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REVIEW

Old meets new: Innovative and evolving uses of herbaria over time as revealed by a literature review

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Societal Impact Statement

Herbaria, as collections of preserved plants, contain large amounts of data both in the labels and the specimens themselves, which can be applied in different study fields. A literature review was conducted to discover how the uses of herbaria have evolved over time since records began. This analysis revealed insights into how herbaria are presently used. Uses include traditional taxonomic review, as well as advanced technological tools, which are being applied to herbaria material to address societal and global challenges and therefore contribute to decision-making in conservation.

Summary

Herbaria as collections of preserved plants contain large amounts of data and prominent information, both on the labels and on the specimens themselves. There are 400 million specimens preserved in herbaria worldwide, with great potential for studies in conservation and effects of global change on plants. (1) In this paper, we investigate the array of herbaria uses through a systematic review of the scientific literature in SCOPUS covering the period 1842–2022. (2) We reviewed a total of 2900 papers and classified them in different areas of knowledge, as well as the taxonomic level studied. (3) Our results show that taxonomic use is the most relevant over time. This taxonomic use, together with the use as primary source of plant diversity data, is essential for documenting, planning, and acting on the conservation of threatened plants. Furthermore, our results have shown that new and diverse uses have emerged since 1990, mostly related to ecological issues, as herbaria provide a historical record of plant diversity and distribution, as well as their ecological and evolutionary responses, allowing scientists to track changes over time. (4) This contributes to improve the knowledge of biodiversity and to increase the effectiveness of conservation strategies and policies, which are a priority to address on going global change. Therefore, our study shows the relevance and potential of herbaria in ecology, including new or forthcoming uses, which are different from the uses originally intended by collectors. Thus, their preservation is critical as the unique and exceptional record for the knowledge of changes in biodiversity over space and time.

KEYWORDS
biodiversity, global change, herbarium, plant conservation, taxonomy

1 | INTRODUCTION

Currently, there are 3522 active herbaria containing ca. 400 million specimens (Thiers, 2021). Together with the rest of biological collections, they house the largest biodiversity dataset in the world (Page et al., 2015). Herbaria, which emerged during the 15th and 16th centuries (Lane, 1996), have been pivotal for the development of natural sciences, particularly plant taxonomy—the discipline encompassing the classification, identification, and naming of plants (Morton, 1981). These collections have become the bedrock upon which botanical studies rely, offering an invaluable resource for researchers and scientists to explore and comprehend the plant diversity.

Nowadays, a wide range of uses are emerging that the researchers who fostered herbaria could not even imagine, rendering them into a solid source of data in a multitude of scientific studies (Heberling et al., 2019). As both science and society advance, herbaria are undergoing important changes, not only in their management but also in variety of uses that researchers make of the information housed in the collections (Carine et al., 2018). Thus, the preservation of specimens makes possible the use of emerging techniques, such as next-generation DNA sequencing, with a high potential transfer to conservation biology (Staats et al., 2013).

In addition, other applications have appeared due to pressing societal challenges such as facing the current biodiversity crisis, which the scientific community has to address by means of a multidimensional approach (Wilson, 1985). This requires the management of large amounts of data for the construction of accurate predictive models showing their impacts and implications in the future, as well as supporting decision-making focused on conservation in a wide sense (i.e., remediation, mitigation, and adaptation to global change) (James et al., 2018).

Herbarium collections are an important source of historical biodiversity data, providing reliable evidence of the occurrence of a particular organism at a specific point in space and time (Paton et al., 2020). For instance, among the more than 440 million data on plant occurrences in the global biodiversity information facility (GBIF), over 109 million come from specimens preserved in herbaria. Nevertheless, there are still millions of data that are neither computerized nor available on open access biodiversity portals. Due to that, in the last few years, many herbaria have started a major effort to digitize their collections with the aim of making them more easily accessible and useful (Rønsted et al., 2020).

Finally, other potential uses of herbaria could be applied in the education, as Funk (2003) stated, providing material for teaching, exposing students to systematic research, or running education courses for a general audience.

We have evidence that the use of herbarium collections has changed along their history, and therefore, a review of historical and current uses can contribute in highlighting the value of this key source of biodiversity data information. We hypothesize that, alongside the traditional uses of herbaria, there is a set of emerging uses, which can be identified in the literature and that point in the direction toward how herbarium data should be organized to optimally fulfil their role for researchers and society at large, such as a universal format for data sharing to increase the use and improve the usefulness of data (e.g., standard Darwin Core) (Wieczorek et al., 2012). For this reason, we aim to explore how the uses of herbarium specimens have evolved over a wide time frame, also evaluating their unexplored potential for the pending challenge of preserving plant biodiversity.

2 | MATERIALS AND METHODS

To evaluate the diverse historical uses of herbaria, an extensive literature review was conducted using the Scopus database. This bibliographic analysis was made using the key search terms: "herbaria" OR "herbarium" in the title and/or keywords, in order to retrieve only papers where herbaria played a prominent role. After the search, 2900 documents covering the period from 1842 until 2022 were obtained. Dataset S1 includes metadata on title, authors, year of publication, source, abstract, and keywords were retrieved from the Scopus database.

