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Forum

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Ethical collectomics: A guide to the responsible and fair mobilization of natural history collections

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Abstract

Natural history collections are being revitalized by emerging technologies, especially artificial intelligence. These advances enable collectomics—the large-scale extraction and analysis of specimen-derived data—creating new opportunities to address biodiversity loss, ecosystem change, and food security. However, they also raise ethical questions. Many collections are rooted in colonial and imperial histories, prompting questions about control, benefit sharing, representation, and responsibility, especially during political and social upheaval. As AI-powered collectomics expands, it may reproduce historical inequities and create new dilemmas. This article synthesizes the ethical dimensions of collectomics and offers practical recommendations for key stakeholders to support the responsible and fair mobilization of natural history collections, balancing scientific progress with equality, transparency, and fairness. This approach can help prevent the continuation of exploitative practices, strengthen global collaboration, and increase the societal value of collections in the Anthropocene.

Keywords **access and benefit sharing, biodiversity data, collectomics, digital equity, natural history collections**

What is collectomics and why should it be carried out ethically?

Natural history collections are experiencing a renaissance; after a period of decline in the shadow of technological advances, they are once again vital research infrastructures providing irreplaceable spatio-temporal records of species distributions, ecological networks, and human–environment interactions (Meineke et al. 2019). As biodiversity loss accelerates, expectations that these collections inform conservation planning and environmental policy have intensified. Global frameworks such as the Convention on Biological Diversity (CBD) and the Kunming–Montreal Global Biodiversity Framework (KM–GBF) call for better use of existing biodiversity knowledge in decision-making (Meineke et al. 2019). Meeting these demands increasingly depends on **collectomics**: the large-scale extraction, integration, and analysis of specimen-derived and specimen-associated data from natural history collections and dispersed databases, using a range of advanced technologies, including—but not limited to—digitization, imaging, genomics, spectroscopy, artificial intelligence, interoperable data infrastructures, and automated workflows (Sigwart et al. 2025, reviewed in Bucher et al. 2025, figure 1). Thus, it extends the concept of museomics, centred on recovering and analyzing historical DNA from museum and herbarium specimens, into a broader, integrative framework (Staats et al. 2013, Raxworthy and Smith 2021).

Collectomics builds on the idea of the **extended (digital) specimen**, which links physical objects (e.g., herbarium specimens) with their associated genetic, phenotypical, environmental, and historical data (Webster 2017, Lendemer et al. 2020, Hardisty et al. 2022). In this perspective, the **collectome** represents the totality of interlinked specimen data distributed across institutions and infrastructures as FAIR Digital Objects (FDOs; FAIR standing for Findable, Accessible, Interoperable, and Reusable; Wilkinson et al. 2016), rather than as isolated holdings (Bucher et al. 2025, Kapun et al. 2025, Sigwart et al. 2025, Wanke et al. 2025). High-throughput digitization pipelines (Kapun et al. 2025), AI-based image and label recognition, and major genomic initiatives (PAFTOL 2026, GAP 2026, ABP 2026) open many avenues for the large-scale mobilization of the collectome for research (Lendemer et al. 2020, Hardisty et al. 2022, Davis 2023, Bucher et al. 2025, Kapun et al. 2025, Sigwart et al. 2025), with platforms such as the Atlas of Living Australia (ALA 2026), the Global Biodiversity Information Facility (GBIF 2026), the integrated Digitized Biological Collections (iDigBio 2026), and the pan-European Research Infrastructure Distributed System of Scientific Collections (DiSSCo 2026), already providing access to millions of specimens.

The capacity to digitize and mobilize specimen-associated data is expanding rapidly thanks to AI and machine learning (Webster 2017, De Smedt et al. 2020, Younis et al. 2020, Grieb et al. 2021, Hardisty et al. 2022, Koureas et al. 2024, Rajendran et al. 2025). For instance, automated label extraction has been greatly aided by the use of large language (LLMs) and vision models (LLVMs) (Weaver et al. 2023, Körschens et al. 2026). Such advancements allow tracing specimens and their associated data across global databases, and linking them back to their environmental and socio-historical contexts. By restoring this full picture, we can move from simple observations towards predictive analyses on regional to global scales.

