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Review

Collections-based systematics: Opportunities and outlook for 2050

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Abstract Systematic biology is a discipline rooted in collections. These collections play important roles in research and conservation and are integral to our efforts to educate society about biodiversity and conservation. Collections provide an invaluable record of the distribution of organisms throughout the world and through recent and geological time, and they are the only direct documentation of the biological, physical, and cultural diversity of the planet: past, present, and future. Recent developments in bioinformatics and cyberinfrastructure are transforming systematics by opening up new opportunities and as a result major digitization efforts have increasingly made available large amounts of biodiversity data. The collections-based systematics community needs to train the next-generation of systematists with integrative skills, address grand questions about biodiversity at different scales, develop a community-wide cyberinfrastructure, effectively disseminate systematic data to biologists and the public, and proactively educate the public and policy makers on the importance of systematics and collections in the biodiversity crisis of the Anthropocene. Specifically, we call for a new global Biodiversity CyberBank, comparable to GenBank for genetic data, to be the repository of all biodiversity data, as well as a World Organization of Systematic Biology to lead major initiatives of the field. We also outline a new workflow for taxonomic monographs, which utilizes both the traditional strengths of synthesizing diverse collections-based taxonomic data and the capacity of online resources and bioinformatics tools.

Key words: Biodiversity CyberBank, collections-based systematics, e-monograph, Systematics Agenda 2050, World Organization of Systematic Biology.

Systematics is a discipline firmly based in and dependent on biological collections. Although influenced by early workers such as Tournefort and de Jussieu, the field was founded as a scientific discipline in the 1700s by Carl Linnaeus. It has experienced several major periods of revolution including the production of the first comprehensive world flora (de Candolle & de Candolle, 1824–1873), incorporation of Charles Darwin's theory of evolution, J. D. Hooker's biogeographic discoveries, cladistics and the proposition of phylogenetic hypotheses, and DNA-based molecular systematics (Funk, 2006; Wheeler, 2008; Wen et al., 2013). Recent bioinformatic developments related to systematic collections are also transforming systematics by opening up new opportunities for the discipline (Anderson, 2012; Tripp & Hoagland, 2013). As we enter the era of genomics there is a need for collections to grow even stronger in order for us to interpret the large amounts of molecular data that are being generated. At the present time with genomics and bioinformatics transforming the field of systematics, collections in general face major challenges and a proactive strategy is needed to ensure a robust future.

Systematic collections play important roles in research in biological sciences as well as in educating society on biodiversity and conservation (Fig. 1). They provide an invaluable record of the distribution of plants and animals throughout the world and through recent and geological time, and they are being used in many types of studies including those focused on climate change, movement of invasive species, and niche modeling (O'Connell et al., 2004; Johnson et al., 2011; Robbirt et al., 2011). Collections are the only direct documentation of the biological, physical, and cultural diversity of the planet: past, present, and future (Lujan & Page, 2015). Herbaria and museums that house collections are not static repositories, instead they are essential tools for research and education in biological sciences (Fig. 2; Funk, 2006; Schilthuizen et al., 2015).

Collections-based systematics encompasses the naming, describing, and classifying of biodiversity, the synthesis of this information into a wide array of checklists, floras/faunas and monographs, and the interpretation of these data in light of phylogenetic and biogeographic hypotheses (SA2000, 1994;

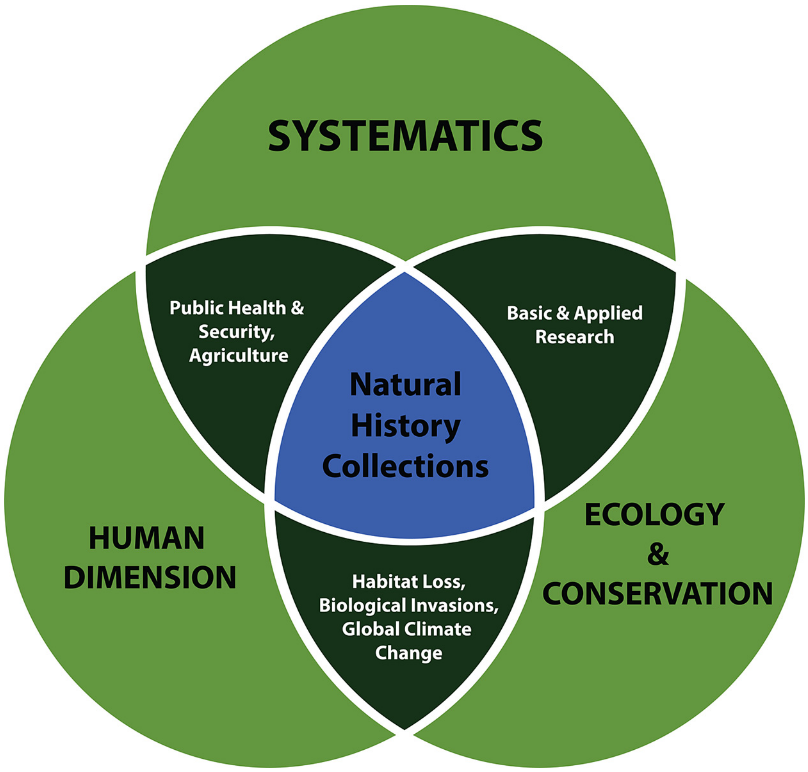

Fig. 1. The importance of systematic collections in biology and society.

Lavoie, 2013). The discipline and its collections should continue to play a central role in today's biology and society, because we are still in the infancy of understanding the diversity and assembly of our planet's floras and faunas, especially in the tropics, under the sea, and in the soil (Wilson, 1992). Natural history collections now play an unprecedented role in documenting climatic and biodiversity changes and shifts in the critical age of our time, a period known as the Anthropocene, which denotes the current interval of anthropogenic global environmental change (Zalasiewicz et al., 2011; Ellis et al., 2012).