Afterwards, we performed a search for commonly used terms in the literature using VOS Viewer software (version 1.6.19, as described in Eck & Waltman, 2017). This software allows to perform a co-occurrence analysis of terms extracted from a corpus text based on the title and abstract of the papers selected. We used a full counting method with a term frequency threshold of 33 occurrences, also selecting the 60% of the most frequent terms (184 terms) to plot in the map after removing country names. These thresholds are being selected by recommendations of the software itself and by exploratory analyses for this particular data. Finally, we generated a network map of the terms in which terms are placed in such a way that the distance between two terms indicates the relatedness between them based on the co-occurrences in the corpus text (the number of times they appear together in the same sentence, i.e., the smaller the distance between two terms, the stronger the relationship between them). In addition, the size of the terms is correlated with the number of times it appears in the corpus text (i.e., term "herbarium" and "specimen" are the biggest because they have a high co-occurrence and are related with a short distance due to the times they appear together in the same sentence).

Also, we assigned to each record (article) three variables by analyzing the information retrieved from the Scopus database (Dataset S1) as follows: (i) Collection type, following the most accepted classification in which herbaria are arranged (Thiers, 2021) as: "Algae," "Fungi," "Lichen," "Bryophyte," "Vascular Plant." With two additional categories as "Various" (when several categories were involved, i.e., Fungi and Lichen), and "Others" (paper dealing with organisms not specifically housed in herbaria, i.e., Bacteria, Viruses, or Animalia) (ii) Phylum (according to Ruggiero et al., 2015), as: "Tracheophyta," "Marchantiophyta," "Bryophyta," "Anthocerotophyta," "Charophyta," "Chlorophyta," and "Rhodophyta" (for kingdom Plantae); "Pseudofungi," "Ochrophyta," "Miozoa" (Chromista); "Glomeromycota," "Zygomycota," "Chytridiomycota," "Basidiomycota" (for kingdom Fungi), "Amebozoa" (Protozoa), "Various" (references mixing two or more Phyla), and "Others" (references dealing with organisms not specifically housed in the herbaria, i.e., Bacteria, Viruses, or Animalia). (iii) Topic: We categorized by expert judgement (including possible synonymy) the main topics (potential uses) addressed in articles by merging and simplifying the 72 uses identified by Funk (2003) into 27 topics as follows: "Bioaccumulation," "Biochemistry," "Biodiversity," "Bioindicators," "Conservation," "Ecology," "Ethnobotany," "Genetics," "Global Change," "Invasion," "Palynology," "Pharmacology," "Phenology," "Phylogeny," "Physiology," "Phytopathology," "Reproductive Biology," "Taxonomy," "Palaeobotany," "Bioinformatics," "Digitization," "Environmental Education," "Herbarium Protocols," "Herbarium Resources," "Molecular Methods," and "History." In addition, we indicate in the dataset whether taxonomic techniques involving DNA sequencing were used or not (Taxonomy Type in the dataset).

For the graphs included (except for the network map), we used the "ggplot2" library in R (Wickham, 2016).

3 | RESULTS

The number of papers over the assessed period (2900 in total) experienced a clearly exponential growth pattern. However, the rate of increase was lower in the first 154 years (only 326 papers), before increasing dramatically since the late 1990s onwards, when the rest of the papers emerged (2574) (Figure 1).

3.1 | Co-occurrence network of terms

An analysis of the co-occurrences in the corpus text clearly evidenced the presence of four clusters, all of them linked to the most frequent and relevant term "herbarium" (Figure 2).

Cluster number 1 (Figure 2 in red) was related to biodiversity terms (i.e., studies about ecology, global changes, patterns, responses, richness, and distribution). Cluster number 2 (Figure 2 in green) included terms related to taxonomic studies, such as lectotype, isotype, description, and taxon. The third cluster (Figure 2 in blue) addressed the most frequent terms: herbarium and specimen, both acting as hubs for the rest of the terms. Thus, this indicates

