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The fate of natural history museums in the face of good intentions

Emmanuel F.A. Toussaint, FLS[1,*], Conrad P.D.T. Gillett[2] and Ivan Löbl[1,*]

[1]Natural History Museum of Geneva, 1 Route de Malagnou, 1208 Geneva, Switzerland
[2]Finnish Museum of Natural History, Pohjoinen Rautatiekatu 13, 00100 Helsinki, Finland

[*]Corresponding authors. Natural History Museum of Geneva, 1 Route de Malagnou, 1208 Geneva, Switzerland.
E-mail: emmanuel.toussaint@ville-ge.ch; ivan.lobl@bluewin.ch

A recent opinion advocating for a reorientation of natural history museums to hold 'compassionate collections' that minimize harm to wildlife (Byrne 2023) begs commentary. Such collections are defined by four premises, only the first of which (avoiding the killing of organisms to obtain specimens) is controversial. The remaining three principles promote optimization of the maintenance and study of existing collections, whilst fostering a more inclusive community (Byrne 2023), which museum curators already strive to do. In our opinion, because the fundamental functioning of natural history museums would be impacted by this doctrine, its promotion and potential consequences should therefore elicit an in-depth evaluation by museum scientists. We hope to demonstrate here that compassionate collections would not fulfil the urgent exigencies of scientifically assessing biotic diversity, which is vital to our understanding of ecosystems and evolution. Neither could they stimulate anything other than a more superficial connection to the complex and intricate realities of the natural world than presently exists. Rather, if endorsed, such a dogmatic vision would result in a progressive and dramatic loss of knowledge, with an inevitable concomitant threat to the future of biotic studies.

Compassion in biodiversity research

As humans, we commend compassion as a quality that enables us to appreciate humans and nature more fully. However, as museum taxonomists we believe that compassionate collections as described in Byrne (2023) hold the power to fundamentally influence epistemology. The compassionate collection vision forms part of a recent spate of opinion pieces promoting alternative and often iconoclastic approaches in museum science (e.g. Minteer *et al.* 2014, Guedes *et al.* 2023). Because we welcome discussion relating to the evolution of museum science, such as that which Byrne's (2023) proposal has stimulated, a response to it is required in order to present a wholly divergent perspective.

We agree that natural history museums are places of wonder that induce powerful emotions in visitors. That awe only intensifies with contemplation of the enormous scientific value of their specimen collections and the great responsibility and effort spent to conserve them for posterity.

Assessing biotic diversity

Biologists try to understand how life functions at molecular and cellular levels, in addition to at the scale of ecosystems. While tremendous progress has been achieved in understanding life functions and mechanisms at a microscopic level, knowledge of ecosystems lags far behind (Kim and Byrne 2006). The difficulty is due primarily to the fact that the basic units of ecosystems are species, along with their functional traits. Because knowledge of species diversity forms the foundation of study of the living environment (Wilson 2000), the assessment of species (i.e. the forms of life that evolved on our planet) should be considered a priority. However, it is sobering to observe the discrepancy between the bewildering species richness on our planet and the dwindling number of researchers seeking to discover, name and study it (Engel *et al.* 2021). To date, only a small proportion of extant species diversity has been recognized and described (Mora *et al.* 2011). Estimates of the total number of species are inconsistent, ranging from millions to billions (e.g. Erwin 1982, Costello *et al.* 2012, Dijkstra 2016, Sinniger *et al.* 2016, Larsen *et al.* 2017, Stork 2018, Louca *et al.* 2019). However, it appears that at best only 20% of extant animals have been hitherto described (Chapman 2009), with biological information lacking entirely for many of them. Because invertebrates alone constitute about 97% of the animal kingdom, they therefore exemplify the enormous gaps in our knowledge (Zhang and Shear 2007). Although some of the as-yet-unnamed species have already been collected and are preserved in museum collections awaiting formal description, the majority have yet to be sampled,

