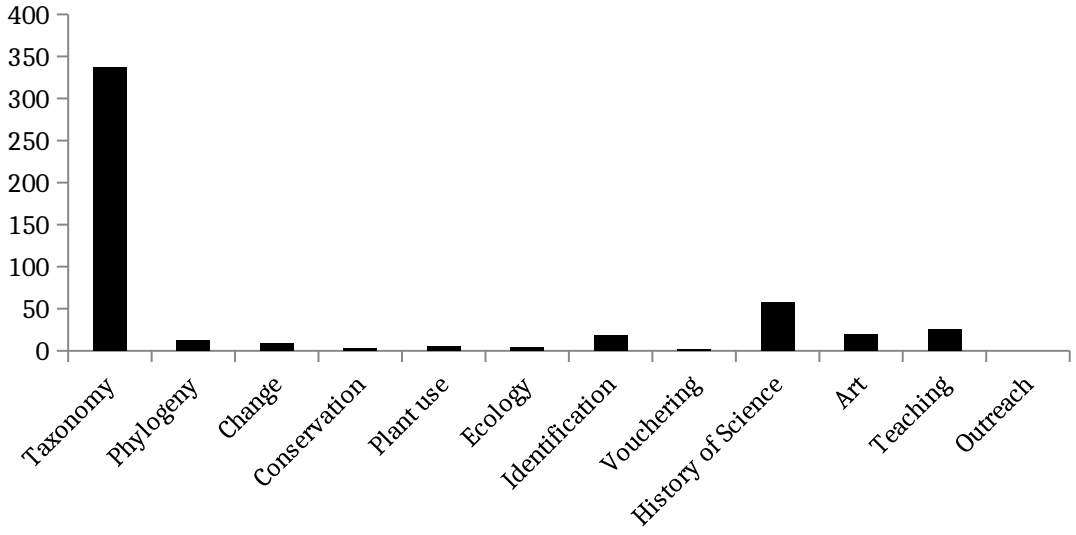

Figure 3 – Herbarium sheet of *Ophrys sphegodes* collected by F. J. Hanbury in May 1878 and used in the study of Robbirt et al. (2011) to investigate decadal changes in flowering times.

Figure 4 – Cyanobacterial collection made during the 1902 Discovery expedition to the Antarctic led by R. F. Scott. The specimen was used by Jungblut and Hawes (2017) to investigate changes in Antarctic cyanobacterial communities.

Figure 5 – Specimen of *Ipomoea batatas* collected by Joseph Banks and Daniel Solander in Tahiti in 1769 and used by Roullier et al. (2013) to investigate the source of sweet potato in the Pacific islands.