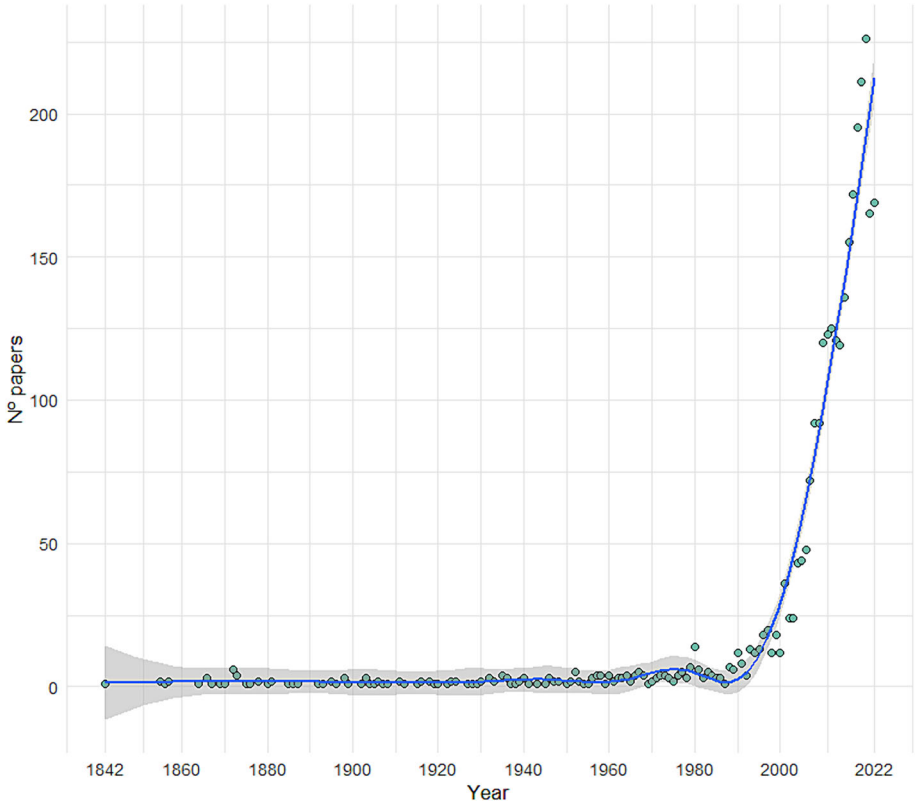

FIGURE 1 Scatterplot showing the number of papers per year using herbarium data for the assessed period (1842–2022). Curve was fitted using generalized additive model (GAM) method showing the 95% confidence level (gray area).

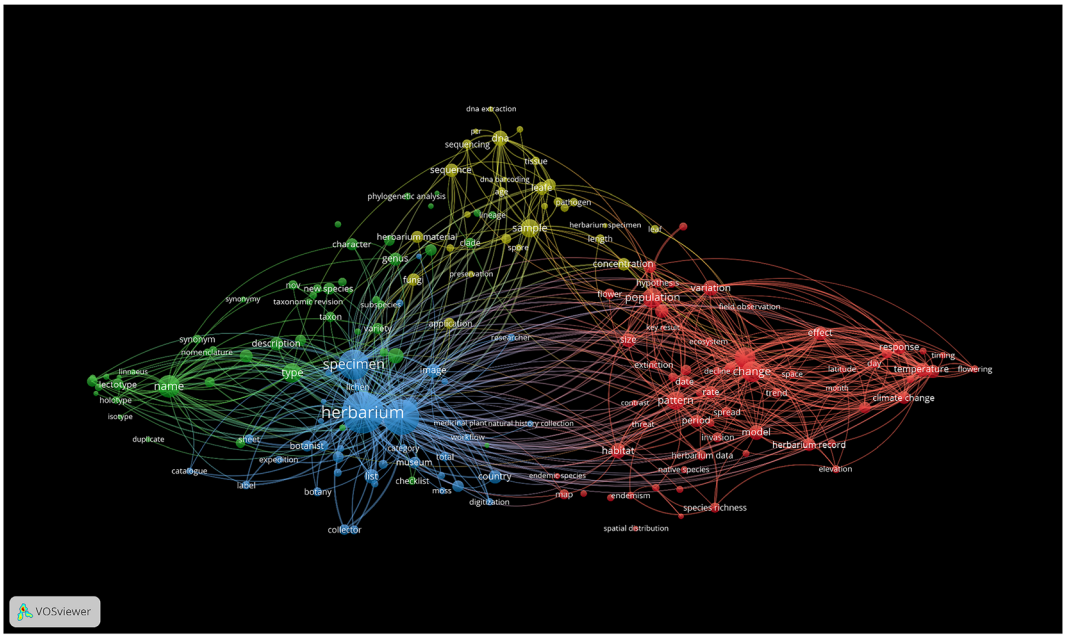

FIGURE 2 Co-occurrence network terms showing 60% of the most frequent terms and their associations from the corpus text (extracted from Scopus containing "herbarium" OR "herbaria"). Cluster 1 (red), cluster 2 (green), cluster 3 (blue), and cluster 4 (yellow). Note: Nodes sizes are proportional to their frequency. Each color-coded category indicates the main clusters formed by the co-occurrence of terms.

that these two terms are the basis of all studies. In addition, this cluster included the terms: workflow, digitization, or image. In the fourth cluster (Figure 2 in yellow), we found terms associated with herbarium protocols or different techniques involving PCR and DNA extraction related to molecular studies protocols. Figure 2 also show that clusters number 2, 3, and 4 are closer to each other, while cluster number 1 was more distant, pointing to it as a cluster with greater singularity.

In addition, we found some terms referred to different collection types, which give us a preliminary idea of which ones have been studied the most studied, in terms of their frequency and relevance in the corpus text. This was the case, in order of importance for: "plant," "plant specimen," and "vascular plant" all of them ultimately referred to vascular plants. Following was "moss" or "bryophyte," then "algae" and, finally "lichen."

3.2 | Type of collection and phyla

Out of the total number of papers selected (2900, see Table 1), the analysis of the type of herbaria collections showed that most of the studies were made with vascular plants, summarizing 1688 (59.8% of the total), whereas the least studied collections were those of the lichen, with only 61 papers (2.1%). Between both, fungi, bryophyte, and algae appeared (in this order respectively). Also highlight 653 studies (23%) that mixed two or more of these groups. Regarding phyla, we found the phylum Traqueophyta as the most studied group with 1688 papers (59.8%), while Ascomycota with 110 papers (3.9%) was the most studied phylum within the Fungi kingdom, and Ochrophyta (Chromista kingdom), with 24 papers (0.9%), was the most studied within the algae functional group. In 661 papers (24.4%), we found a mixture of two or more phyla studied, while 105 papers, the phyla studied were not determined (Table 1).

