Enabling botanical collaboration through digitization of the Meise Botanic Garden and Central African herbaria

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Abstract

Collected over centuries of field explorations, herbarium collections provide a permanent record of global plant diversity. Knowledge derived from specimens has made important contributions to botanical research. However, collections are still underused due to their accessibility, which is especially critical for researchers from developing countries. The earliest collections in tropical regions were often made during European exploring expeditions, and a large share of these specimens are stored in European institutions, hampering traceability. Digitisation of collections removes the obstacle of untraceability. Meise Botanic Garden made significant efforts in digitising its herbarium collections, including the largest collection of vascular plants from Central Africa on a global scale, increasing knowledge-sharing and collaboration with researchers from DR Congo, Rwanda and Burundi. In addition, Meise Botanic Garden continues its efforts in rehabilitation and digitisation of collections housed in tropical African institutions, including the Herbarium of the Institut National pour l'Étude et la Recherche Agronomiques at the Yangambi Research Station. The European initiative DiSSCo (Distributed System of Scientific Collections) offers new perspectives for increasing access to digital collections by ensuring that all collection data is easily findable and accessible.

Key words: Biodiversity, Africa, Digitisation, Herbarium, Natural history collections

A glimpse into herbaria's historical roots

The roots of herbaria can be traced back to the collection and preservation of medicinal plants, which were initially bound in books and predominantly held within private collections (Thiers 2020). The 16th century practice of pressing and preserving plants in bound books rapidly gained popularity across Europe, leading to the establishment of personal collections among researchers who eagerly exchanged specimens with fellow botanists. During the 18th century, Carl Linnaeus faced the challenge of reordering collections according to his classification system, and to facilitate this, he separated herbarium sheets that allowed for easy reordering and proposed a standardised sheet size. These standards, with minor variations, continue to be utilised today. Remarkably, the appearance of herbarium specimens has remained largely unaltered over the past few centuries, as the preservation method of pressing and drying plants on paper has stood the test of time, allowing these botanical treasures to endure for centuries under appropriate storage conditions.

While herbaria may be perceived by outsiders as stagnant repositories, they have always served as open data sources (even long before the advent of the term "open data"). By exchanging material and sending specimens on loan they not only laid the foundation for plant taxonomy but also offered a vast array of botanical data, making them indispensable resources for researchers worldwide. Taxonomists became progressively aware of the importance of referencing specimens as permanent vouchers for taxonomic publications, a practice finally translated into an obligation in the Botanical Code (Turland et al. 2018).

Today, herbaria encompass vast collections of preserved plants and associated data meticulously catalogued within publicly accessible institutions. Globally, there are over 3,100 registered herbaria, collectively storing more than 390 million plant specimens (Thiers 2023). The largest collections are found in European and North American institutes. Most of them, although rooted in earlier times, expanded between the late 18th and early 20th century when botanical knowledge expanded exponentially (Park et al. 2023).

Among these institutions, Meise Botanic Garden has a long history dating back to 1827, when Belgium was under Dutch rule (Diagre-Vanderpelen 2011). Today the herbarium (BR) houses about 4 million specimens, including notable collections like the private and worldwide herbarium of Carl von Martius and Henri Van Heurck and the important rose collection of François Crépin, a world reference collection of Central African plants, acquired mainly during Belgian’s colonial period, a well-documented and extensive collection of Belgian and South-West European plants, and various other collections of mosses, algae, lichens and fungi. Over time, the geographical focus of the collection shifted from Latin America

(mid-late 19th century) and Belgium (19th century) to Central Africa (20th century) and South-West Europe (late 19th and 20th century), and more recently other regions such as the Antarctic region, and the Indo-Pacific. The shift from Latin America to Central Africa reflects the colonization of the Congo by Belgium in the late 19th-early 20th century. The shift from Belgian collections to south-west European collections on the other hand reflects the increasing possibilities for amateur and professional botanists to travel more easily over longer distances. It is noteworthy to mention that the majority of the collections housed in the herbarium of Meise Botanic Garden were not collected by staff members but by external researchers and collectors.

The diverse applications and future relevance of herbarium collections

Herbarium collections have historically played a pivotal role in botanical research. However, in an era of advancing technologies and changing research priorities, questions may arise regarding the continued relevance of herbaria. Recent studies are presented convincing evidence supporting the continued significance of herbarium collections, highlighting a substantial rise in the use of herbarium specimens across various botanical research fields (Besnard et al. 2018, Carine et al. 2018, Heberling et al. 2019, Bakker et al. 2020, Davis 2023).