The expansion of collectomics brings ethical, legal, and political questions to the forefront. Major collections are concentrated in the Global North, whereas much of the world's biodiversity—and a substantial share of preserved specimens—originates from countries in the Global South (Meineke et al. 2019, Kapun et al. 2025). Colonial and imperial histories have shaped where specimens are held and who speaks with authority about them, so that control over material, data, and interpretation often lies far from the landscapes and communities from which they were originally taken (McCartney et al. 2022, Kapun et al. 2025, Sigwart et al. 2025). Meanwhile, as elements of natural and cultural heritage, collections are subject to expectations concerning provenance, authenticity, and the rights and interests of source communities (Hurtado-Ortiz et al. 2019).

Against this backdrop, the ethical dimensions of collectomics require clearer synthesis and practical guidance. The emerging literature points to a consistent conclusion: technical innovation alone is insufficient, and the mobilization of natural history collections must

Figure 1. Various examples of scientific, technical, and socio-cultural contexts of collectomics. (a–c) Comprehensive digitization of *Acanthus carolialexandri* Hausskn. (Acanthaceae) type specimen. The whole type specimen (a); unstructured, handwritten 19th century specimen label (b) and its AI-extracted content converted into a structured, machine-readable record (c)—Herbarium Senckenbergianum: Herbarium Haussknecht, Jena, Germany. (d) Digital microscopy as a non-destructive method to capture functional traits such as stomatal size and density directly from herbarium specimens. Abaxial leaf surface of *Carex caucasica* Steven (Cyperaceae)—Herbarium Senckenbergianum: Herbarium Haussknecht. (e) Taxonomically validated wood samples deposited in xylaria, function as libraries for high-throughput identification pipelines (e.g., mass-spectrometry–based wood identification), supporting conservation practice and enforcement by enabling screening of timber during trade inspections and efforts to curb illegal logging—Xylarium "Professora Doutora Maria Aparecida Mourão," Botucatu, Brazil. (f) An 18th-century herbarium compiled by Helwing and Boretius, documenting plant phenotypes 300 years ago, including useful and cultivated species, with vernacular names valuable for ethnological research—University of Warsaw Herbarium, Warsaw, Poland. (g) Institutions in the Global North house vast biological collections, many of which originate from the Global South. The mass digitization of such specimens is a critical ethical step toward democratizing science; it allows researchers and stakeholders worldwide to access vital records without the barrier of costly international travel—United States National Herbarium, Smithsonian Institution, Washington D.C., USA (photo by Chip Clark). (h) A researcher preparing a ray specimen from the SAIAB National Fish Collection for imaging as part of the nationally coordinated imaging effort. This initiative highlights the importance of locally led digitization through shared national imaging standards and practices—Natural Science Collections Facility, South Africa. (i–j) Entomological voucher specimens illustrating common label-visibility challenges: pinned beetles with stacked labels (i) and butterflies whose wings partly obscure labels (j). High-throughput robotic mass-imaging systems are increasingly enabling large-scale digitization of diverse insect collections by capturing and/or computationally resolving partially occluded labels that previously required manual handling—Natural Science Collections Facility, South Africa (photos by Margaret Bartkowiak and Louwtjie Snyman).

be guided by principles of equity, transparency, and responsibility. In the following sections, we synthesize these issues and propose a practical framework for the ethical mobilization of natural history collections.

Conducting collectomics lawfully

One could simply define "ethical mobilization" as the "lawful use of biological materials held by collections." Although biological collections are governed by various international instruments the ethical dimension of their use is primarily addressed through the access and benefit-sharing (ABS) legal framework. This framework is shaped by the Convention on Biological Diversity (United Nations Environment Programme 1992), the Nagoya Protocol (Conference of the Parties to the CBD 2011), and national ABS legislations. Together, these instruments set the legal obligations and ethical standards for accessing, utilizing, and sharing biological material, its associated traditional knowledge (aTK) and data.

The CBD has three objectives: the conservation of biodiversity, the sustainable use of its components, and the fair and equitable sharing of benefits arising from the utilization of genetic resources. The Nagoya Protocol operationalizes this third objective by affirming state sovereignty over genetic resources and recognizing Indigenous Peoples and Local Communities as holders of aTK, and by requiring that access is based on Prior Informed Consent and Mutually Agreed Terms, which define permitted utilizations and benefit-sharing. These range from monetary payments to non-monetary benefits such as results-based recommendations for conservation and sustainable use of biodiversity, information and data sharing, capacity building, and co-authorships with local partners. Importantly, these ABS considerations follow the material throughout its entire research lifecycle, from initial collection to data publication and future reuse (Hartman Scholz et al. 2022). The Protocol also establishes compliance obligations, requiring countries to ensure genetic resources used in their territories were legally accessed per provider countries' ABS rules.