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whilst their threatened habitats continue to shrink around them. In the field, taxonomists regularly find undescribed species whenever, for example, they enter a tropical or subtropical forest, examine deep-sea samples, or seek intestinal parasites in other animals (our personal observations, Appeltans *et al.* 2012, Scholz and Choudhury 2014). Hence, describing species diversity on Earth is arguably one the most challenging tasks confronting biologists, with increasing urgency in the face of ever diminishing and declining biotopes. Species are concepts—we are faced with contemplating no fewer than 32 of them (Zachos 2016). Notwithstanding, all species descriptions are necessarily based upon specimens, with each species being distinguished according to the idiosyncratic criteria of individual taxonomists, influenced by pre-existing knowledge and available technology at a given time. Because no two specimens can be identical, each species exhibits variation that is usually incompletely known. Robustly assessing the limits of variation within a species requires the study of numerous specimens, a task that is only achievable using natural history collections. Therefore, assessment of biodiversity relies on museum collections and faces theoretical and practical problems. A second major issue derives from the innumerable characters that each specimen exhibits. Only some of these are conspicuous, and relatively few are selected to discriminate individual species. Historical data, based on fewer recognized species and outdated technology, frequently become obsolete. Consequently, taxonomists spend a large part of their time unravelling, verifying, and updating previously published information, a tedious but crucial task based on study of important voucher specimens held in collections. Because science, by definition, requires continuous hypothesis testing and revision as new information becomes available, there is no reason to believe that vouchers will lose their 'raison d'être'.

Complete specimens are falsifiable vouchers

Collections in natural history museums are and will remain prerequisites for sound biodiversity studies (Lister 2011, Miller *et al.* 2020), and they represent much more than solely archives of hitherto described and studied life forms. They document the changing distribution of species across space and time and are essential as falsifiable vouchers when published data appear dubious and in need of scrutiny. Physical vouchers of collected species are, and arguably will remain, key to gaining deeper insights into our understanding of the natural world for generations to come (Ruane and Austin 2017, Schmidt *et al.* 2019, Raxworthy and Smith 2021, Warnett *et al.* 2021).

The recommendation of replacing preserved specimens by photographs and tissue samples (Byrne 2023), which could avoid killing wildlife and which are easier to store, is not new (Minteer *et al.* 2014). Accepting this suggestion would limit knowledge of species to a minute fraction of the most obvious characters, impede recognition of similar syntopic species, and render information much less verifiable and falsifiable, thereby shifting taxonomy away from the realm of science (Ceríaco *et al.* 2016). Furthermore, in many cases meaningful photography of the informative anatomical structures of living animals is impractical or impossible and would relegate important biological fields, such as parasitology, to the sidelines. But even proposing photography of living animals as an alternative is a moot point because most animals are very small species of invertebrates that simply could not realistically be found and sampled alive in the field, let alone be kept alive long enough to enable compassionate collection, including the requisite viable release into the wild. For example, many insect species are known only from specimens collected with necessarily lethal traps (Malaise traps, flight-interception traps, etc.).

Another parochial assertion is the proposal that DNA samples can replace entire specimens. The encrypted information in genomes is certainly useful as support for the discrimination of species and in efforts to unravel evolutionary relationships and patterns. Both reliable identifications and comprehensive phylogenies are important in understanding the evolutionary history of species. In fact, the recently introduced field of museomics has already demonstrated the untapped potential of collection specimens to resolve long-standing taxonomic and evolutionary questions (Chomicki and Renner 2015, Raxworthy and Smith 2021, Toussaint *et al.* 2021). Nevertheless, assuming that DNA is sufficient to understand organisms and ecosystems is as misleading as assuming sequences in a genome are sufficient to understand how life functions. For instance, metabarcoding used as a tool to recognize organismal diversity in environmental samples only provides quantitative data (Dell'Anno *et al.* 2015), because the method is incapable of distinguishing endemic taxa from pests and therefore appears to lack reliability (Förster *et al.* 2023). Overall, DNA is merely a piece of the jigsaw puzzle that the complexity of describing biodiversity represents.

Therefore, the cost of avoiding collecting entire specimens, measured by the loss of potential data available for future study, would be high. The lives of compassionately spared individuals are not indispensable to the sustainability of their respective ecosystems (Hope *et al.* 2018), excepting cases such as some large animals now rarely collected by zoologists, and critically endangered species.