Herbarium collections have been and still are mainly used for taxonomy. Herbarium collections facilitate the description and accurate identification of plant species, and act as repositories for vouchers, including type specimens, ensuring repeatability of taxonomic studies. Additionally, herbaria serve as sites for species discovery, as numerous undescribed species await identification within their collections (Bebber et al. 2010).

Herbarium specimens offer a wealth of useful data for a range of biodiversity studies due to the diverse information they encapsulate. Each specimen holds a unique narrative that begins with the label, providing essential details such as the time, location, and habitat of the collection, along with a taxonomic identification. Additional labels indicate ownership, curational notes or identification labels, and provide information on the travel history of the specimens through collections or on the application of taxonomic concepts used by researchers. Beyond this valuable contextual information, morphological and anatomical data can be extracted from the physical specimen. Additionally, herbarium specimens can yield genomic and biochemical data, enabling genetic analyses and investigations into metabolic processes.

By considering this collective information contained within herbarium specimens, researchers can gain a multifaceted and comprehensive understanding of biodiversity, contributing to a wide range of studies.

Indeed, researchers are discovering innovative uses for herbarium specimens, expanding the breadth of knowledge they can provide. Examples include ecological and phenological research, including global change biology (e.g. Dolan et al. 2011, Davis et al. 2015, Willis et al. 2017, Meineke et al. 2018, Bauters et al. 2020), invasive species research (e.g. Groom et al. 2019), conservation biology (e.g. Nualart et al. 2017, Stévart et al. 2019, Albani Rocchetti et al. 2021), and ethnobotanical studies (e.g. Souza & Hawkins 2017). The ability to extract DNA from herbarium specimens also opens new avenues for phylogenetic and evolutionary research (e.g. Bakker 2017, Leliaert et al. 2018), as well as integrated taxonomy where for example DNA sequencing of type specimens can help to resolve long standing nomenclatural problems (e.g. Vieira et al. 2016, Leavitt et al. 2019).

Enhancing accessibility of herbaria through digitisation

One persistent challenge associated with herbaria has been their limited accessibility. Researchers often face the hurdles of requesting specimens on loan, which carries risks of damage or loss of collections, or the need to travel to institutions where the collections were housed. Limited access to collections is especially critical for researchers from developing countries, who often lack the financial means to visit European or North American institutions to study specimens, and small collections in remote places. This is especially problematic given that the earliest collections in tropical regions were often made during European exploring expeditions, and as a consequence a large share of these specimens are stored in European collections institutions, hampering accessibility for researchers overseas.

In response to these challenges, a transformative trend has emerged over the past three decade, with institutions worldwide undertaking initiatives to transcribe label data, digitise specimens, and make specimen text and image data openly accessible online (e.g. Barkworth & Murrell 2012, Thiers et al. 2016, Le Bras et al. 2017, Helminger et al. 2020). Digital records of collection specimens have been mobilised through institutional data portals, as well as through international data infrastructures such as the Global Biodiversity Information Facility (GBIF). To improve discoverability of these digital records on the internet, permanent persistent identifiers (PID) have been proposed, such as URLs, DOIs, and CETAF Stable Identifiers (Hardisty et al. 2021).

This has granted unprecedented access to herbarium collections for the global research community, including researchers from developing and tropical countries. It should be stressed, however, that digitization does not replace the need to physically study specimens, but that it first and foremost serves findability (knowing what is kept where), and on top of that the digital images may serve additional purposes which do not require physical examination.

The herbarium of Meise Botanic Garden has been at the forefront of this movement, with a commitment to fully digitise its collection. This comprehensive effort involves imaging the specimens, digitising associated data, and making both images and data openly available to everyone. The journey towards digitisation began with several pilot projects initiated as early as 2003, within the EU funded ENBI (European network for biodiversity information) project (Los & Hof 2016). In 2004, Meise Botanic Garden joined forces with the African Plants Initiative, funded by the Mellon Foundation (Smith & Figueiredo 2014). As part of this collaboration, Meise Botanic Garden digitised 60,000 botanical type & historical specimens, making them accessible on the JSTOR (short for 'Journal Storage') Global Plants website (https://plants.jstor.org).