Despite its good intentions, the Nagoya Protocol poses significant challenges for researchers. Those include heterogeneous national ABS legislation, incomplete or outdated information on ABS rules and procedures, incomplete metadata for historical material, and high due diligence workload and costs (Overmann and Scholz 2017). Moreover, ABS rules may also apply to pre-CBD and pre-Nagoya ex-situ materials, depending on each country's definitions and rules for "ex-situ access."

Ex-situ collections are pivotal within ABS regimes because they preserve specimens and data from many countries and time periods, and share these with researchers and companies. As long-term stewards, they manage legal and ethical responsibilities by documenting provenance, permits, and use conditions. Although the complete legal history of most specimens remains unknown, there are exceptions. The Leibniz Institute DSMZ (Braunschweig, Germany) became the first "registered collection" under the EU ABS Regulation. This means their entire catalog has undergone legal review, ensuring every resource is accompanied by the necessary Nagoya-related documentation. This eases the due diligence process for users downstream (Yurkov et al. 2019). It is now one of three such collections in the European Union.

In simple words, good ABS practices require collections to exercise internal due diligence, which can be achieved by treating the life of a specimen as a series of control points—starting from field collection, followed by accessioning and digitization, and culminating in sharing specimens with researchers. At each stage, collections should preserve ABS documentation and clearly communicate use conditions to downstream users, as a good practice. This systematic approach embeds legal considerations directly into standard workflows, though it significantly increases the operational costs of maintaining collections and making them available to researchers (Yurkov et al. 2019).

Beyond the Nagoya Protocol, new discussions and rules have arrived to ensure benefit-sharing from the use of publicly available genetic sequences and other digital biological data, known as digital sequence information (DSI; Mc Cartney et al. 2022). Collections and users of genetic resources must stay updated (Muñoz-García and DSI Scientific Network 2025).

For historical specimens, full compliance with modern legal standards is often unattainable; the communities from which they were taken may no longer exist, or their legitimate successors may be impossible to identify. Given these complexities, legacy collections require sensitive, case-by-case ethical management. Simultaneously, we must embed transparency in contemporary acquisitions to ensure future research does not repeat the mistakes of the past.

Avoiding historical pitfalls in the future of collectomics

Researchers from the Global North have made significant contributions to the inventory and systematization of organisms in biodiversity-rich regions (Pethiyagoda 2023), resulting in highly valuable natural history collections. However, this also led to a globally uneven landscape with major, well-resourced institutions and infrastructures concentrated in the Global North (Delves et al. 2024, Simões et al. 2025). This asymmetry is rooted in colonial and imperial histories, where specimens and knowledge were exported without leaving duplicates or records of withdrawal, turning type specimens into a form of scientific and political "currency" inaccessible to biodiversity-rich regions. In this context, collectomics provides a pragmatic solution to the challenge of equity. Although the physical repatriation of specimens is often a just and desirable goal, it is frequently hindered by a lack of local infrastructure. Since building relevant facilities often exceeds the immediate reach of the scientific community and rarely is the priority for modern governments, collectomics offers a "digital bridge." By mobilizing collections through high-resolution imaging and linked metadata, a distributed infrastructure is created where researchers have access to materials without the need for costly travel (Davis 2023). A successful example is the REFLORA program (Pinheiro et al. 2024), which digitized plant specimens collected in Brazil, housed in-country and abroad, mainly in the Global North. REFLORA allowed the "digital repatriation" of these important specimens, so that Brazilian scientists could take ownership of the studies of their own flora. In Africa, the African Plants Initiative (Smith 2004), and more recently, the African Plants Portal (2022), were founded with a similar intention.

However, for this digital mobilization to be transformative and not degenerate into "digital colonialism," it must be coupled with sustained capacity building within biodiverse regions. This includes providing hardware but, more importantly, also investing in taxonomic expertise and curation skills, which are not geographically evenly distributed (Simões et al. 2025). As discussed in later sections, technological acceleration in collectomics only yields usable knowledge when it is accompanied by the human expertise required to validate and interpret the underlying data derived from specimens. Hence, investing in taxonomic and curation training in areas of high biodiversity (e.g., through targeted educational initiatives and regional partnerships for knowledge and resource sharing) will need to accompany the mobilization of the collectome. Only through such integrated support can researchers in the Global South fully leverage these digital assets to advance research and conservation efforts in their own landscapes.