3.3 | Use of herbaria

Concerning the use of herbaria, among the 27 selected topics, most of the studies (Figure 3) dealt with taxonomy, followed by herbarium history, herbarium resources, herbarium protocols, biodiversity, biogeography, conservation, and invasion. The analysis showed that between 2% and 3% each of the topics were (see Figure 3): global change, phylogeny, bioinformatics, ecology, digitization, phytopathology, molecular methods, and phenology. The remaining topics accounted less than 2%.

Regarding the temporal evolution of the topics (Figure 4), we can note that the first reported use in literature was pharmacological (by 1842), followed by the taxonomic one (by 1855). Despite this, pharmacological use was almost neglected afterwards.

Other topics that have emerged in the last 30 years, such as global change, phenology, reproductive biology, palaeobotany, and environmental education, constitute the most novel applications. Moreover, we can remark (Figure 4) that there are some recent topics that show a high frequency in a very short time span. In general, for all the topics, we can observe that the highest frequency of uses is concentered since shortly before 2000.

TABLE 1 Distribution of the number and percentage of papers (extracted from SCOPUS) which referred to the different collection types and phyla for the assessed period (1842–2022).

Collection type	*n*	%
Vascular plants	1688	59.8
Fungi	174	6.1
Bryophyte	124	4.3
Algae	83	2.9
Lichen	61	2.1
Various	653	23
Others	40	1.4
Total	2823	
Phyllum	***n***	**%**
Tracheophyta	1688	59.8
Various	661	23.5
Ascomycota	110	3.9
Undetermined	105	3.7
Bryophyta	97	3.4
Basidiomycota	49	1.7
Marchantiophyta	25	0.9
Ochrophyta	24	0.9
Others	24	0.9
Oomycota	10	0.4
Rhodophyta	9	0.3
Amebozoa	6	0.2
Chlorophyta	6	0.2
Charophyta	4	0.1
Cyanobacteria	3	0.1
Zygomycota	2	0.1
Total	2823	

Note: "Various" when several categories were involved, i.e., Fungi and Lichen. "Others" paper dealing with organisms not specifically housed in herbaria.

An analysis with the eight topics most used along the data frame (Figure 5) revealed that "taxonomy," "history," "herbarium resources," "herbarium protocols," and "biodiversity" experienced a very sharp increase in the last 25 years that are still ongoing, except for the use in "biogeography," which has decreased in recent years. However, the topics related to "conservation" and "invasive species" have experienced a gradual increase throughout the assessed period. Even though they started much later than the rest of the topics (since 1989 and 1998, respectively), they are among the top eight most frequent topics.

In addition, throughout our review, we found that molecular taxonomy using herbarium material has emerged strongly in the last 30 years due to the improvement of ancient DNA extraction. We performed a comparative analysis between the studies of traditional taxonomy and the taxonomy using molecular techniques (Figure 6). As a result, we observed a sharp increase in their use over the years because they appeared, but this has not implied a decline in their use in traditional taxonomy.

4 | DISCUSSION

After the literature review, we hereby confirm that herbarium specimens are intended for a wide range of uses, having been used mostly in taxonomic works. However, biodiversity and plant conservation studies are gaining importance in recent decades as a response to address the current biodiversity crisis. Herbaria house extensive collections of dried plant specimens that were collected to build botanical reference "libraries" for taxonomic purposes (Greve et al., 2016). In fact, it is the only source of plant biodiversity data for some regions (Bromberg, 2020). These collections serving as a reference for taxonomists, researchers, and conservationists to study and identify plant species accurately. They provide a historical record of plant diversity and distribution, allowing scientists to track changes over time, together with ecological and environmental important issues (Meineke et al., 2019). While the particular uses of herbaria have been addressed and discussed in other papers (see Davis, 2023 for a recent review), these uses have not been sufficiently connected to the important role they can play in current ecology studies in a broad sense and how to promote their use.

4.1 | Plant taxonomy

Traditionally, herbaria have served as the fundamental hub for taxonomic research (26.9% of the total in our results, see Dataset S1), and this use is the main one nowadays, which involves preservation, classification, identification, and description of plant species (Bebber et al., 2010). Taxonomic studies are crucial for understanding plant diversity and clarifying relationships among different plant groups (Bieker & Martin, 2018).

Herbaria contribute to the first description and documentation of new plant species (Bebber et al., 2010). Through field expeditions and collaborations with researchers, herbarium collections often contain specimens of previously unknown or undescribed species. The process of identifying and documenting these new species provides valuable information, because an accurate taxonomy is paramount for effective biodiversity conservation planning and management (Davis, 2023; Greve et al., 2016).

The application of genome sequencing to herbarium specimens (herbariomics, sensu Davis, 2023) has revolutionized plant taxonomy. In this sense, we have found numerous recent articles on phylogeny and molecular methods that use herbarium material. Molecular techniques that allow the extraction of ancient DNA from dried herbarium samples started in the late 1980s, and, due to the improvement of these techniques (e.g., improved extraction, decreased amount of plant material needed, and a more efficient DNA amplification), led to widespread use of herbaria in this regard (Link et al., 2017), as it is showed in our results. This has the potential to give new value to herbaria as huge repositories of genetic information (Kuzmina et al., 2017) that could be used to answer various evolutionary questions (Bieker & Martin, 2018) or to conduct genetic studies on plant population genetics or phylogenetics (Stern & Eriksson, 1996).