Building on this progress, Meise Botanic Garden received substantial grants from the Flemish government in 2015 and 2019 to embark on two large-scale digitisation projects, aimed at digitising 2.7 million herbarium specimens (De Smedt et al. 2016). To achieve this ambitious goal, Meise Botanic Garden collaborated with Picturae, a specialised Dutch service provider specialised in the field of large-scale digitisation of libraries and natural history collections. This resulted in a high-speed conveyor belt system, capable of imaging approximately 4,000 specimens per day. While detailed technical aspects are beyond the scope of this article, figure 1 highlights the workflow that facilitates the publication of images and data, as well as the long-term preservation of the images for future generations (Guiraud et al. 2019, Nieva de la Hidalga et al. 2020, De Smedt & Bogaerts 2022).

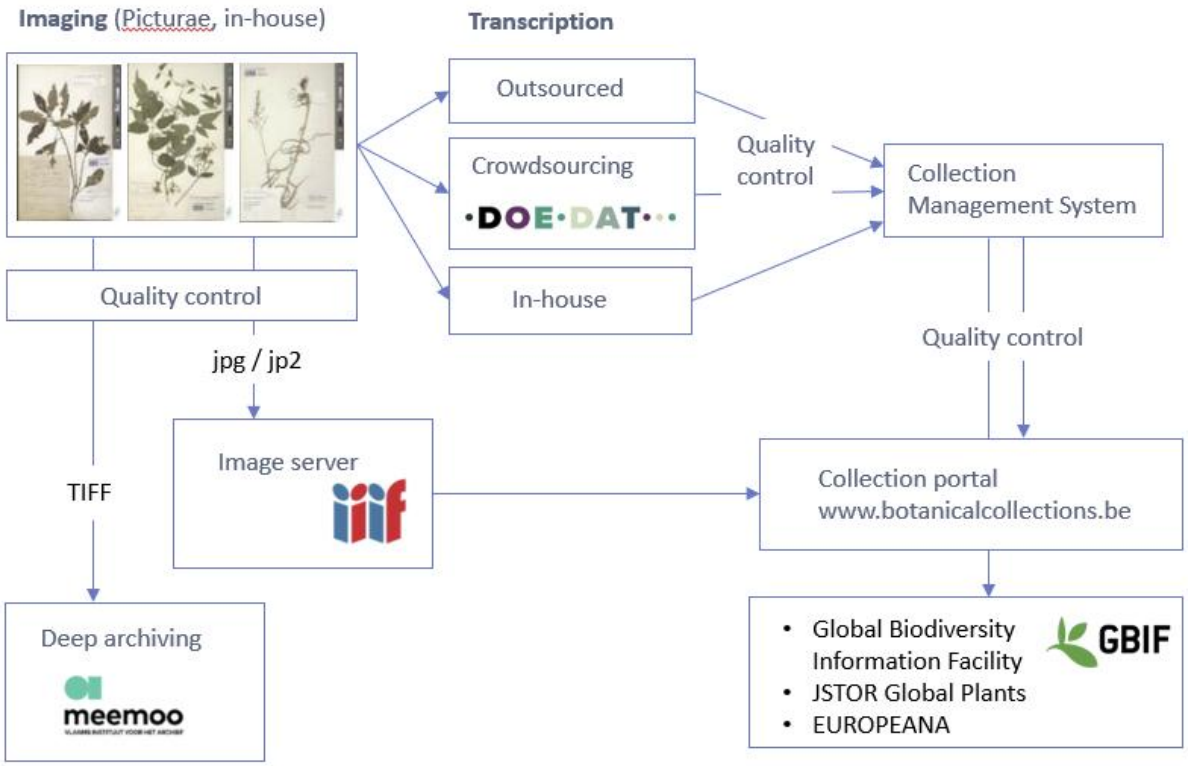

Fig. 1. Simplified workflow for the online publication of images and data, as well as the long-term preservation of the images.

In 2018, Meise Botanic Garden launched its own virtual herbarium platform (www.botanicalcollections.be) serving as a centralised hub for accessing all the digitised images and associated data. This user-friendly platform provides easy search functionalities, enabling researchers and enthusiasts worldwide to explore the collection seamlessly, and makes the collection data machine readable (Fig. 2). In addition images and data are available on GBIF (Meise Botanic Garden 2023a).