Professional taxonomic knowledge is equally important as taxonomic stability. Although addressing historical injustices is vital, radical disruptions of scientific naming (e.g., by bulk removal of all eponyms) risk creating nomenclatural chaos (Jiménez-Mejías et al. 2024). This notion is reflected in the latest reform of the *International Code of Nomenclature for algae, fungi, and plants*, adopted at the 2024 International Botanical Congress (Turland et al. 2025). The reform provides a formal pathway to reject derogatory names published after 31 December 2025 while leaving legacy nomenclature largely unchanged. This approach promotes nomenclatural stability, which is a technical necessity for collectomics, while retaining transparent, case-by-case mechanisms to evaluate names where demonstrable harm is identified (Mosyakin 2023a, 2023b, Lee et al. 2025, Turland 2025).

Given that the world's most significant natural history collections were established primarily by Global North scientists, yet rely heavily on the biological heritage of Global South communities (Park et al. 2023), it is only just to view these collections as the common heritage of all humanity. If they belong to everyone, it follows that their preservation and stewardship are a collective global responsibility. Protecting these assets is not a task for individual institutions, but a duty we owe to our shared future.

Seeing collections as vulnerable objects of humanity's biohistorical heritage

Natural history collections defy simple distinction between cultural and natural heritage and represent a unique synthesis of scientific tools, archives, and works of art (Grenda-Kurmanow 2026). They serve as carriers of aesthetic and historical values that go far beyond the basic definition of a research instrument. In the spirit of collectomics, the International Council of Museums defines these collections as "three-dimensional archives of the natural world and relationships of societies with their environment" (ICOM 2013). Through these complex associations, collections act—perhaps unexpectedly—as repositories of *intangible* heritage (UNESCO 2001, 2015a, ICOM 2017). Consequently, the ethical codes of conservation and ethnobiological societies emphasize the deep interrelation of biological and cultural diversity, acknowledging the inevitable impact that research activities have on local communities (ISE 1988, Salick et al. 2014).

Being physical entities with intangible value, collections require informed conservation planning, as each object may demand a different conservation approach depending on the prioritized values. Therefore, conservation must begin by identifying the cultural, natural, and documentary values to be preserved, and by defining the acceptable level of intervention (ICOM 2017), so that implemented strategies ensure specimen integrity, authenticity, and reliability (UNESCO 2015b).

The vulnerability of natural history specimens is rooted in their composition itself—that is, biological material intertwined with historical mounting techniques and diverse types of substrates and structures—further complicated by the history of storage conditions and the use of biocides. These past treatments, intended to provide protection against pests, have led to permanent organic and inorganic contamination that now poses risks to both the objects and

their users (Odegaard and Zimmt 2008). Consequently, modern collection management must be interdisciplinary, balancing the need to slow natural degradation with the demands of active use, such as loans, exhibitions, and research (Cornish and Nesbitt 2014). This is particularly challenging with regard to destructive sampling, for example, for genetic analyses, which results in the loss of unique historical material (Nesbitt 2014). Since traditional conservation guidelines rarely address destructive sampling—with the notable exception of ICOM (2017)—decisions must be based on research evaluation protocols and a deep understanding of the object's condition. Ultimately, selecting the appropriate specimen requires close collaboration between researchers and curators to ensure research viability, whereas safeguarding the specimen's integrity (Canales et al. 2022, Davis et al. 2025). This places the curator as an advocate for the collection—responsible for shaping its future through both daily care and long-term protection (ICOM 2017, Rabeler et al. 2019, Thiers 2020).