Bioinformatic developments in the last decade have helped us explore ways to enhance the efficiency in organizing, publishing, and utilizing systematic information. Online

Fig. 2. The US National Herbarium in Washington, D.C. (US) (photo by Chip Clark).

resources coupled with the advent of new molecular and genomic technologies that are helping make use of older specimens, coupled with an ability to publish results quickly via online outlets (Miller et al., 2012) will no doubt result in dramatic changes in the next decade. More than ever collections and those who study them are central to understanding the results from modern studies.

In this paper, we highlight the opportunities available for today's collections-based systematics and outline directions for the coming decades, emphasizing the role of collections in charting the biosphere in the era of bioinformatics and genomics. We wrote this paper targeting the systematics community, including professionals and students, as our principal audience. Even though some of the points have been made elsewhere, we hope this broad synthesis will prove to be useful to readers to help them understand the current state and the possible future of collections-based systematics. We especially encourage next-generation systematists to fully incorporate collections-based components in developing their integrative research programs in systematics.

Opportunities

An organized, informed systematics community

In general major professional societies/associations in systematics and botany are well organized. The goals of these organizations usually go far beyond promoting the science, as they often value and promote efforts for the long-term sustainability of collections-based systematics. One successful example is the *Systematics Agenda 2000* initiative (SA2000, 1994). It was an important effort organized by the systematics community in the United States under the auspices of the Society of Systematic Biologists (SSB), the American Society of Plant Taxonomists (ASPT), the Willi Hennig Society, and the Association of Systematics Collections (ASC). The initiative set an agenda for a 25-year period for systematics, and the agenda was also widely circulated in Europe (Claridge, 1995). This initiative developed into *Diversitas* (http://www.diversitas-international.org/), a global effort, the organizers of which met regularly for a number of years. There were more recent discussions on *Systematics Agenda 2020* (Daly et al., 2012), but these were at a much smaller scale. The systematics community needs to reassess the status and missions of the major areas of systematics, and to take actions to strategically move the important systematics agenda forward in this century.

The systematics community has taken positive steps towards assessing the world's biota, making use of online resources in the informatics age of biology. *Species 2000* (www.species2000.org/), a "federation" of database organizations working closely with users, taxonomists, and sponsoring agencies, has the goal of creating a validated checklist of all the world's species (plants, animals, fungi, and microbes). This program brings together an array of global species databases covering each of the major groups of organisms. The program in partnership with the *Integrated Taxonomic Information System* (ITIS) of North America currently produces the *Catalogue of Life*, which is used by the *Global Biodiversity Information Facility* (GBIF) and the *Encyclopedia of Life* (EoL) as the taxonomic backbone of their web portals.

Rapid advances in digitization of systematics collections

The systematics community has advanced rapidly in digitizing specimens and establishing various data portals for natural history collections and biodiversity assessments (Beaman & Cellinese, 2012; Blagoderov et al., 2012; Fig. 3). Some examples of major initiatives are discussed as follows.

The *Global Biodiversity Information Facility* (GBIF, http://www.gbif.org/) is an international open data infrastructure funded by governments. It facilitates the global digitization and dissemination of primary biodiversity data. Since 2004 GBIF has been the largest single gateway to specimen data from herbaria and museums despite deficiencies concerning data quality and lack of a direct feedback mechanism (Yesson et al., 2007).

The JSTOR *Global Plants* (GP, http://about.jstor.org/content/global-plants) database includes more than 2.2 million digitized herbarium type specimens from more than 300 herbaria and museums worldwide as partners. Although GP began with type specimens, it increasingly includes other historical and geographically defined specimens. The JSTOR database grew tremendously for ten years until the main funding by the Andrew W. Mellon foundation ended in 2014. Now a membership fee is in place for those wishing to access the high-resolution images, while the low-resolution images remain available free of charge.

Integrated Digitized Biocollections (iDigBio, https://www.idigbio.org/) is the national resource in the United States for digitized information about natural history collections. Among many diverse functions, iDigBio serves as the coordinating center for a national digitization effort, fosters partnerships and innovations, and promotes the use of collections data in science, education, and other sectors of society. Digitization efforts have also gone beyond the traditional imaging and metadata capture. More recently, digitization has used the principles of automation and crowd sourcing, with minimal initial metadata collection (Blagoderov et al., 2012).

The *Catalogue of Life* (CoL, http://www.catalogueoflife.org/) is a currently available global index of species, with a single integrated species checklist and taxonomic hierarchy. The Catalogue holds taxonomic information on the names, relationships, and distributions of over 1.5 million species. The information is updated regularly from diverse sources around the world.

The *Integrated Taxonomic Information System* (ITIS, http://www.itis.gov) represents a partnership of agencies in the United States, Canada, and Mexico (ITIS-North America), other organizations, and taxonomic specialists. ITIS provides authoritative taxonomic information on plants, animals, fungi, and microbes of North America and the world. It is also a partner of Species 2000 and GBIF.

Some countries have either established virtual herbaria or are in the process of doing so. Perhaps the first one was the Australian Virtual herbarium (http://avh.chah.org.au/). More recent ones are from France, the Netherlands, the United States, and China where progress has been made in digitizing herbarium collections and in disseminating the information. The world's largest herbarium in Paris was digitized during its recent physical renovation (https://science.mnhn.fr/). In the Netherlands, the National Herbarium in Leiden was