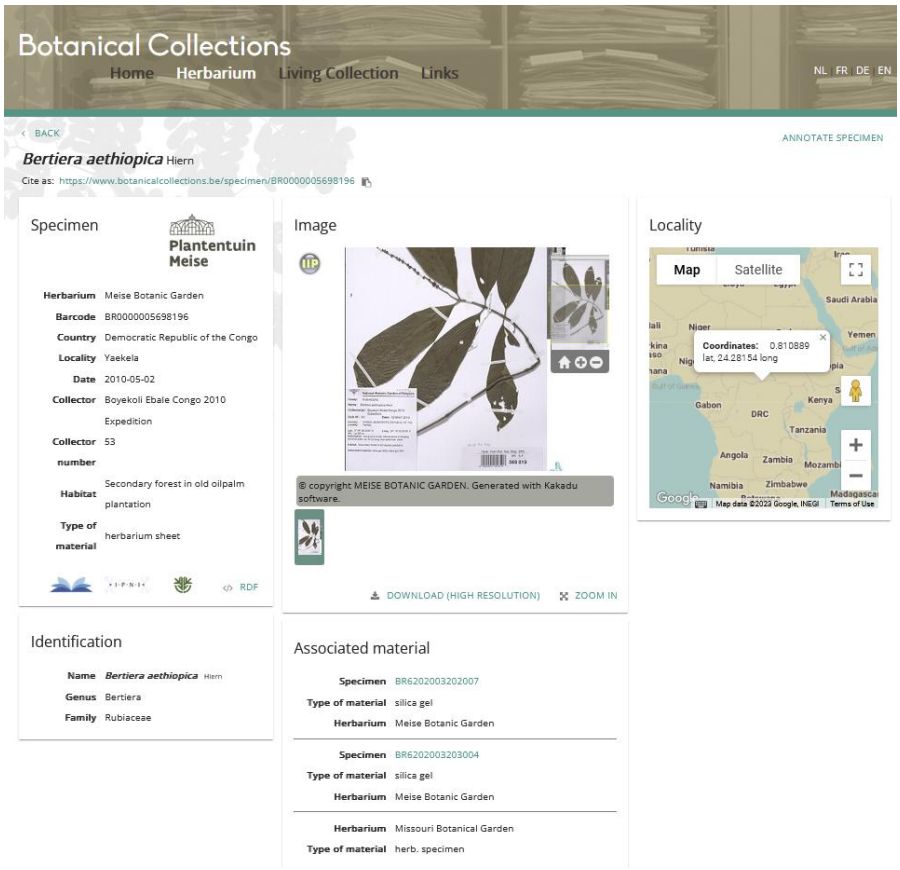

Fig. 2. Screenshot of the virtual herbarium platform of Meise Botanic Garden (www.botanicalcollections.be), showing a specimen of *Bertiera aethiopica* collected from Yaekela, DR Congo (BR0000005698196) with CETAF stable identifier (https://www.botanicalcollections.be/specimen/BR0000005698196), a machine-readable (RDF) metadata record, collection data, taxonomic identification, a high-resolution image of the herbarium specimen, a map showing the collection locality, associated material within Meise Botanic Garden and other institutions, and links to external platforms.

An essential aspect of the digitisation process involves the transcription of label data and the enrichment of information, such as adding geographical coordinates. In addition to in-house transcription by professional herbarium staff, Meise Botanic Garden also engages citizens in their work through a crowdsourcing platform called DoeDat (www.doedat.be) (Fig. 3). This participatory approach allows interested individuals to contribute their time and efforts to enhance the accessibility and richness of the digitised herbarium data. Citizens' input undergoes quality control administered by the QC officer at Meise Botanic Garden. The officer consistently validates a selection of specimens from each contributor and offers feedback as needed.