We understand that many, if not most, museums already at least partially house collections that can be described as 'compassionate', especially owing to the explosion of digitization efforts during the last two decades (Balke *et al.* 2013, Drew *et al.* 2017). But the fact remains that only collections of complete biological specimens will provide the 'gold standard' in scientific samples allowing for long-term means of gaining insights into dozens of research disciplines (morphology, anatomy, evo-devo, parasitology, population genetics, phylogeny, chemistry, physics, materials, etc.). Conversely, compassionate collections contain objectively suboptimal samples that are arguably incompatible with modern proposals promoting 'holistic sampling' (Schindel and Cook 2018), the 'extended specimen' (Webster 2017) and calls for increased voucher specimen collection (Krell and Wheeler 2014, Rocha *et al.* 2014; Thompson *et al.* 2021).

Complete specimens are future-proof

In addition to being invaluable falsifiable scientific vouchers, complete museum specimens are an enduring source of potentially new data that cannot be predetermined, especially whenever a new data-gathering technology becomes available. The call for compassionate collecting ignores the potential for future technological progress to enable access to hitherto inaccessible or unforeseeable data that are physically preserved in whole specimens. For instance, high-resolution imaging systems (CT scanning, SEM, tomography, etc.) have been revolutionizing nondestructive visualization of specimens (Sumner-Rooney and Sigwart 2017), and the now routine analysis of genetic information extracted from historical museum specimens that were collected and preserved before DNA was understood to be the hereditary material would have been unimaginable to their collectors. Had only compassionately collected photographs of these specimens been preserved, this valuable data source would not exist. Indeed, museum specimens have been shown to be a source of environmental DNA, including ingested DNA, and are thereby inadvertently useful even in providing information on organisms other than themselves from their ecosystem (Siddall *et al.* 2019). Compassionate collecting would reduce the study of the biological world to geolocalized photographs and swabs of DNA. An excellent example of the limitations inherent in the compassionate collection paradigm can be envisioned when applying it to beetles, the most diverse group of animals on Earth, consisting of about 400 000 species described to date. A significant number of these species are not only minute and therefore difficult to photograph alive, but also simply impossible to diagnose without resort to anatomical dissections and careful examination of morphological characters under a microscope. An equally compelling example can be made of parasites, representing dozens if not hundreds of branches across the tree of life (Poulin & Morand 2000). Their existence is only known to us because their hosts—larger invertebrates and vertebrates—have been collected and preserved, as 'parasite time capsules' (Greiman *et al.* 2020, Wood and Vanhove 2022), allowing for their bodies to be subsequently dissected and examined, revealing the incredibly underestimated diversity of parasites still to be discovered (Carlson *et al.* 2020). To preserve portions or images of specimens only selectively, according to a priori assumptions of the scope of future research, that is unimaginable today, only robs tomorrow's scientists of precious information (Rohwer *et al.* 2022).

Threatened wildlife

Natural history museums exhibit large numbers of species. In fact, nowhere else are so many species and individuals concentrated in so limited a space. In the face of the ongoing erosion of biodiversity, it is not surprising that the public may be emotionally affected by displays of unanimated wildlife in museum collections and exhibits. Several years ago, the number of dead animals deposited in collections was estimated to total 3 billion (Kemp 2015). This number may be shocking in the absence of adequate contextualization, which is often not provided by museums. The suggestion that collecting may jeopardize the populations of threatened wildlife is not new (e.g. Minteer *et al.* 2014) although specimens of large species that are displayed in museum exhibits are often those of animals having died in zoos or originating from illegal trade intercepted by customs. However, most museum specimens are not on public display, particularly small animals that have short lifetimes and reproduce quickly in nature, such as insects. Populations of such species are controlled by multiple factors, notably by predators. A single group of predators—spiders—annually kills 400–800 million tonnes of insects (Nyffeler and Birkhofer 2017), i.e. about 1 million times more than all those ever collected by humans. But although predators kill billions of individuals daily, the respective ecosystems remain in equilibrium and species survive. Recent biodiversity collapse is the result of the destruction and pollution of habitats, combined with climatic changes; the latter are also correlated to destructive deforestation, exploitation of moorlands, and excessive use of freshwater resources (Wagner *et al.* 2021). In this context, scientific collecting has a negligible effect on animal populations compared to the impact of other large-scale human activities. The decline of the Apollo butterfly *Parnassius apollo* (L., 1758) may be used as an example highlighting popular but erroneous opinions of the effect of collecting on populations. This species was desirable and collected by hundreds of European lepidopterists during the 19th and the first half of the 20th century. It became protected in Germany in 1936, and strictly protected in 1977 under the Convention on International Trade of Endangered Species (CITES Annex II). Although thereafter no longer being collected, its populations only decreased significantly after 1975, and have been vanishing only since 2000 (Nakonieczny *et al.* 2007, Segerer 2019, and our unpublished personal observations).