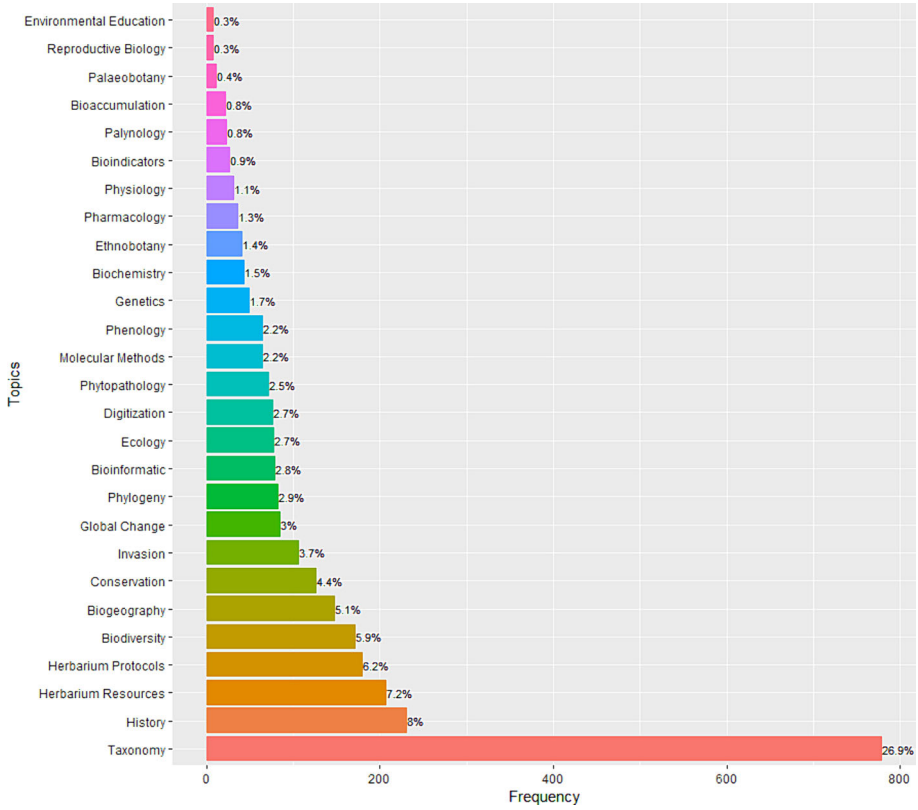

FIGURE 3 Horizontal barplot depicting the number of published papers using herbarium data in the 27 established topics in the period 1842–2022. The relative percentage of articles is indicated to the right of each bar.

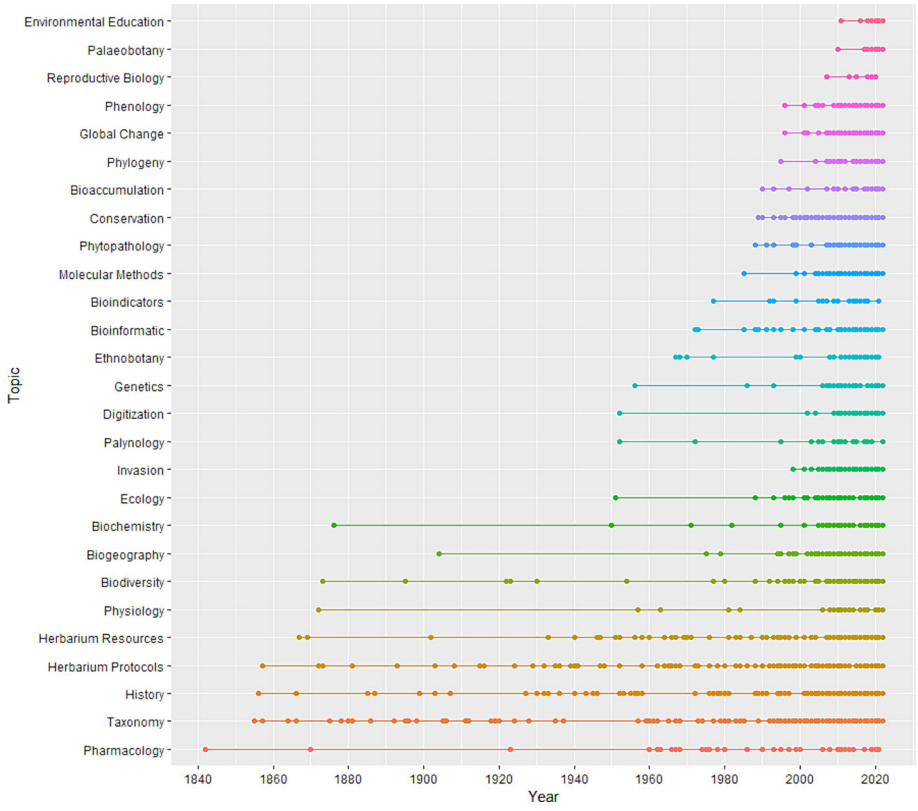

FIGURE 4 Timeline reflecting the year of publication of a given paper and its topic related to herbarium use over the assessed period (1842–2022). Each point shows the occurrence of the topic in a given year.

Ultimately, this information is vital for understanding genetic diversity, identifying distinct populations, and designing effective conservation strategies. An emerging topic is the analysis of image data using artificial intelligence tools for taxonomic determination, which can help in locating misidentified specimens, new species unnoticed, and so forth. (Nelson & Ellis, 2019).