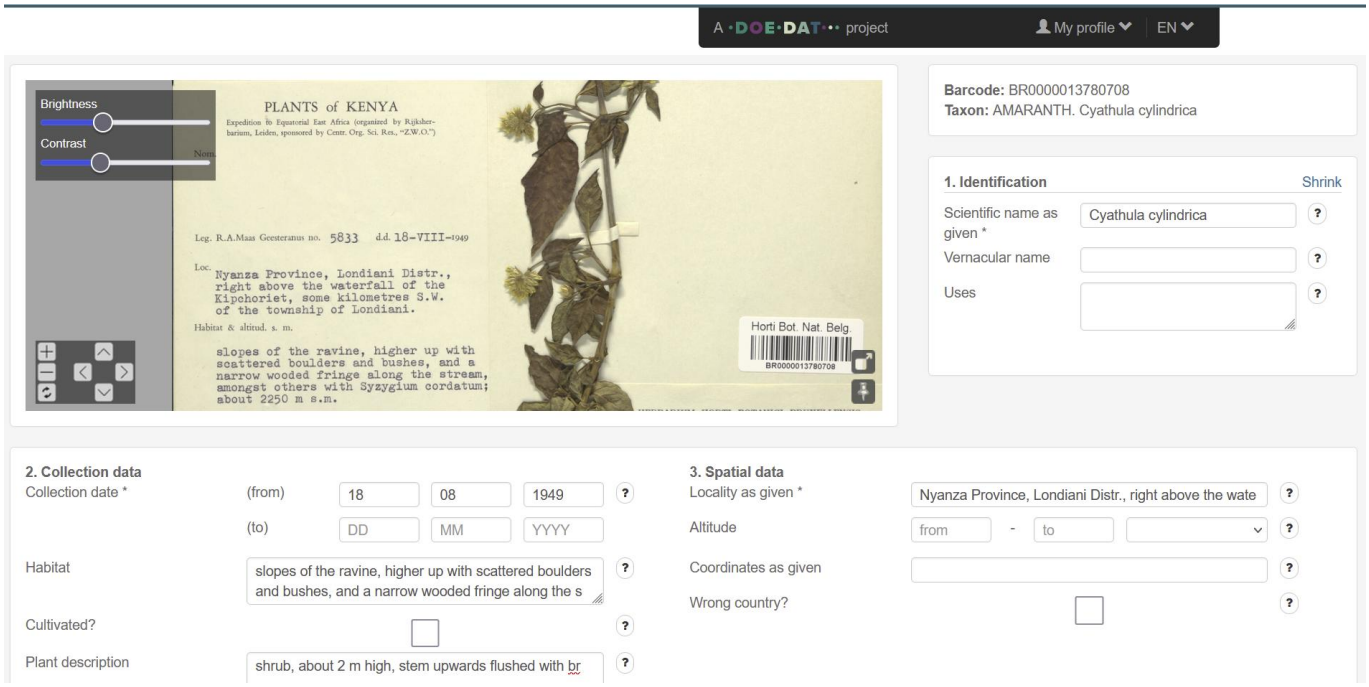

Fig. 3. Screenshot of the crowdsourcing platform DoeDat (www.doedat.be), where citizens can contribute in the transcription of label data from herbariumspecimens, including data on taxonomic identification, collection data and more.

Through these concerted efforts in digitisation, the Meise Botanic Garden Herbarium has emerged as an example of accessibility, bringing collections out of the dark and into the digital realm. In the 5-year period between 2018 and 2022, more than 1.5 million digital specimens were consulted on the Meise Botanic Garden herbarium portal and international platforms such as GBIF and JSTOR Global Plants (Meise Botanic Garden 2023b). By providing open access to the digitised specimens and their associated data, Meise Botanic Garden fosters collaborative research, transcending geographical boundaries and

empowering researchers to unlock the wealth of botanical knowledge contained within herbarium collections.

Digitisation of DR Congo's herbarium collections

Recognizing the need to rehabilitate infrastructure, contribute towards management, accessibility and capacity building of herbarium collections situated in tropical Africa, Meise Botanic Garden has been at the forefront of initiatives, actively contributing to the preservation and digitisation of DR Congo's important botanical resources over the past two decades.

Initially, the focus of rehabilitation efforts centred on restoring the botanic gardens of Kisantu (Province of Kongo Central) and Eala (Mbandaka) (Province of Équateur) with EU funds between 2004 to 2008. Subsequently, with support of the EU projects REAFOR ('Relaunch of Agricultural and Forestry Research in the Congo', 2005-2009) and REFORCO ('Forestry Research in the Congo', 2009-2013), the building and equipment of the herbaria of Kisantu (Province of Kongo Central), Kisangani and Yangambi (Province of Tshopo), and Kinshasa (Province of Kinshasa) were rehabilitated. The INERA herbarium in Yangambi is fully equipped for preservation, digitisation and research on herbarium samples and has autonomous electricity supply by solar panels and batteries. In other institutes more focussed interventions were made, e.g. by providing equipment for digitisation and disinfection. Additionally, Meise Botanic Garden supports the rehabilitation, evaluation and valorisation of the *ex situ* coffee collections in Yangambi (within the EU funded FORETS project, coordinated by the Center for International Forestry Research, CIFOR) and in Lwiro (project funded by the King Baudouin Foundation).

From 2007 onwards, Meise Botanic Garden expanded its activities to include the digitisation of nomenclatural types and specimens from species endemic in Central Africa, from ten herbaria across DR Congo and Burundi (Table 1). This initiative was made possible through the support of the African Plants Initiative, Sud Expert Plants, and the EU. As a result of these collaborative efforts, over 10,000 historical specimens stored within African herbaria, have been successfully digitised and made available online on https://plants.jstor.org (Mwanga Mwanga et al. 2014).