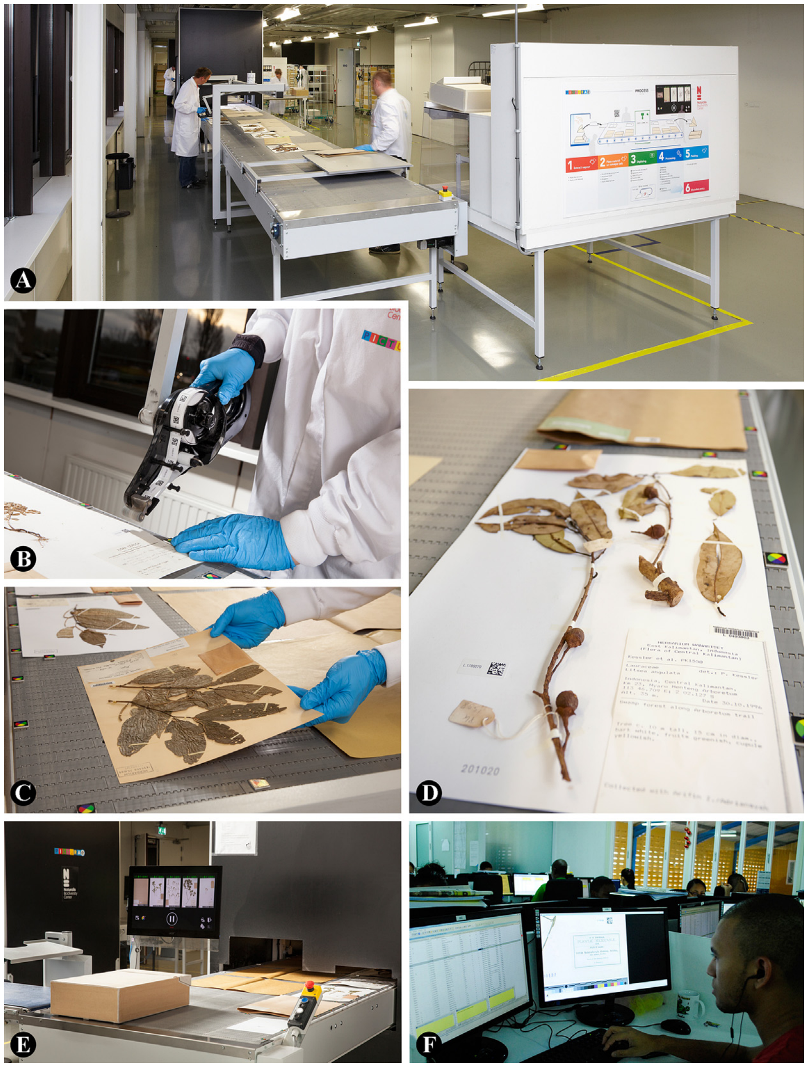

Fig. 3. Workflow for rapid digitization of herbarium specimens, as shown by the digitization in the herbarium in Leiden (L), the Netherlands. **A,** Overview of the digitization pipeline "Herbarium digistreet." **B,** Labeling the herbarium sheets with a barcode. **C,** Herbarium sheet placed on the "Herbarium digistreet." **D,** Close-up of a herbarium sheet with a barcode. **E,** Pictures of scanned herbarium sheets that are automatically cropped and color-corrected. **F,** Metadata being added to a database from scanned herbarium labels (photos by Picturae with permission to use in this paper).

completely digitized in a short timeframe using the digitization pipeline *Herbarium digistreet* (Fig. 3; https://science.naturalis.nl/en/collection/naturalis-collections/botany/). *The US Virtual Herbarium* project (USVH, http://usvhproject.org/) (Barkworth & Murrell, 2012) has its goal digitize all specimens in all United States herbaria, making these data accessible via a single portal iDigBio. Likewise, the *Chinese Virtual Herbarium* (CVH, http://www.cvh.org.cn/) is an online portal allowing access to herbarium specimen information and other botanical knowledge in China. CVH is a collaboration among more than 20 major herbaria in China to create global, comprehensive, and sustainable access to China's plant biodiversity. The project has been much better funded via the main funding agencies in China than the USVH has been in the United States. The *Council of Heads of Australasian Herbaria* (CHAH) (Council of Heads of Australasian Herbaria, 2010, 2013) is an organization comprised of the major herbaria in Australia and New Zealand with the objective of promoting all matters of interest to herbaria in Australasia and increasing cooperation and understanding between herbaria.

BRAHMS (Botanical Research and Herbarium Management System, http://www.brahmsonline.com) is a database management system developed at the Department of Plant Sciences, University of Oxford for botanical research and for managing collections in herbaria, botanical gardens, and seed banks. It provides a platform to gather, edit, analyze, and publish systematic data, optimizing these data for curation services and research outputs. The largest database employing BRAHMS to date is in the Netherlands with the herbarium specimen data of the National Herbarium of the Netherlands folded into this system.

Recent major changes to the *International Code of Nomenclature* (ICN)

Recent major changes to the *International Code of Nomenclature for algae, fungi, and plants (Melbourne Code)* (ICN; McNeill et al., 2012) have had a positive impact on revisionary/monographic systematic studies (Miller et al., 2011). The relevant major changes to botanical systematics include: (i) Starting on January 1, 2012, electronic publication is permitted for new scientific names in Portable Document Format (PDF) in online publications with an International Standard Serial Number (ISSN) or International Standard Book Number (ISBN) (ICN Articles 29–31); and (ii) Starting on January 1, 2012, English may be used as an alternative to Latin for the descriptions or diagnoses of new taxa (Article 39).

Systematists have adopted nomenclatural rules varying by organism that were at first unwritten but later came to be codified in the early 19th century for zoologists (ICZN, 1999) and the late 19th century for botanists, including those who study fungi and algae (de Candolle, 1867; McNeill et al., 2012). Nomenclature for bacteria and viruses, which was in part regulated by earlier botanical codes, is now regulated by a separate code (Lapage et al., 1992). A BioCode was proposed by Greuter et al. (1996, 2011) to provide a unified context for all codes across all organisms, but it was not accepted by the taxonomic community (Flann, 2011). The 2011 IBC in Melbourne declined to consider the BioCode proposal.

