Articulating Loss:

Quantifying Skeletal Incompleteness in Natural History Collections

Alaina Harmon

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Wilson O'Donnell

Rebecca Kaczkowski

Gregory Wilson

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Abstract

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Alaina Harmon

Chair of the Supervisory Committee:
Wilson O'Donnell
Museology

The purpose of this instrumental case study was to characterize the degree to which element loss has occurred in natural history museum skeletal collections, which elements were lost, and what types of loss occurred. Through a combination of element-by-element inventory of the non-human primate specimens within the University of Washington's physical anthropology collection and document analysis of departmental and Washington National Primate Research Center records, data was collected for quantitative analysis. No statistically significant correlation was found between loss and specimen body size, relative element size, or specimen rarity. There was some indication that loss occurred either at a low level in collections or during specimen preparation, that loss might be related to element use, and that loans of undefined length duration impact skeletal completeness. Collection loss might result in faulty anatomical inference or "shifting backbone syndrome," a consequence introduced in this study. The primary limitation of this study arose from the study design—the results of a case study are not generalizable beyond the case. However, case study design removed potential bias that might have been introduced by sampling within collections, and the results, in conjunction with existing studies of loss, further refined suggestions for future areas of research.

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Chapter 1: Introduction

If the continuous building of an archive of life for future reference is key to the life sciences as practiced today and, presumably, into the future, what of natural history collection losses? Can one assume that collections remain perfectly preserved and specimen attrition does not occur? Do collections continue to build over time without experiencing setbacks in specimen number resulting from years of storage, education, loan, study, and exhibit? Anecdotal evidence from informal conversations within collection departments and data from a small number of published studies suggest that collections are not immune to losses in the form of lost loans, research "souvenirs," misplacement within the collection, data disassociation resulting in the lack of utility of a specimen, and as a result of additional processes.[1] Of the formal studies that do exist, none focus specifically on zoological collections, and none are explicitly linked to risk management formulae. The purpose of this study was to contribute to the literature on collection loss by characterizing the degree to which element (bone) loss occurs in natural history museum skeletal collections, which elements are lost, and what types of loss occur.

"Mind-boggling numbers,"[2] the Natural History Museum of Los Angeles County website opens its explanation of the importance of natural history specimen collections with this phrase. Reference to the expansive nature of collections can even be found in popular culture. Author China Miéville describes entering a fictional collection in his novel *Kraken: An Anatomy*, "The visitors stopped still. They were in a specimen maze. Ranked intricacies. Kilometres of shelves and jars. […] There were hundreds of bottles, from those chest-high down to those the size of a glass of water."[3] In reality, natural history museums hold an estimated 3 billion specimens worldwide.[4]

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[1] Anwen C. Caffell et al., "Pressures on Osteological Collections - the Importance of

[2] "Why We Have Collections," Natural History Museum of Los Angeles County, 2018, https://nhm.org/site/about-our-museums.

[3] China Miéville, *Kraken: An Anatomy* (New York: Del Rey/Ballantine Bookes, 2010), 8.

[4] Jorge Soberon, "Linking Biodiversity Information Sources," *Trends in Ecology & Evolution* 14, no. 7 (1999): 291.

Each specimen is held in perpetuity as what is known as a voucher specimen, a physical reference point on which studies can be based as an example of life at a particular point in time and space,[5] essentially an ecological time capsule. Andrew J. Pekarik, then of the Smithsonian Institution's Office of Policy and Analysis, described the importance of these collections as a global archive in "Long-Term Thinking: What About the Stuff?": "The value of this archive is not diminished in any way by the fact that few museum visitors will ever see more than a tiny fraction of the holdings. Their preciousness lies in the information they can provide to researchers—information that can have a significant impact on our understanding of the world and the changes and problems that we face."[6] By keeping collections, natural history museums permit new questions to be asked and explored as technological and methodological advances occur, as with the introduction of molecular genetics to natural history research.[7] Based on the ratio of specimens to known species, Q. D. Wheeler et al. proposed in "Mapping the Biosphere: Exploring Species to Understand the Origin, Organization and Sustainability of Biodiversity" that collections would need to hold as many as 18 billion specimens in order to represent the estimated 10 million total species worldwide.[8] This number in itself may be an underestimate, as predictions of global biodiversity have been as rich as 50 million total species.[9]

Each gain in collection quantity sees an exponential return in the scientific field. Writing of the Museum of Texas Tech University's Natural Science Research Laboratory in "Assessing

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[5] Bryan McLean et al., "Natural History Collections-Based Research: Progress, Promise, and Best Practices," *Journal of Mammalogy* 97, no. 1 (2016): 291.