In parallel with the ongoing rehabilitation and digitization, capacity building activities for local herbarium staff and botanists were organised in DR Congo as well as in Meise in the framework of the above mentioned projects, as well as the GBIF Biodiversity Information for Development program (GBIF BID, https://www.gbif.org/fr/programme/82243/bid-biodiversity-information-for-development). These capacity building activities comprises training in fieldwork, identification, all aspects of collection management and digitisation. Dozens of collaborators from more than 12 institutions in Central Africa

were trained. Collectively, these efforts are creating a solid foundation for durable conservation, research and digitisation endeavours of the Central African plant diversity.

Table 1. Herbarium collections in DR Congo and Burundi, with numbers of herbarium specimens digitised in the framework of the Global Plant Initiative project, and available on JSTOR Global Plants. Note that BJA, LWI, LUKI, and YBI have continued their digitisation efforts, with total numbers of digitised specimens indicated between brackets.

Institution with Index Herbariorum code between brackets	Number digitised specimens	Period of digitisation
Centre de Formation et de Recherche en Conservation Forestière – ICCN, Epulu, DR Congo (EPU)	190	2014
Centre de Recherche en Sciences Naturelles – CRSN, Lwiro, DR Congo (LWI)	1,072 (2,891)	2011-2012, 2018
Institut National pour l'Étude et la Recherche Agronomiques, Kipopo, DR Congo (KIP)	1,434	2012-2013
Institut National pour l'Étude et la Recherche Agronomiques, Mulungu, DR Congo (MLGU)	618	2011-2012
Institut National pour l'Étude et la Recherche Agronomiques, Luki, DR Congo (LUKI)	294 (329)	2011, 2013
Institut National pour l'Étude et la Recherche Agronomiques, Centre de Recherches, Yangambi, DR Congo (YBI)	4,345 (11,723)	2010-2011, 2017, 2019-2020
Jardin Botanique d'Eala, Mbandaka, DR Congo (EALA)	17	2013
Jardin Botanique de Kisantu – ICCN, Inkisi-Kisantu, DR Congo (KISA)	184	2011

Université de Lubumbashi, Lubumbashi, DR Congo (LSHI)	1,021	2012
Institut National pour l'Étude et la Recherche Agronomiques, Kinshasa & Université de Kinshasa, Kinshasa, DR Congo (IUK)	3,157	2012-2013
University of Burundi, Bujumbura, Burundi (BJA)	4,383 (3,000)	2011-2013, 2021

Among the herbarium collections within DR Congo, the Yangambi herbarium stands out as the most significant, housing approximately 150,000 specimens (Ndjele & Lituka 2023). With a long and storied history, the Yangambi herbarium served as the main repository for plant specimens in Central Africa during the period from 1933 to 1962 when it was part of the Institut National pour l'Étude Agronomique du Congo belge (INEAC). Subsequently, it became a part of the Institut National pour l'Étude et la Recherche Agronomiques (INERA) in 1970.

The rehabilitation and digitisation of the Yangambi herbarium have been significant undertakings (Fig. 4). While the collection itself has been preserved in a relatively good state by INERA staff, the infrastructure had suffered from neglect, and the bulk of the herbarium specimens remained unmounted and unlabelled. In 2007, efforts were initiated by Meise Botanic Garden to assess the situation and began the necessary actions to restore the herbarium's physical space. From 2011 to 2018, EU-funded projects such as REFORCO and FORETS, coordinated by CIFOR and executed by Meise Botanic Garden played a crucial role in the restoration process. These projects focused not only on rehabilitating the infrastructure, including buildings and the installation of solar panels and equipment but also on restoring, mounting, and labelling of the herbarium specimens, prior to digitisation. In addition, training programs were implemented to build capacity in databasing and digitisation techniques, ensuring the sustainability and long-term success of the digitisation efforts.

Today, thanks to the availability of extensive historic data (kept in the archives, herbaria, xylotheca, and (grey) literature, as well as the presence of old experimental plots and the reserve) Yangambi, as well as Luki, do have huge potential for biodiversity research and conservation. Thanks to this unique historic heritage, the rehabilitation of the collections and the creation of new research infrastructures, Yangambi and Luki represent modern research hubs, facilitating cutting-edge research activities focused

on biodiversity, wood biology, sustainable forest management, and climate change monitoring (Beeckman 2019, Vanden Abeele et al. 2021, Sibret et al. 2022).

Fig. 4. Rehabilitation and digitisation of the Yangambi herbarium. (a,b) Restoration and mounting of herbarium specimens, (c) Databasing, (d) Digitisation. Image courtesy of Axel Fassio/CIFOR (a-c) and Alonso Austerio (d).