In 2013 a user's guide for botanical nomenclature was published (Turland, 2013) and this has greatly expanded the accessibility of the Melbourne Code. In addition IAPT has conducted workshops around the world (e.g., in Argentina, Brazil, and China) teaching the basics of the ICN to hundreds of young scientists. There is little doubt that dealing with botanical nomenclature is complicated and that few people in the community truly grasp the complexities of the ICN, but it is also true that the basic principles are straightforward and can be simply explained. We recommend further actions on the simplification of the ICN along with additional training workshops to ensure the sustainability of nomenclature.

Wealth of online botanical literature

Unlike many other biological disciplines, systematists need to have knowledge and access to historic literature to determine where and when a name was published. Databases of names have become very helpful in the process of determining which name has nomenclatural priority and which should be considered a synonym. Similarly, biographical information with respect to authors of names and collectors of specimens is important because such information is often the key to locate literature and find collections that serve as type specimens. Organization and management of these sorts of collections-based data have improved dramatically in the last few decades.

One of the most useful databases for plant systematists is the *International Plant Names Index* (IPNI, http://www.ipni.org), which came about through a collaboration between the Royal Botanic Gardens, Kew, the Harvard University Herbaria, and the Australian National Herbarium (Croft et al., 1999; Lughadha, 2004). IPNI has been continuously updated since its launch in 1999. The Harvard University Herbaria maintain authority files (http://kiki.huh.harvard.edu/databases/botanist index.html) that are used for editing IPNI. However, with a plant name, its author, and its place of publication in hand it can still be difficult to locate the original publication and protologue. Several printed resources have recently become available electronically. One of the most valuable guides to botanical and fungal literature, which is also of value to zoologists, is *Taxonomic Literature*, ed. 2 (TL-2; 1976–2009; see Schmid & Dorr, 2009). After the final volume of *Taxonomic Literature*, ed. 2 was published, the entire work was made available on-line as a searchable document (http://www.sil.si.edu/digitalcollections/tl-2/) and in a more static form via the *Biodiversity Heritage Library* (BHL) (http://www.biodiversitylibrary.org/bibliography/48631-/summary).

With the digitization of serials and books, collections-based systematics literature is available to anyone with a computer and internet access. For a systematist engaged in writing revisions or monographs, what once was a long, tedious process of locating which library held which volume is now something that can be resolved almost immediately.

Botanicus (http://www.botanicus.org/) introduced about 1995 was an effort by the Peter H. Raven Library of the Missouri Botanical Garden to make digitized copies of botanical literature freely available. Although still available, this Garden effort was subsumed by the efforts of a dozen natural history libraries that launched the *Biodiversity Heritage Library* (BHL, http://biodiversitylibrary.org) in 2005. BHL is now a large, worldwide consortium of natural history and botanical libraries that have digitized over 100 000 titles. Other important and large-scale literature digitization projects that include material of interest to collections-based systematists are *Gallica* (http://gallica.bnf.fr/) and the HathiTrust Digital Library (https://www.hathitrust.org/). The latter is a consortium of universities in the United States, Canada, and Europe and their website offers content digitized via the Google Books project as well as content digitized locally by libraries. Another invaluable resource for locating specimens via a search based on a collector's name is the *Index Herbariorum* (http://sciweb.nybg.org/science2/IndexHerbariorum.asp).

We anticipate that institutions and/or societies will experiment with new interlinked electronic resources in a way that will make monographs more dynamic in the future. Perhaps this represents the area of greatest need for most comprehensive monographic series (e.g., *Systematic Botany Monographs* published by the American Society of Plant Taxonomists), which otherwise have remained relatively classical in their approach.

Innovative rapid publications in systematics

Innovative rapid electronic open access publications in systematics have become established and are gaining popularity in the community. These advances include rapid electronic publications, Open Access, the linkage of electronic registers, indices and aggregators to important taxonomic databases, and the development of Web 2.0 technologies (see Kress & Penev, 2011). In the future, journal articles need to be fully integrated with all of the resources systematists use to formulate their hypotheses such as GenBank (http://www.ncbi.nlm.nih.gov/genbank/) and DRYAD (http://datadryad.org/). We fully expect that these innovative interlinked ways of publication will revolutionize the way we disseminate our research.

A few journals have been designed to rapidly document, analyze, and publish the world's taxonomic diversity. This more innovative model of publication has been pioneered by Pensoft (http://www.pensoft.net/), a leading publisher of open access cybertaxonomy. Pensoft publishes *ZooKeys*, *PhytoKeys*, and *MycoKeys* (Zhang, 2006, 2008; Christenhusz et al., 2009; Penev et al., 2010a, 2010b; Lumbsch et al., 2011). These journals disseminate biodiversity data in both traditional and innovative ways, and register all new nomenclature with databases such as ZooBank (http://www.zoobank.org/) and IPNI (http://www.ipni.org/). These journals also provide species descriptions to the more public oriented *Encyclopedia of Life* (EOL) as part of their routine workflow.

Outlook for 2050

Building the Biodiversity CyberBank — an ambitious global community-wide cyberinfrastructure

An ambitious global community-wide cyberinfrastructure needs to be established and funded long-term by governments, the biodiversity community, the public, and the private sector (also see Wheeler, 2010; Beaman & Cellinese, 2012; Wheeler et al., 2012). We envision the cyberinfrastructure or CyberBank (Fig. 4) to be similar to GenBank for genetic data, but with enhanced multifunctionality and biodiversity collections data as the core, along with links to genetic, ecological, paleontological, morphological, and conservation databases. Such a biodiversity cyberbank will be critical for safeguarding the community-wide data on collections and biodiversity, and for serving as the biodiversity data repository for the scientific community, applied agencies, and the public. Existing efforts especially GBIF and iDigBio have highly compatible goals, and can function as the foundation for a broader biodiversity cyberbank, with more emphasis on serving the broader scientific community with sustainable development of the necessary informatics tools for biodiversity, especially collections-based and integrative systematics.