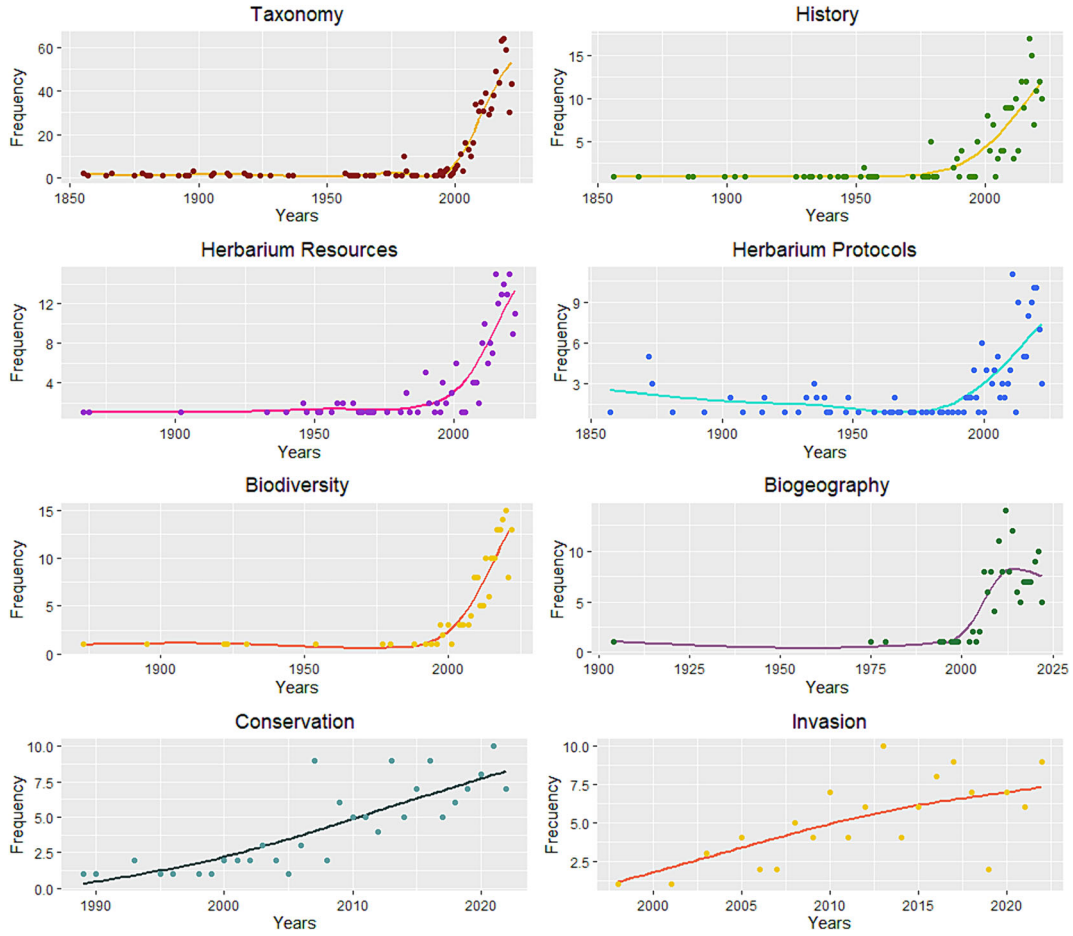

FIGURE 5 Scatterplots panel showing the number of papers per year for the six most frequent topics (after the bibliographic review and assessment) in the assessed period (1842–2022). Curves were fitted using generalized additive model (GAM) method.

4.2 | Plant conservation and other hot topics

Biodiversity worldwide is increasingly under threat due to global change; thus, there is a growing need for long-term monitoring of biodiversity to ensure its effective conservation (Magurran et al., 2010). Specimens in herbaria are becoming primary resources of biodiversity data, as they are valuable records across biomes and time (James et al., 2018; Meineke et al., 2018). In fact, from 1985 to 2022, we have recorded 14.35% of papers reporting or discussing the use of collections in selecting areas for conservation or assessing the conservation status of species, especially in relation to climate change (James et al., 2018; Lavoie, 2013; Pyke & Ehrlich, 2010).

A key role in the exponential growth in this use has been played by GBIF, the most important biodiversity data portal offering more than 443 million plant species occurrence data that include date, 24.7% of which belongs to specimens preserved in herbaria (Source: https://www.gbif.org/es/species/6, accessed 11/22/2023).

Also, by comparing historical specimens with current samples, researchers can determine whether a species has declined or become extinct in certain areas (Schatz, 2002). Moreover, in order to preserve populations, species, and ecosystems, we need to know not only the distribution but also the morphological and ecological traits of the species.

This information can be gleaned from herbarium labels and from specimens. Because the specimens also contain a wealth of additional data, this is due to the remarkable fact that a given specimen captures diverse ecological and evolutionary responses at a given point of time (Meineke et al., 2019), such as nutrient composition (Denys, 2006), heavy metals concentrations (Herpin et al., 1997), signatures of pollinator interactions (Geerts & Pauw, 2009), herbivore interactions (Ivison et al., 2023), diseases (Davis & Crouch, 2022), or physiological processes (Magaña-Ugarte, 2022). All this information is key for mapping and modelling species distribution (Evans et al., 2016). Thus, specimen data can be used to develop models to help predict the way and intensity that different drivers of global change impact species.