The fragmented landscape of natural history collections: towards digital unification

While the availability of collection data online is a promising development, the landscape of natural history collections remains highly fragmented on a global scale. Thousands of institutions worldwide house valuable collections, leading to significant challenges in finding and using them effectively. Given the physical impossibility of consolidating all collections in one location, efforts have focused on achieving defragmentation at the digital level.

In addition, although large-scale digitisation efforts have made large volumes of collection data openly accessible on the internet, these have largely remained disconnected from associated and derived data. Addressing this challenge, the Distributed System of Scientific Collections (DiSSCo) has emerged as a pioneering initiative funded by the European Union (Raes et al. 2020). DiSSCo brings together 114 museums from 21 European countries, and over 5,000 scientists, united by a common vision to unify

natural history collections into one comprehensive digital repository. By digitally unlocking these collections, DiSSCo aims to revolutionise research possibilities by interconnecting various collections and integrating them with other data streams. On other continents, similar large-scale infrastructure initiatives have been initiated, including the US-based iDigBio (Integrated Digitized Biocollections), the National Specimen Information Infrastructure (NSII) of China, and the Atlas of Living Australia (ALA). On a global level, GBIF acts as a central aggregator, harmonising and integrating biodiversity data from various sources, including biological observations and taxonomic checklists, into a standardised format. The core concept behind DiSSCo and infrastructures alike revolve around the creation of digital extended specimens (also known as digital specimen, open digital specimen or extended specimen) which allows for entirely new ways of interacting with collections compared to physical specimens alone (Lendemer et al. 2020, Hardisty et al. 2021, 2022) (Fig. 5). In a digital extended specimen, the physical specimen remains at the core, but is augmented by a "digital twin" that may incorporate collection data, taxonomic information, a scanned image of the specimen, etc. Leveraging information technology, the digital specimen can establish machine-readable connections to various types of associated data (including literature, DNA sequences, taxonomic treatments, trait data, etc.), enabling unprecedented data integration and discovery.

The digital extended specimen encompasses both authoritative data, which consists of the primary specimen data provided by the collection provider (i.e. information directly related to the physical specimen, typically extracted from its label, including taxonomic identification, collector name, locality, date, and institutional information), and non-authoritative data, including derived and associated data, as well as images and other forms of media (Hardisty et al. 2022). Derived data are acquired directly from the physical specimen, and include for example morphological traits and DNA sequence data. Associated data, on the other hand, are not directly derived from the specimen, and include for example taxonomic and nomenclatural information, species descriptions, and the species' conservation status. It is important to note that a digital extended specimen does not necessarily store all the actual data but rather serves as a collection of links to other locations where the data can be accessed. Presently, however, linking specimens with their associated data poses significant challenges. For instance, DNA sequence databases often lack links to the corresponding voucher specimens, and similarly, institutional collection management systems are still improving methods to link specimens to molecular sequences (Buckner et al. 2021, Groom et al. 2021). These challenges underscore the difficulties in establishing connections between specimens and their associated data.

By utilising persistent identifiers (PIDs), such as DOIs, a digital extended specimen can be transformed into a FAIR (findable, accessible, interoperable, and reusable) digital representation of a specimen, enabling unambiguous citation in scientific literature. Furthermore, digital extended specimens will be machine-actionable, facilitating more effective enrichment and curation of biodiversity data. The transformation of specimen data into machine-actionable, FAIR digital objects on the Internet will enable the integration of diverse data types and will simplify data sharing among institutions and information systems.