Establishing a World Organization of Systematic Biology

In the next decades, we believe the global systematics community must reorganize and become a bolder and more forceful entity. This community should seek every opportunity to advance the goals of the discipline. Specifically we should convene an open discussion on the development of a *Systematics Agenda 2050* that includes the future of natural history collections. An earlier effort in the late 1990's and early 2000's was launched and called the "International Federation of Systematic Societies", which had societies as members, but this effort failed because of a lack of strong leadership. To

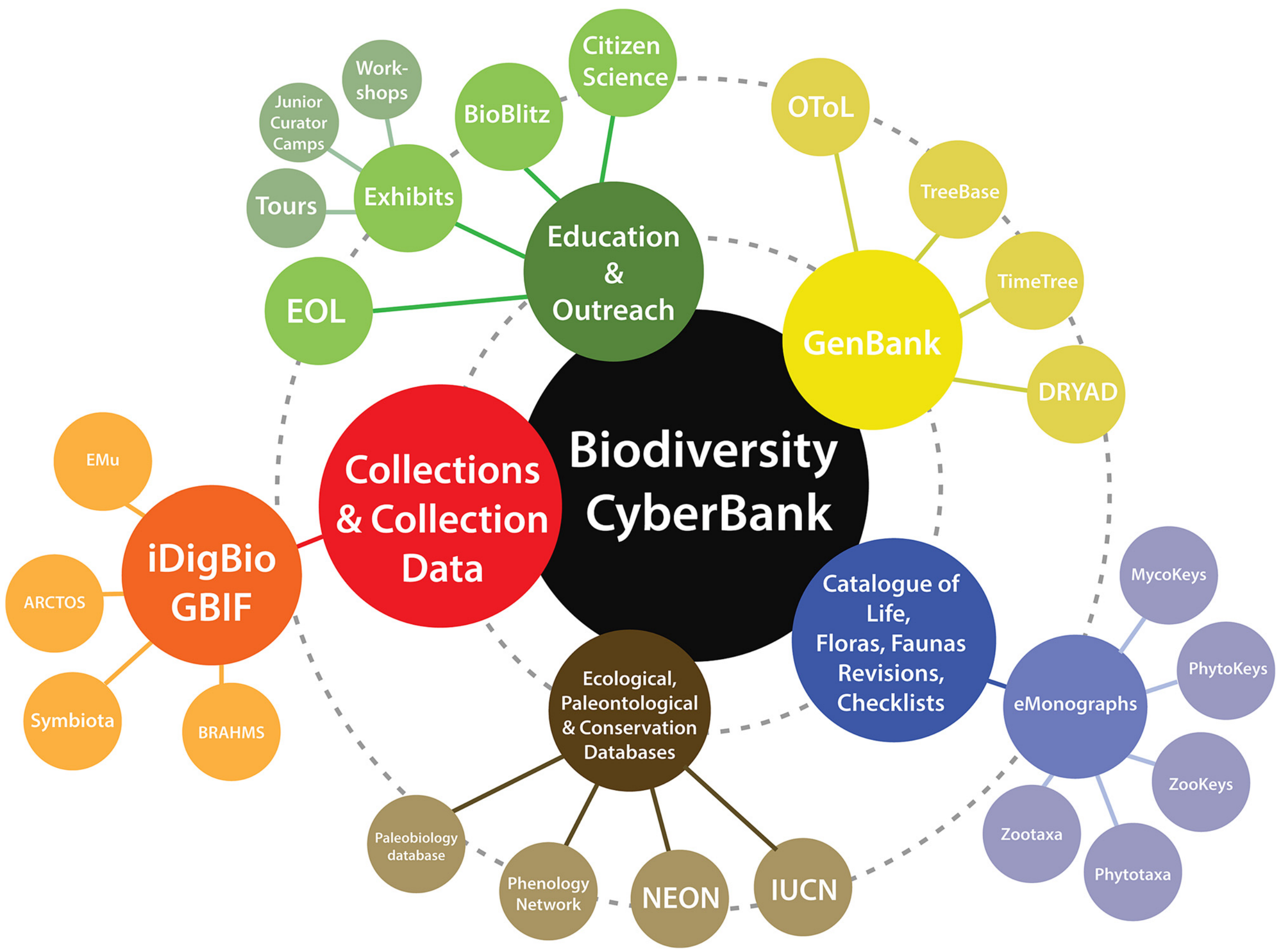

Fig. 4. Vision of the Biodiversity CyberBank, an ambitious global community-wide cyberinfrastructure.

ensure that such an organization survives and accomplishes its goals it should be led by international organizations such as the International Association for Plant Taxonomy (IAPT) and the Society for Systematic Biologists (SSB). In fact, an opportunity to push for a Systematics Agenda 2050 and the World Organization of Systematic Biology is approaching because the global botanical community meets every 6 years at the *International Botanical Congress* (IBC; next meeting in 2017 in Shenzhen, China). The IBC is an excellent platform for botanists to have an open dialogue and create a strategic plan for the healthy development of systematics and collections. If an organization can be discussed and agreed upon at the IBC then it may be easier to involve the SSB.

Preparing next-generation systematists with a solid foundation in systematic collections

Next-generation collections-based systematics research should be designed to be highly integrative, interactive, and stimulating. A revisionary or monographic project should also employ cutting-edge tools available in bioinformatics, morphology, and molecules/genomics and be able to answer important questions concerning delimiting species and higher taxa, biogeographic reconstructions, and hypotheses such as modes of speciation, and morphological character evolution. Although the scientific products from these integrative studies will be highly multifaceted, they will continue to have collections as their foundation. Such creative collections-based programs led by our students will expand the reputation of taxonomy as an important, rigorous, and stimulating scientific discipline.