SUMMARY

A plea for compassionate collection, whilst well-intentioned, is misguided. It overlooks the fact that organisms representing most branches in the tree of life are too small to be adequately sampled and documented according to the proposed paradigm shift and rejects the fact that collections of entire specimens will be more useful in answering as-yet-unknown questions in a multitude of disciplines in the future than compassionate collections. We agree that compassion is important when collecting in the field to minimize the suffering of organisms. Professional researchers have been collecting for centuries for the clear purpose of advancing science, not the aimless storage of dead animals in museums, and certainly not in a quest for cruelty. As time goes by, societal evolution permeates into the scientific world, and modern scientists are thankfully more sensitive to the well-being and survival of animals than those of the 18th century. We argue that physically capturing the morphological, molecular, and ecological diversity of lineages remains a requirement for the comprehensive study and understanding of the living world we live in, probably more so now than ever before. This can only be realistically achieved through continuous enrichment of physical collections of whole specimens.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

REFERENCES

Appeltans W, Ahyong ST, Anderson G *et al.* The magnitude of global marine species diversity. *Current Biology: CB* 2012;**22**:2189–202. https://doi.org/10.1016/j.cub.2012.09.036

Balke M, Schmidt S, Hausmann A *et al.* Biodiversity into your hands – A call for a virtual global natural history 'metacollection'. *Frontiers in Zoology* 2013;**10**:1–9. https://doi.org/10.1186/1742-9994-10-55

Byrne AQ. Reimagining the future of natural history museums with compassionate collection. *PLoS Biology* 2023;**21**:33002101. https://doi.org/10.1371/journal.pbio.3002101

Carlson CJ, Dallas TA, Alexander LW *et al.* What would it take to describe the global diversity of parasites? *Proceedings Biological Sciences* 2020;**287**:20201841. https://doi.org/10.1098/rspb.2020.1841

Ceríaco LM, Gutiérrez EE, Dubois A *et al.* Photography-based taxonomy is inadequate, unnecessary, and potentially harmful for biological sciences. *Zootaxa* 2016;**4196**:435–45. http://doi.org/10.11646/zootaxa.4196.3.9

Chapman AD. *Numbers of Living Species in Australia and the World*. Canberra: Australian Biological Resources Study, 2009.

Chomicki G, Renner SS. Watermelon origin solved with molecular phylogenetics including Linnaean material: another example of museomics. *The New Phytologist* 2015;**205**:526–32. https://doi.org/10.1111/nph.13163

Costello MJ, Wilson S, Houlding B. Predicting global species richness using rates of species descriptions and estimates of taxonomic effort. *Systematic Biology* 2012;**61**:871–83. https://doi.org/10.1093/sysbio/syr080

Dell'Anno A, Carugati L, Corinaldesi C *et al*. Unveiling the biodiversity of deep-sea nematodes through metabarcoding: are we ready to bypass the classical taxonomy? *PLoS One* 2015;**10**:e0144928. https://doi.org/10.1371/journal.pone.0144928

Dijkstra K-DB. Restore our sense of species. *Nature* 2016;**533**:172–4. https://doi.org/10.1038/533172a

Drew JA, Moreau CS, Stiassny MLJ. Digitization of museum collections holds the potential to enhance researcher diversity. *Nature Ecology & Evolution* 2017;**1**:1789–90. https://doi.org/10.1038/s41559-017-0401-6

Engel MS, Ceríaco LM, Daniel GM *et al*. The taxonomic impediment: a shortage of taxonomists, not the lack of technical approaches. *Zoological Journal of the Linnean Society* 2021;**193**:381–7. https://doi.org/10.1093/zoolinnean/zlab072

Erwin TL. Tropical forests: their richness in Coleoptera and other arthropod species. *The Coleopterists Bulletin* 1982;**36**:74–5.