In fact, we have found numerous studies on global change and other hot topics closely related to it and to the conservation of biodiversity (e.g., phenology, ecology), which are relatively frequent throughout the entire period but particularly in recent years. Noteworthy is research related to climate change, specifically changes in phenology (i.e., the timing of plant life cycle events) because herbarium specimens provide an invaluable records of plant phenology.

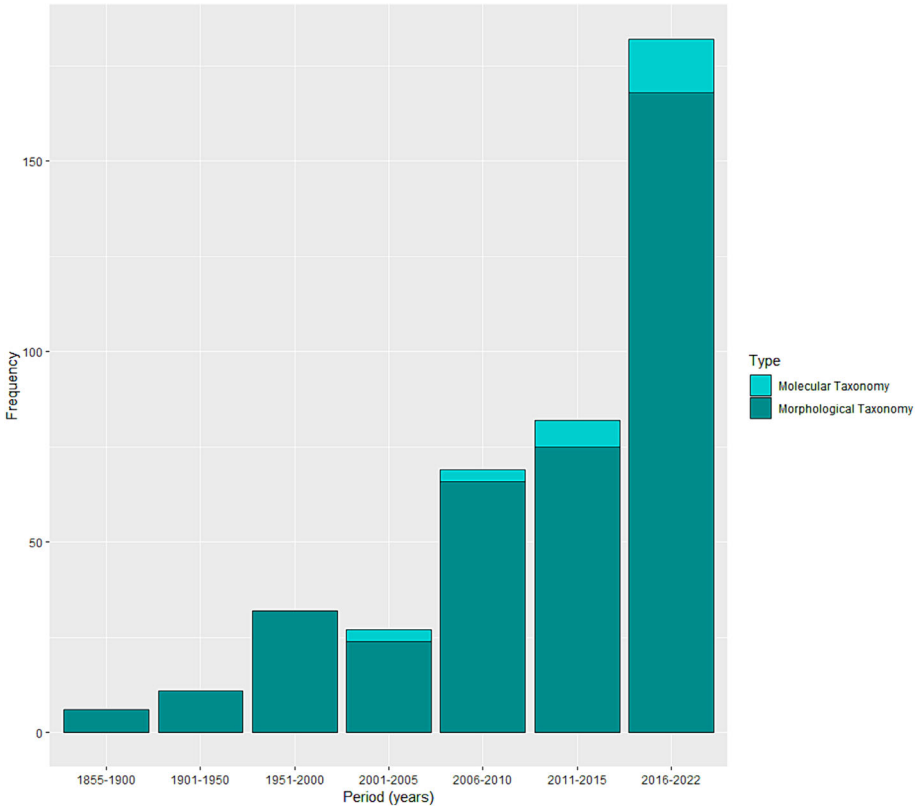

FIGURE 6 Stacked barplot representing the number of papers dealing with herbaria data for taxonomic purpose in the assessed period (1842–2022). Data divided into morphological taxonomy (green color) and molecular taxonomy (blue color).

Comparison of specimens collected over time allows researchers to study changes in the main plant phenophases, such as flowering onset, flowering peak, fruiting, and leaf emergence in response to climate change (Yang et al., 2022). The percentage of papers covering this topic in our results is not excessively large, but it is expected to grow significantly in the coming years due to the importance of this type of results in plant conservation (e.g., herbarium collections help to study climate-driven changes in the geographic range of species and their potential impact on plant communities, Lang et al., 2019).

By analyzing herbarium collections, it is possible to find information on plant-pollinator interactions, such as the presence of specific pollinators on plant specimens or changes in the floral morphology over time (Peng et al., 2012). Historical records inform researchers about changes in pollinator abundance, diversity, and behavior, which are crucial to understanding the impacts of global change on pollination services and plant reproductive success, a key step in the conservation of threatened plants and often a bottleneck in population dynamics.

In relation to the important role of herbariums for the evaluation of global change, we found papers dealt with the invasion topic. Botanical collections assist in monitoring and documenting the spread and impacts of invasive plant species, which play an important role as a driver of global change (Foster et al., 2022). Specimens collected from different locations and periods can help track the expansion of invasive species, study their interactions with native plants, and inform management strategies to control their spread (Chauvel & Cadet, 2011).

In addition, herbaria contribute to the study of ecosystem function and resilience in the face of global change (Jungblut & Hawes, 2017). A percentage of 2.7 of papers in our results are related to ecology in a broad sense. Researchers can analyze specimens to assess changes in plant community composition, ecosystem structure, and ecosystem services.

Finally, herbaria can play an important role in disseminating and raising public awareness about global change and its impact on plant biodiversity, although in our results, this topic was the less represented. However, exhibitions, educational programs, and outreach activities using herbarium collections may help educate the public about the importance of preserving plant diversity, understanding global change processes, and taking action to mitigate its effects (Erickson & Smith, 2021).

In summary, herbaria assist to understand the impacts of global change on plant diversity, serving as a reference for assessing the conservation status of plant species (i.e., identifying threats and threatened species) and also for conservation planning (prioritizing conservation efforts and implementing appropriate conservation measures) (James et al., 2018; Willis et al., 2003). Results can be useful for researchers, managers, policy makers, and other stakeholders working on protected species or areas (James et al., 2018).