Beyond individual specimen decay, entire holdings face catastrophic risks from infrastructure failures, climate change, civil unrest, or armed conflict (NASEM 2020, pp. 72–84). The 2018 fire at the Museu Nacional in Rio de Janeiro, caused by an electrical fault, demonstrated how quickly thousands of irreplaceable items can be lost despite desperate salvage efforts (Araujo 2019, Carvalho and Juliace 2025, González et al. 2025). Such risks are increasingly compounded by the climate emergency. For example, the 2021 fire that devastated Cape Town's Jagger Library and threatened Bolus Herbarium housed in a nearby building was fueled by intensifying wildfires in the surrounding fynbos ecosystem, highlighting the vulnerability of institutions to regional environmental shifts (Kirkwood et al. 2023). Armed conflict remains a persistent threat to biological archives. Historical examples include the National Herbaria of Sierra Leone and Liberia, where civil wars (1991–2003) led to the near-total destruction of collections and supporting infrastructure. Due to limited resources, re-establishing these herbaria from the ground up has proven exceptionally difficult. More recently, the ongoing conflict in Ukraine provides a grim validation of the need for disaster planning. Prior to the outbreak of the Russian invasion on Ukraine in 2014, the country's 82 herbaria housed over five million specimens, including globally significant historical collections and at least 12,000 identified types (Shiyan 2011, 2014, 2021). By 2026, twelve years of military offensive have left a staggering toll: 14 herbaria remain inaccessible due to occupation, four have sustained damage, and three collections have been physically decimated. This destruction has taken many forms, from missile strikes on major research centers in Kyiv and Kharkiv (KW, CWU, CWP; Mosyakin and Shiyan 2022) to the use of Askania-Nova specimens as fuel for heating. Furthermore, the herbarium of the Black Sea Biosphere Reserve was lost in the flooding caused by the destruction of the Kakhovka Dam. Although three collections were targeted for evacuation, only two are currently undergoing conservation in safer locations; the fate of the Herbarium of the Luhansk Pedagogical University remains unknown.

These experiences show that large-scale loss of natural history collections is a persistent reality. However, maintaining relevant preparedness—much like ABS compliance, physical conservation, and digitization—generates a significant financial burden (NASEM 2020, pp. 141–148). These costs raise a fundamental ethical question: are societies getting their money's worth from these investments, when public funds are desperately needed for competing priorities?

From specimens to solutions: the strategic value of collections for society

Global biodiversity targets, specifically the KM–GBF and its 30 × 30 ambition, aim to focus limited resources on areas where they can maximize conservation impact. Implementing these targets relies on systematic conservation tools such as Key Biodiversity Areas and (Tropical) Important Plant Areas (TIPAs/IPAs), which guide protected-area planning, risk screening for development, and National Biodiversity Strategies and Action Plans (Darbyshire et al. 2017, Wu et al. 2025, Plumptre et al. 2026, Goldstein et al. 2026). The effectiveness of these instruments depends on robust threat assessments using criteria standardized by the International Union for Conservation of Nature, which require high-quality evidence on species distributions and habitat changes (IUCN 2012a, 2012b, 2024). Collectomics provides the essential data that enable the accurate application of IUCN criteria, identification of "biodiversity dark spots" where exploration should be prioritized (Ondo et al. 2024), and that support the design of restoration interventions. Furthermore, collections offer the long-term baselines necessary to detect trends, evaluate claims, and adapt interventions over time (Bachman et al. 2024). Even smaller collections are useful, as they can close distribution gaps present in larger holdings, thanks to locally active communities of professional and amateur scientists and their continuous focus on certain taxa (Monfils et al. 2020, Delves et al. 2024, Sawa et al. 2025).

Collections also keep generating taxonomic discoveries: approximately 1850–2000 new plant species are described annually from specimens already deposited in herbaria, a rate consistent since 1970. This highlights the magnitude of undocumented diversity and the continuing dependence of conservation-relevant knowledge on expert taxonomists having access to natural history collections (Lewis et al. 2016, Cheek et al. 2020).

However, taxonomy and specimen curation capacity are declining. Taxonomists are becoming rare as fewer taxonomy courses are taught and employment opportunities dwindle (NASEM 2020, pp. 123–124, Simões et al. 2025). Consequently, for many taxonomic groups revisions and day-to-day curation lag behind. For instance, a coordinated effort by five Zingiberaceae taxonomists, who examined specimens from 40 herbaria in 21 countries, found that 58% had been misidentified prior to their revision (Goodwin et al. 2015). Similar taxonomic uncertainty is present across biological groups, with detrimental consequences for all applications that require correct species identification: new methodologies can only mobilize trustworthy information if the underlying specimens are correctly identified and curated to a high standard (García-Roselló et al. 2023, Meyer et al. 2026). Furthermore, currently, even when an expert revises a specimen in a certain collection, the re-identification rarely reaches duplicates held elsewhere.