Next-generation systematists should include systematic collections as an important component in the research program, as well as field work. Field work facilitates the development of evolutionary hypotheses on the plant groups under study. It has been rewarding for us to observe how much our students and interns have enjoyed field classes and field trips with us over the years. The field serves as an open laboratory of systematic biology and is eye-opening for young students who discover the diversity of plants and their interactions with other organisms and the environment. Collections that students and researchers make during their studies also contribute to the overall sustainability of natural history collections.

The systematics community needs to work to facilitate the permitting process for scientific research in systematic biology. One unintended outcome of the Convention on Biological Diversity (CBD) is that it has become more difficult and sometimes impossible to obtain collecting permits in parts of the world with rich biodiversity. Major systematics organizations (societies and associations) should initiate a dialogue with their respective memberships and funding agencies about the importance of fieldwork, training of the next-generation with more field opportunities as well as nomenclature (ICN), and incorporating collections and collections-based questions in broad integrative systematics projects.

Bridging collections-based systematics with other fields of biology without losing the identity of systematics

Collections-based systematics is relevant to many fields of biology. In the past, systematic research on collections has allowed us to document the Cambrian explosion of animals (Marshall, 2006), the 'Big-Five' mass extinctions responsible for a loss of over 75% of species in the last 540 million years (Jablonski, 1994; Barnosky et al., 2011), and the last glacial-interglacial transition from rapid warm-cold-warm fluctuation under climate change (Hoek, 2008; Lenton, 2011; Barnosky et al., 2012). These critical planetary-scale transitions and state shifts would not have been possible to detect without contributions from systematic collections-based research.

At finer scales, the systematic study of herbarium specimens allowed Woodward (1987) to document a decline in stomatal density as a result of increased CO_2 emissions in the industrial era and this has major implications for future aridification scenarios and the spread of C_4 grasses (Edwards & Smith, 2010). The inverse relationship of stomatal density and CO_2 emission has also been used to look at the fossil record to infer CO_2 concentrations in past epochs (McElwain & Chaloner, 1995). Several studies have used herbarium specimens to demonstrate earlier flowering in response to a warming climate (Primack et al., 2004; Panchen et al., 2012) and species distributional dynamics (Feeley, 2012). The hypothesis that climate change is threatening a large portion of the endemic flora of California has been extrapolated from occurrence data on herbarium specimens and niche modeling (Loarie et al., 2008).

Microbial ecology, biogeography, and phylogenetic relationships of microbes such as grass-infecting viruses have been studied based on the preservation of these viruses in herbarium specimens and their human-mediated spread (Borer et al., 2007; Malmstrom et al., 2007). The link between human settlements in the 18th and the 19th centuries and the displacement of native perennial and bunchgrasses in California has been linked to the importation of invasive Mediterranean grasses such as *Avena fatua* L. that carry cereal yellow dwarf viruses and their ability to increase vector populations of yellow dwarf viruses and promote incidences in native grasses thus causing shifts in grassland ecosystem composition in California and other countries (Malmstrom et al., 2007).

Our knowledge of the origin of polyploid crops and their domestication is closely tied to collections-based systematics because the identification of wild relatives involves comparative systematic research based on sampling of wild populations and species to recover putative progenitors (Spooner et al., 2008; Emshwiller et al., 2009). Additionally, ethnobotanical, ethnographic, and archaeological studies often rely on systematics collections in order to better understand which taxa are used by certain ethnic groups, or which materials were used. Several major herbaria have ethnobotanical holdings of vouchered specimens (e.g., BM, F, K, MO, NY, P, and US).

The value of collections-based systematics for society as a whole is also reflected in the use of collections for combatting infectious diseases (e.g., influenza, West Nile virus, hantavirus), agricultural pests, detecting environmental contaminant levels, and studying the many effects of global climate change (e.g., habitat loss and biological invasions; Suarez & Tsutsui, 2004) (Fig. 1).

Developing floras as major platforms for documenting plant diversity as well as educating the public

Many floras have been published (see Frodin, 2001). An example of a significant new flora is the *Flora of China* (FOC).

FOC represents a major achievement of international collaboration, yet it is still a static flora in the traditional sense. Similarly, the ongoing *Flora of North America* (FNA) series is progressing as paper-published volumes covering all vascular plant species found in North America north of Mexico. The format of FNA is similar to that of FOC. The funding for such major floras has been limited and hence the production of FNA has been slow.

In the future, floras should be electronic. They should be online, searchable, with interactive keys, images of diagnostic characters, morphological descriptions, ecology, conservation status, distribution, collections-data to model future distributions, and have links to species biology. Several e-flora projects have done a good job and examples include the Jepson e-flora (http://ucjeps.berkeley.edu/IJM.html), the Flora da Reserva Ducke (http://peld.inpa.gov.br/publicacoes/guias), and Flora of Nepal On-line Accounts (http://padme.rbge.org.uk/floraofnepal/?page=onlineflora).

In addition to floras, we also value electronic field guides in engaging the public on biodiversity. As an example, the *Leafsnap* project (http://leafsnap.com/) utilizes visual recognition software to help identify species from photographs. *Leafsnap* is a series of electronic field guides being developed to help identify tree species from photographs of their leaves and also contains high-resolution images of their flowers, fruits, petioles, seeds, and bark. It was originally developed in the United States but has become an international effort with pilot projects in the United Kingdom, and elsewhere. This type of project reaches broad audiences using personal electronic devises of individuals who are interested in the woody flora of their respective country.

Charting next-generation monography and taxonomic revisions in the bioinformatics era

A monograph of a natural group of plants (i.e., a subgenus, a genus, or a family) is a comprehensive account of all the taxonomic data relating to that group, involving the integration of previously known information with results of the monographer's own research (Stuessy, 1993). A monograph usually covers the entire geographic range of the taxonomic group and includes a complete synonymy, descriptions, and a detailed listing of ecological, geographical, cytological, chemical, and anatomical information (e.g., Wen, 2011), while a revision is restricted to a certain geographic region (e.g., Wen & Shi, 2012). Monographs and revisions differ primarily in their scope and completeness (see Stuessy & Lack, 2011; Marhold et al., 2013).