4.3 | Gaps and threats to herbarium collections

According to our analysis, vascular plants have been the most studied group throughout the entire time span, while other group (fungi, bryophytes, algae, and lichens) are clearly underrepresented in literature (Riera et al., 2015; Sancho et al., 2019), especially aquatic groups (Wernberg et al., 2011; Yaakub et al., 2014), mirroring the uneven representation in the herbarium collections as well (Williams & Pearson, 2019). This has a negative consequence on the conservation

of these groups, because the scarcity of studies makes it difficult to build effective conservation strategies for them. On the other hand, recent studies (e.g., Davis, 2023) estimate that at least 70,000 new species remain to be described and/or misidentified in herbaria, being more than 50% of them from the tropics, where biodiversity is higher, and herbaria have lowest resources. Facing this problem is really challenging with the current taxonomy crisis (Rouhan & Gaudeul, 2021), which affects even the countries with the highest scientific production. This fact poses a major drawback, because the lack of correct identification and description of specimens limits their use even for basic taxonomic or distribution studies and, of course, is a challenge for assessing the first steps of plant conservation (Dubois, 2003).

Despite the potential value of herbaria to global change research, as we have shown in our results, herbaria were not originally intended to be used in relation to ecological/environmental issues and have some inherent biases (skewed representation of species and taxonomic groups or incomplete spatial representation and time series) and limitations (e.g., incomplete or inaccurate information in the label) (Heberling & Isaac, 2017; Lavoie, 2013). However, its use has not been diminished as these can be mitigated with new analytical tools developed for such type of data (including machine learning or novel Bayesian statistical modelling approaches; Meineke et al., 2019). Improving these tools and creating new ones would help to increase the use of herbaria-derived data, making them increasingly higher quality and reliability.

However, other challenges, such as specimen loss and deterioration, may be more difficult to overcome. Hence, in the last few years, many herbaria have initiated a major effort to digitize their collections (Rønsted et al., 2020), and most herbaria have an ongoing or are initiating an agenda to digitize collections. Also, to digitize collections, fulfils another aim: to make the information contained widely available (images and data) through bioinformatics portals such as the above-mentioned GBIF. Improving direct access to data means making greater use of them for different studies, exponentially increasing the usefulness of biological collections. (Drew et al., 2017; Meineke et al., 2018). In this way, the use of these digital resources helps to preserve the physical specimen for purposes that the "digital specimen" cannot serve (e.g., molecular studies).

4.4 | Conclusions

Our analysis, based on literature review, clearly reflects how the uses and management of herbaria have evolved over nearly two centuries. Over time, uses have become increasingly diversified, and new uses never imagined by first collectors have emerged. Consequently, herbaria have redefined their mission from a primary research mission of documenting the diversity of life to one more focused in the study of conservation and global change. Yet, new uses do not eclipse or invalidate previous ones, adding value to the classical use of the herbaria for the species description and basic documentation.

The taxonomic use remains the most relevant over time and, given that most conservation targets are based on taxon diversity, becoming this role essential in these studies. In addition, with increasing pressures imposed by global change, there is a critical need to identify taxa at risk and prioritize conservation efforts.

Thus, herbaria constitute the most important and reliable source of biodiversity data, posing an enormous legacy of data across time and space, in order to explore and mitigate the multiple effects of the current global change. Indeed, tens of new research studies are emerging in recent years, setting conservation challenges and priorities. Herbaria are becoming key centers of research in conservation biology, providing a forward-looking vision for policy decisions in restoration and conservation.

The wide range of uses that have emerged nowadays using herbarium specimens can be considered an exaptation (Heberling & Isaac, 2017) of the taxonomic primary use and clearly illustrates the need to preserve collections for future and yet unexplored ends.

Due to the creation and preservation of herbaria in the past centuries, they have acquired a high value and potential for use, forming part of the great leap in current plant research. Therefore, the management of herbaria and the preservation of specimens must be a priority, as well as their funding, ensuring their role in conservation biology and botanical research in general. To address these important challenges, collaborative efforts and innovative solutions are needed for a diversification of funding resources. Collaborating with public and private entities by means of innovative approaches (e.g., citizen science) can help achieve the ultimate goal of preserving the important botanical heritage housed in herbaria.

AUTHOR CONTRIBUTIONS

Macarena Marín-Rodulfo: Conceptualization; investigation; methodology; data curation; analyses; writing—original draft preparation. **Katy Virginia Rondinel-Mendoza**: Data curation; methodology; writing—reviewing and editing. **Isabel Martín-Girela:** Writing—reviewing and editing. **Eva María Canadas:** Writing—reviewing and editing. **Juan Lorite:** Conceptualization; investigation; methodology; writing—reviewing and editing.

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CONFLICT OF INTEREST STATEMENT

As corresponding authors of the manuscript entitled "Exploring the uses of herbaria over time by a literature review" submitted to Plants, People, Planet, we, on behalf of all contributing authors, hereby declare there are no potential competing interests that might influence or bias our work. We affirm that transparency and disclosure are paramount in maintaining the integrity and credibility of our research.

Should further information or clarification be required, please do not hesitate to contact the corresponding author.

DATA AVAILABILITY STATEMENT

The authors confirm that the data supporting the findings of this study are available within its Supporting information.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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