The extended digital specimen framework could solve this by propagating revisions globally across interlinked databases (Sandall et al. 2023). This, however, creates a risk of a "minefield of authority"—the challenge of prioritizing conflicting identifications, especially when historical biases may favor Global North specialists over local taxonomists. The community vetting model implemented by iNaturalist (2026) offers a promising direction to navigate this, provided it is anchored by regional experts. A prime example is the work of the Compton Herbarium (NBG) within the South African National Biodiversity Institute (SANBI), where taxonomists verify all observations of specific groups from a given geographic area, ensuring that datasets for

at least some South African endemics remain authoritative and trustworthy (Baczyński et al. 2025). Furthermore, the involvement of local experts allows for real-time decision-making regarding sensitive data sharing, such as masking geolocations in response to shifting poaching trends to balance the need for open access with the protection of species from wildlife crime (Smith et al. 2023).

A clear example of an applied, high-impact pipeline from collections to enforcement is the growing role of herbaria and xylaria as taxonomically validated reference libraries used for curbing illegal logging through mass-spectrometry–based wood identification (Raobelina et al. 2023). Mass spectrometry provides a rapid and reliable screening tool capable of revealing taxonomic identity and, in some cases, geographic provenance of timber, enabling customs and enforcement agents without specialized botanical training to assess wood identity during high-volume trade inspections (Finch et al. 2017, Raobelina et al. 2023).

Beyond serving as taxonomically validated reference libraries for law enforcement or biodiversity monitoring (Puillandre et al. 2012, Davis 2023, Marín-Rodulfo et al. 2024, Dopheide et al. 2025, Schmid et al. 2025, Zhou et al. 2025), natural history collections are critical for global food security. By preserving crop wild relatives and landrace diversity no longer present in modern industrial agriculture, they provide genetic material for breeding climate-resilient crops (Gutaker et al. 2019, Perez-Escobar et al. 2022, Albani Rocchetti et al. 2024, Kistler et al. 2025). Furthermore, collections clarify the complex history of domestication—including past gene flow and biotic interactions—which can be leveraged to restore beneficial traits in contemporary agricultural systems (Flowers et al. 2019, Perez-Escobar et al. 2021, Burbano and Gutaker 2023, Daru and Zhigila 2025). Finally, by combining historical specimens with phytochemical analysis and AI, these collections accelerate the discovery of novel medicinal compounds, directly fueling public health and bioeconomy (Richard-Bollans et al. 2023). The remaining challenge is to deliver these benefits at scale.

Ethically mobilizing collections at scale will increasingly depend on strong collaborative networks (Krishtalka and Humphrey 2000, Johnson et al. 2023). These networks bring together very different people—curators, taxonomists, data scientists, policy-makers, and practitioners—so collaboration needs to happen in psychologically safe spaces where difficult conversations and decisions can take place (Edmonson 1999, Wheatley 2006). Experience from the establishment of South Africa's Natural Science Collections Facility (NSCF 2021) shows that building such a network is a gradual, iterative process, grounded in co-developed standards and frameworks and embedded through targeted capacity development and peer learning. Comparable models are needed widely in other countries and regions. Ultimately, investing in the conditions that enable collaboration across diverse backgrounds, roles, and disciplines is a pragmatic necessity for sustaining mobilization of collections at scale; in turn, where collections data can meaningfully inform biodiversity protection, advance environmental justice, or strengthen local livelihoods, failing to mobilize them or unduly restricting their use is ethically indefensible.

Policy implications and guidelines for stakeholders

Mobilizing the vast archives of natural history collections is a critical frontier in addressing the multifaceted challenges of the Anthropocene. Although the integration of Artificial Intelligence and machine learning is set to accelerate this process toward an unpredictable scale, it also amplifies the ethical tensions inherent in collections often rooted in colonial and imperial legacies. Because these responsibilities are difficult to capture in rigid legal frameworks, we—a globally distributed group of collection-based scientists and practitioners affiliated with institutions from Belgium, Brazil, Colombia, France, Germany, Mexico, Poland, South Africa, Ukraine, the United Kingdom, and the United States—provide here a set of pragmatic recommendations to guide the ethical mobilization of biodiversity data across three key stakeholder groups:

For curators and their collection-holding institutions, "ethical mobilization" means embedding responsibility into existent and future routines by doing the following:

- **Addressing history:** Enabling access and authority for partners in countries of origin through duplicate exchange or repatriation, shared physical and/or digital curation, and capacity building initiatives.
- **Embedding reflective and learning-oriented practice:** Creating regular spaces for dialogue, peer learning, and critical reflection on activities.
- **Co-developing standards, protocols, and tools:** Adopting and contributing to collaboratively produced manuals, training programs, and monitoring tools that support institutions in identifying risks, prioritizing improvements, and tracking progress.
- **Integrating due diligence into workflows:** Introducing legal-ethical checks into accessioning, cataloging, databasing, and digitization and ensuring that provenance documentation and use conditions remain legible across infrastructures and throughout downstream data release.
- **Governing further use**: Ensuring that sharing material with commercial potential—like viable germplasm—adheres to the Nagoya Protocol and national ABS legislation to prevent legal infringements and ensure fair returns to countries of origin.
- **Balancing open access with biodiversity risks:** Making data and subsequent findings accessible for stakeholders, whereas implementing adaptive protocols to restrict public access to locality data for taxa vulnerable to poaching or over-exploitation. This requires active monitoring, as the "market value" of specific groups shifts with societal trends.
- **Implementing the "preserve everything" formula:** Adjusting basic curation workflows to preserve not only the main specimen, but also soil fragments, co-occurring species, or evidence of human interaction with the specimen. With rapid development of new technologies for extracting specimen-derived data, this will allow collection-based research to open up to other disciplines like history, social, and geophysical sciences, increasing the societal value of the holdings.

For researchers, "ethical mobilization" means designing projects, so that access, benefits, and authorship are shared rather than assumed. This implies the following:

- **Building equal partnerships and networks:** Establishing strong collaborative networks with institutions and local or indigenous communities. Such collaborations should use co-authorship and acknowledgements as tools of equity.
- **Transparent documentation and data sharing:** Verifying and documenting ABS conditions in a transparent way while ensuring that resulting data are shared in a manner that is both FAIR and

sensitive to CARE (Collective Benefit, Authority to Control, Responsibility, and Ethics) principles for Indigenous Data Governance.
- **Mindful narrative and nomenclatural framing:** Paying attention to how histories of collecting, violence, and exclusion are represented. Researchers must handle scientific language and nomenclatural debates carefully, maintaining usability of taxonomic nomenclature while acknowledging historical contexts and avoiding past pitfalls in the future.
- **Passing knowledge to the next generation:** Taking active responsibility for mentoring the next generation of curators and taxonomists to ensure that the expertise required to maintain and use these collections in the future is preserved.

For funders and policy-makers, "ethical mobilization" is a long-term commitment that goes beyond short-term digitization targets and sustains less visible foundations of biodiversity research:

- **Valuing collections as humanity's heritage:** Recognizing the scientific, historical, and socio-cultural significance of natural history collections as irreplaceable records of biodiversity and its changes.
- **Maintaining foundational expertise and infrastructure:** Funding the training of the next generation of taxonomists and curators, as well as the physical conservation of objects and ensuring permanent and interoperable infrastructures.
- **Encouraging collective efficiencies and impact:** Supporting network approaches that reduce duplication, align priorities, and enable coordinated mobilization of collections and data at scales relevant to societal and environmental challenges.
- **Rewarding international partnership-based models:** Creating policies that reward equitable collaborations and treat collections as essential, evidence-based sources for conservation decision-making and Anthropocene research.
- **Supporting physical safety in a volatile world:** Providing dedicated support to protect collections from escalating threats, ranging from climate-related catastrophes to hostile actions and war in an increasingly unstable world.

Author Contributions

K.E.F., S.G., and A.R.G.S. conceptualized the manuscript. K.E.F. led the writing of the article; A.R.G.S. contributed "From Specimens to the Solutions", together with M.R.P., M.A.J., A.R.M., O.A.P.E., C.R.M., D.S.P., and prepared the photo plate; A.E. and M.M.G. contributed "Conducting collectomics lawfully"; M.G.K. and N.M.S. contributed "Seeing collections as vulnerable objects", S.L.M., A.M.M, K.E.F. contributed "Avoiding historical pitfalls", A.R.M., C.R.M., D.S.P., K.E.F. contributed materials for figures; K.E.F., S.G. and A.R.G.S edited the final version. All authors reviewed and approved the submitted version.

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