Förster T, Creutzburg F, Anton E *et al*. Metabarcoding versus morphologische Identifizierung: der Herausforderung gewachsen? *Entomologische Zeitschrift* 2023;**133**:103–16.

Greiman SE, Cook JA, Odom T *et al*. Microbiomes from biorepositories? 16S rRNA bacterial amplicon sequencing of archived and contemporary intestinal samples of wild mammals (Eulipotyphla: Soricidae). *Frontiers in Ecology and Evolution* 2020;**8**:555386. https://doi.org/10.3389/fevo.2020.555386

Guedes P, Alves-Martins F, Arribas JM *et al*. Eponyms have no place in 21st-century biological nomenclature. *Nature Ecology & Evolution* 2023;**7**:1157–60. https://doi.org/10.1038/s41559-023-02022-y

Hope AG, Sandercock BK, Malaney JL. Collection of scientific specimens: benefits for biodiversity sciences and limited impacts on communities of small mammals. *BioScience* 2018;**68**:35–42. https://doi.org/10.1093/biosci/bix141

Kemp C. The endangered death. *Nature* 2015;**518**:292–4. https://doi.org/10.1038/518292a

Kim KC, Byrne LB. Biodiversity loss and the taxonomic bottleneck: emerging biodiversity science. *Ecological Research* 2006;**21**:794–810. https://doi.org/10.1007/s11284-006-0035-7

Krell F-T, Wheeler QD. Specimen collection: plan for the future. *Science* 2014;**344**:815–6. https://doi.org/10.1126/science.344.6186.815

Larsen BB, Miller EC, Rhodes MK *et al*. Inordinate fondness multiplied and redistributed: the number of species on earth and the new pie of life. *The Quarterly Review of Biology* 2017;**92**:229–65. https://doi.org/10.1086/693564

Lister AM; Climate Change Research Group. Natural history collections as sources of long-term datasets. *Trends in Ecology & Evolution* 2011;**26**:153–4. https://doi.org/10.1016/j.tree.2010.12.009

Louca S, Mazel F, Doebeli M *et al*. A census-based estimate of Earth's bacterial and archaeal diversity. *PLoS Biology* 2019;**17**:e3000106. https://doi.org/10.1371/journal.pbio.3000106

Miller SE, Barrow LN, Ehlman SM *et al*. Building natural history collections for the twenty-first century and beyond. *BioScience* 2020;**70**:674–87. https://doi.org/10.1093/biosci/biaa069

Minteer BA, Collins Simpson JP, Love KE *et al*. Avoiding (re)extinction. *Science* 2014;**344**:260–1. https://doi.org/10.1126/science.1250953

Mora C, Tittensor DP, Adl S, Simpson AGB, Worm B. How many species are there on Earth and in the ocean? *PLoS Biology* 2011;**9**:e1001127. https://doi.org/10.1371/journal.pbio.1001127

Nakonieczny M, Kedziorski A, Michalczyk K. Apollo butterfly (*Parnassius apollo* L.) in Europe–its history, decline and perspectives of conservation. *Functional Ecosystems and Communities* 2007;**1**:56–79.

Nyffeler M, Birkhofer K. An estimated 400–800 million tons of prey are annually killed by the global spider community. *The Science of Nature* 2017;**104**:1–12. https://doi.org/10.1007/s00114-017-1440-1

Poulin R, Morand S. The diversity of parasites. *The Quarterly Review of Biology* 2000;**75**:277–93. https://doi.org/10.1086/393500

Raxworthy CJ, Smith BT. Mining museums for historical DNA: advances and challenges in museomics. *Trends in Ecology & Evolution* 2021;**36**:1049–60. https://doi.org/10.1016/j.tree.2021.07.009

Rocha LA, Aleixo A, Allen G *et al*. Specimen collection: an essential tool. *Science* 2014;**344**:814–5. https://doi.org/10.1126/science.344.6186.814