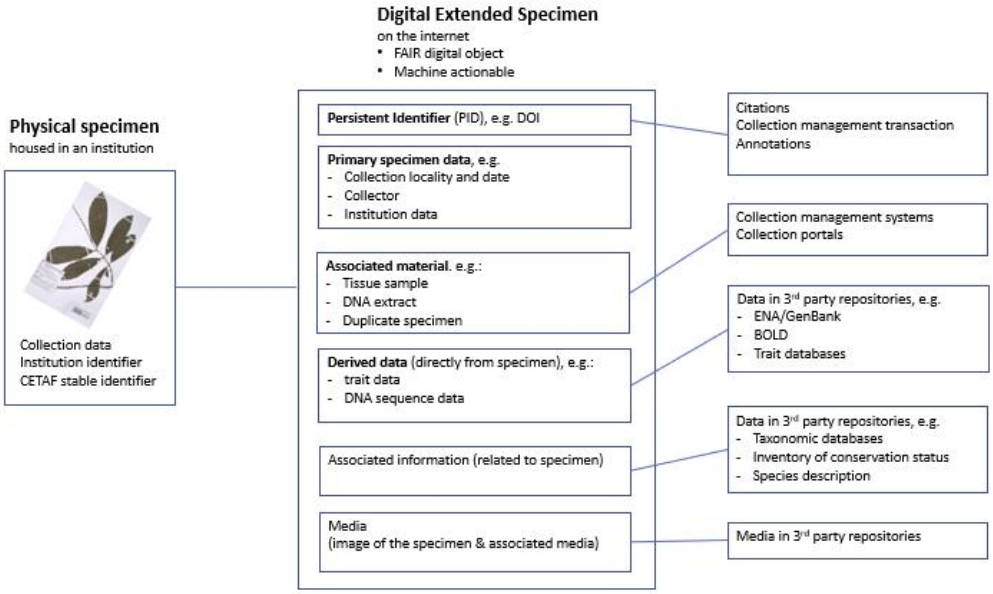

Fig. 5. Concept of a digital extended specimen, representing the digital information about a physical specimen, data derived from the specimen, and data associated with the specimen. A digital extended specimen can be linked to data from associated samples or specimens (e.g. silica gel material), data derived from the specimen itself (e.g. DNA sequences), other related specimens (e.g. duplicate specimens housed in other institutions), as well as a wide range of other associated data (e.g. conservation status of the species, species traits, species description and illustrations). Modified from Hardisty et al. (2022).

The integration of diverse datasets within the digital extended specimen framework holds tremendous potential for scientific research. Researchers will benefit from improved accessibility, as finding specimens will become more efficient, aided by links to taxonomic and nomenclatural information. This holistic approach to data integration facilitates comprehensive investigations and empowers scientists to explore interconnected research questions across collections, fostering collaborative and interdisciplinary studies.

Several EU projects are building on the importance of digital collections and integration of diverse datasets. For example, the TETTRIS project (Transforming European Taxonomy through Training, Research and Innovations, https://tettris.eu) envisions a transformative change in the field of taxonomy by creating joint knowledge in reference collections, training frameworks, and with innovative tools. The BiCIKL project (Biodiversity Community Integrated Knowledge Library, https://bicikl-project.eu/) aims to provide new workflows for an integrated access to data extracted from literature, linking diverse datasets.

Building upon the global DiSSCo initiative, national and regional endeavours have been initiated. In Belgium this includes the DiSSCo-FED (Federal), DiSSCo Flanders (Trekels et al. 2022) and DiSSCo FWB (Federation Wallonia-Brussels) projects in which Belgian institutions are joining forces to unlock their natural science collections, aligning with the broader goal of promoting a unified and interconnected digital repository. Through this collaborative effort, Belgian collections will contribute to the global vision of enhanced research capabilities and accessibility, further advancing scientific understanding of biodiversity and facilitating knowledge exchange among researchers worldwide.

As the fragmented landscape of natural history collections gives way to digital unification, DiSSCo and initiatives alike are revolutionising the way researchers access, utilise, and explore these invaluable resources. By embracing digital technologies and fostering collaboration, the scientific community embarks on a new era of seamless discovery and knowledge integration across diverse collections, driving biodiversity research to new frontiers.

Conclusions

Also in the digital era, herbarium collections continue to hold immense relevance for scientific research, and their applications are expanding in diverse fields. As we move forward, it is imperative that we continue to curate both physical and digital herbarium collections, recognizing their enduring value as repositories of botanical knowledge. The transformation of herbarium collections into digital collections, coupled with the integration of data, is transforming biological research and its associated fields, including conservation and climate research. The availability of digitised specimens and associated data will have a profound impact on the accessibility and usability of these collections, opening new avenues for exploration and analysis. Nevertheless the physical samples remain important as well as a unique and irreplaceable historical reference for taxonomic, biodiversity, and global change studies.

Digitisation of herbarium collections also offer unprecedented opportunities for collaboration, data sharing, and innovation. The creation of comprehensive digital repositories enables researchers

worldwide to access and analyse specimens without the limitations of geographical constraints or physical availability. Given that the Meise Botanic Garden Herbarium houses the largest collection of vascular plants from Central Africa (c. 800,000 specimens), these efforts will increase knowledge-sharing and collaboration with researchers from DR Congo, Rwanda and Burundi (e.g., Tosso et al. 2019, Ouédraogo et al. 2020, Hatangi et al. 2023). This global connectivity and collaborative potential foster a collective effort towards understanding and preserving Earth's botanical diversity.

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