A more efficient taxonomic synthesis needs to be produced, not only for taxonomists, but also for other colleagues in biology and conservation. Monographic and revisionary studies should include ample experimental data to test species delimitations and to take full advantage of online resources (e.g., images of specimens including types, original species descriptions and subsequent early publications, and online and georeferenced collection data) and bioinformatics and analytical tools. So far few studies have been published utilizing all of the available resources.

The systematics community needs to develop methods for more efficient taxonomic syntheses so that taxonomists can produce their work more quickly, making the monographs available to colleagues in other disciplines of biology such as conservation. Carvalho et al. (2015) published such an example of an e-monograph of the economically important papaya family, Caricaceae, in order to showcase the use of biodiversity informatics tools (http://herbaria.plants.ox.ac.uk/bol/caricaceae). The authors brought together all information on this family, including keys, species descriptions, specimen data, and morphological characters, and assigned the 230 published names to 34 recognized species and one hybrid. The treatment can be continuously updated electronically to improve the monograph's quality and utility. Such studies should be undertaken regularly by the collections-based systematists.

We herein outline a new workflow for taxonomic monographs (Fig. 5), which utilizes the traditional strengths of synthesizing diverse collections-based taxonomic data and the capacity of online resources and bioinformatics tools. We also advocate that species distributions incorporate collections data and niche modeling, with the capacity to predict future range dynamics, broadening the utility of systematic treatments, keeping in mind, of course, that collections data from online sources may contain misidentified specimens (Meier & Dikow, 2004; Garcia-Milagros & Funk, 2010). With decreasing costs of DNA sequencing and genomic approaches, it is anticipated that 21st century monographs will have explicit tests of species concepts and criteria of species delimitations. Detailed distribution data coupled with niche modeling should enhance the conservation value of taxonomic monographs. We especially promote e-monographs for the next decades, for efficient and broader dissemination of scientific results. The format may allow some form of hard copy to be produced from online resources. For example, one may only need the taxa in a country for fieldwork, such an e-monograph should be able to generate such data, including a key for the region of interest. In short, the format should be versatile enough that users could set up what they desire to use.

Revitalizing herbaria and natural history museums to engage the public more readily

Museums and herbaria house natural history/systematics collections and are the window into biodiversity: past, present, and future (Funk, 2003a, 2003b; Thomson, 2005; Johnson, 2015). Natural history museums serve a critical role in preserving our Earth's past and educating the public about the planet (Powers et al., 2014; Johnson, 2015). New challenges and evolving expectations are transforming museums and herbaria around the world. A critical issue concerns the role of science in a major museum. Wide applications of personal electronic devices (e.g., iPhone, iPad) and the availability of digital information provide us with new ways to engage the public and share with them information about our collections and science. In addition, natural history museums and herbaria have the potential to expand their roles in explaining scientific discoveries through public education. Citizen- and crowd-source science is another excellent way to engage the public. This area has been utilized by the community and clearly has tremendous potential to develop further. Perhaps this engagement with the public can be used to strengthen support for our institutions and combat what seems to be a rise in indifference by local and national governments as to the importance of museum and university collections.