Rohwer VG, Rohwer Y, Dillman CB. Declining growth of natural history collections fails future generations. *PLoS Biology* 2022;**20**:e3001613. https://doi.org/10.1371/journal.pbio.3001613

Ruane S, Austin CC. Phylogenomics using formalin-fixed and 100+ year-old intractable natural history specimens. *Molecular Ecology Resources* 2017;**17**:1003–8. https://doi.org/10.1111/1755-0998.12655

Schindel DE, Cook JA. The next generation of natural history collections. *PLoS Biology* 2018;**16**:e2006125. https://doi.org/10.1371/journal.pbio.2006125

Schmitt CJ, Cook JA, Zamudio KR *et al*. Museum specimens of terrestrial vertebrates are sensitive indicators of environmental change in the Anthropocene. *Philosophical Transactions of the Royal Society B* 2019;**374**:20170387. https://doi.org/10.1098/rstb.2017.0387

Scholtz T, Choudhury A. Parasites of freshwater fishes in North America: why so neglected? *Journal of Parasitology* 2014;**100**:26–45. https://doi.org/10.1645/13-394.1

Segerer AH. Rückgang der Schmetterlinge in Bayern. *Jahrbuch des Vereins zum Schutz der Bergwelt (München)* 2019;**84**:15–58.

Siddal ME, Barkdull M, Tessler M *et al*. Ideating iDNA: lessons and limitations from leeches in legacy collections. *PLoS One* 2019;**14**:e0212226. https://doi.org/10.1371/journal.pone.0212226

Sinniger F, Pawlowski J, Harii S *et al*. Worldwide analysis of sedimentary DNA reveals major gaps in taxonomic knowledge of deep-sea benthos. *Frontiers in Marine Science* 2016;**3**:92. https://doi.org/10.3389/fmars.2016.00092

Stork NE. How many species of insects and other terrestrial arthropods are there on Earth? *Annual Review of Entomology* 2018;**63**:31–45. https://doi.org/10.1146/annurev-ento-020117-043348

Sumner-Rooney L, Sigwart JD. Lazarus in the museum: resurrecting historic specimens through new technology. *Invertebrate Zoology* 2017;**14**:73–84. https://doi.org/10.15298/invertzool.14.1.11

Thompson CW, Phelps KL, Allard MW *et al*. Preserve a voucher specimen! The critical need for integrating natural history collections in infectious disease studies. *Mbio*, 2021;**12**:10-1128. https://doi.org/10.1128/mbio.02698-20

Toussaint EFA, Gauthier J, Bilat J *et al*. HyRAD-X exome capture museomics unravels giant ground beetle evolution. *Genome Biology and Evolution* 2021;**13**:evab112. https://doi.org/10.1093/gbe/evab112

Wagner DL, Grames EM, Forister ML *et al*. Insect decline in the Anthropocene: death by a thousand cuts. *Proceedings of the National Academy of Sciences of the United States of America* 2021;**118**:e2023989118. https://doi.org/10.1073/pnas.2023989118

Warnett JM, Williams MA, Wilson PF *et al*. The Oxford Dodo. Seeing more than ever before: X-ray micro-CT scanning, specimen acquisition and provenance. *Historical Biology* 2021;**33**:2247–55. https://doi.org/10.1080/08912963.2020.1782396

Webster MS **(Ed.)**. *The Extended Specimen: Emerging Frontiers in Collections-based Ornithological Research*. Boca Raton: CRC Press/Taylor & Francis Group, 2017.

Wilson EO. A global biodiversity map. *Science* 2000;**289**:2279. https://doi.org/10.1126/science.289.5488.2279

Wood CL, Vanhove MPM. Is the world wormier than it used to be? We'll never know without natural history collections. *Journal of Animal Ecology* 2022;**92**:250–62. https://doi.org/10.1111/1365-2656.13794

Zachos E. *Species concepts in Biology – Historical Development, Theoretical Foundation and Practical Relevance*. Berlin: Springer, 2016.

Zhang ZQ, Shear WA. Linnaeus tercentenary: progress in invertebrate taxonomy. *Zootaxa* 2007;**1668**:1–766.