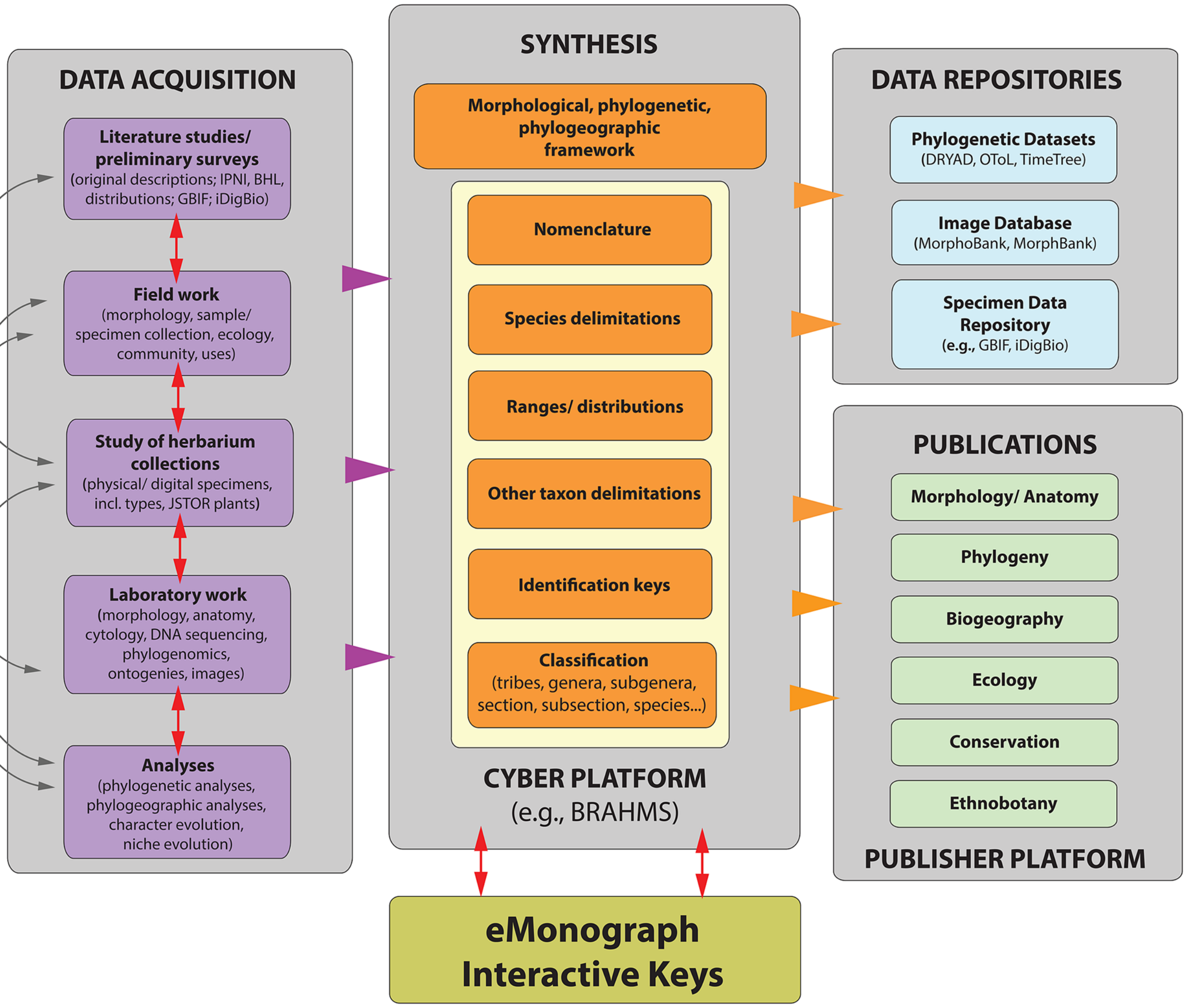

Fig. 5. Workflow of modern plant monography utilizing integrative systematic data and various portals for data dissemination and e-monograph production.

A successful example of advancing an herbarium with coordinated development in the strengths of both science and public programs is the University and Jepson Herbaria of the University of California, Berkeley. Their active research is complemented by the major role they play in the Consortium of California Herbaria (http://ucjeps.berkeley.edu/consortium/). They have helped pioneer data portal development and eFlora projects, and have an active public education program. In addition the molecular lab and the herbarium are well integrated and are incorporated in the plans for the future. Such examples should be sought out and highlighted by the systematics community.

To appropriately appreciate and properly steward biodiversity, ecosystems, and cultural heritage on which our society depends, society needs an extensive and constantly expanding environmental knowledge base. It is imperative that this knowledge base be founded on vouchered observations of nature, and that this knowledge be accessible to all of society, not just one segment of it, so that we can learn to live sustainably on our planet. The systematics community needs to share their systematic knowledge with the general public more readily and engage intensely in public outreach and put more effort into fund-raising in the next decades. Furthermore, collection-based science is the soul of museums and herbaria and it should retain its central role in the multifaceted museums and herbaria of the 21st century.

Conclusions

Natural history collections are important for inventorying the world's biota, undertaking comparative evolutionary analyses, and understanding patterns and processes of biodiversity evolution and assembly of life on Earth (Lane, 1996). Collections and collections data continue to play a significant role in transforming biology in the 21st century. The primary mission of natural history collections has been to serve the communities of systematic biology and biodiversity sciences, and the roles of collections in education and outreach have become more and more prominent in the 21st century (see also Fig. 4).

Digitization of specimen collections and their availability online have progressed dramatically in the last decade

(Vollmar et al., 2010; Beaman & Cellinese, 2012; Haston et al., 2012; Tulig et al., 2012) with many new projects posting data. Yet the community still awaits major progress toward a user-friendly community-wide system to collect, edit, and publish collections-based research such as monographs, revisions, checklists, and floras, and to provide a means for the public to use and contribute to such efforts. More broadly used systems or tools such as BRAHMS have appeared attractive with the potential capacity to link collections, research, and outreach. Nevertheless, such a system needs the infusion of major funding to enhance its efficiency and its utility for the broader botanical community.

With advances in bioinformatics, DNA systematics, and phylogenomics, collections-based systematics needs to be part of an important enterprise of a new era of taxonomy tackling important questions in evolution and gaining insights into biodiversity assembly. Isolated efforts on pure morphological and type-based taxonomy are still vital to our overall understanding but they need to be linked to larger efforts to be maximally useful. Collections-based systematics in the 21st century should be highly integrative, and represent part of an exciting and rigorous program of exploring the evolution of biodiversity in the field, in herbaria or museums, and in the laboratory using cutting-edge tools, methods and theories, and defining and classifying species and taxa objectively.

Changes in the ICN, the availability of e-resources, and more rapid means of publications will facilitate information dissemination of future monographs (see also Marhold et al., 2013). It is essential that authoritative information on nomenclature and species distributions, and high-quality data by taxonomists in revisions and monographs are made widely accessible to the biological community and the public, especially concerning numerous economically important plant groups (Kress, 2004; Scotland & Wood, 2012; Carvalho et al., 2015). Training in collections informatics needs to be emphasized and executed for future revisionary, monographic, and floristic projects. Botanical nomenclature is not easy for a newcomer to taxonomy and the systematics community should increase training in this area.

The journey for charting the biosphere continues in the 21st century, for collecting and curating specimens, for scientific studies on biodiversity today, and for future generations. Collections today play an unprecedented role in documenting climatic and biodiversity changes, and shifts in the critical age of our time of the Anthropocene.

Biological sciences have become highly collaborative and multidimensional in the last decades (Beaman & Cellinese, 2012). Collections-based systematists should recognize the interactive and dynamic roles of natural history collections in today's biology. Nevertheless, collections-based systematics should not be eroded and side-tracked and should maintain its identity as an essential component of today's biological sciences. We are aware that many natural history museums and herbaria face major challenges in funding and that there is an uphill battle in defending the need for such collections, but we think that taking a proactive role in promoting collections-based science is the best path to a stable future.

Perhaps, the most critical need at present is a strong effort by the entire systematics community to strategically plan a *Systematics Agenda 2050* and to move forward with collections-based approaches as its core to chart the biosphere, unravel the evolutionary assembly of the floras and faunas and their interactions in the era of genomics and bioinformatics, and conserve the biodiversity of our planet in the challenging times of the Anthropocene.

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