[6] Andrew J. Pekarik, "Long-Term Thinking: What About the Stuff?" *Curator: The Museum Journal* 46, no. 4 (2003): 368-369.

[7] Peter Wandeler, Paquita E. A. Hoeck, and Lukas F. Keller, "Back to the Future: Museum Specimens in Population Genetics," *Trends in Ecology & Evolution* 22, no. 12 (2007): 634-642.

[8] Q. D. Wheeler et al., "Mapping the Biosphere: Exploring Species to Understand the Origin, Organization and Sustainability of Biodiversity," *Systematics and Biodiversity* 10, no. 1 (2012): 8.

[9] Robert M. May, "How Many Species Are There on Earth?," *Science* 241, no. 4872 (1988): 1447.

the Value of Natural History Collections and Addressing Issues Regarding Long-Term Growth and Care," Robert D. Bradley et al. enumerated the impact of the laboratory's collecting trips. Over the course of 40 years, collections from these trips resulted in identification of ten new mammal species, description of eight new viruses, contributed to more than 100 scientific articles, and resulted in the field training of more than 39 graduate students and 136 undergraduate students. In addition, upwards of 255 graduate students utilized the resulting collections for their theses and/or dissertations.[10] Natural history collections support scientific inquiry, growth of new generations of professional and citizen scientists, and increase our awareness of the life with which we share or have shared the planet. Twenty-five percent of all articles published in the American Society of Mammalogists' journal, *The Journal of Mammalogy*, between 2005 and 2014 used natural history collections, with significantly more articles published using historical and recent specimens as opposed to recent specimens alone.[11]

Beyond scientific goals, all non-profit museums are obligated to provide care for their collections due to their status as charitable corporations, holding "property under an obligation to use that property in the pursuit of certain public benefits."[12] Under Chapter 72 of the United States of America's legal code, a museum, among other characteristics, "owns or utilizes tangible objects [and] cares for them."[13] However, this obligation extends only to museums within the United States and to museums in other nations that have created similar legal requirements. In "Lack of Well-Maintained Natural History Collections and Taxonomists in Megadiverse Developing Countries Hampers Global Biodiversity Exploration," Omid Paknia et al. reported that approximately 26% of all 7,039 natural history collections listed on the Global Registry of Biodiversity Repositories, Index Herbariorum, or University Museums and Collections Worldwide Database of University Museums and Collections are concentrated in the

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[10] Robert D. Bradley et al., "Assessing the Value of Natural History Collections and Addressing Issues Regarding Long-Term Growth and Care," *BioScience* 64, no. 12 (2014): 1153.

[11] McLean et al., 288.

[12] Marie C. Malaro and Ildiko Pogány DeAngelis, *A Legal Primer on Managing Museum Collections* (Washington, D. C.: Smithsonian Institution, 2012), 9.

[13] "20 USC Ch. 72: Museum and Library Services," Office of the Law Revision Council, United States House of Representatives, 1990, http://uscode.house.gov/view.xhtml?path=/prelim@title20/chapter72&edition=prelim.

United States, China, and Australia,[14] leaving the majority of collections outside of the purview of U. S. law. Moreover, the types of institution that hold collections also vary across nations. For example, most natural history specimens in China are held at universities or research centers rather than within museums.[15]

An international lens is a necessity when examining natural history research within museums due to the extent of international holdings and research. The Global Biodiversity Information Facility (GBIF) is "an international network and research infrastructure funded by the world's governments and aimed at providing anyone, anywhere, open access to data about all types of life on Earth."[16] This resource permits access to global specimen data by anyone with an Internet connection. Momentarily ignoring the fact that physical specimens allow for continued observation and measurement, one may be tempted to question if preservation of specimens is necessary with continued digitization. That is, does specimen loss matter if the data is retained? As of 2010, GBIF held a maximum of 3% of the world's specimen data.[17] In "No Specimen Left Behind: Industrial Scale Digitization of Natural History Collections," Vladimir Blagoderov et al. calculated that complete databasing of the Natural History Museum, London's insect specimens would require 25 years of work from all 65 people in the department.[18]

Specimens have long been used in systematics and biogeography,[19] classifying organisms into different categories and understanding their distribution across the Earth. New species

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[14] Omid Paknia, Hossein Rajaei Sh., and André Koch, "Lack of Well-Maintained Natural History Collections and Taxonomists in Megadiverse Developing Countries Hampers Global Biodiversity Exploration," *Organisms Diversity and Evolution* 15, no. 3 (2015): 620.

[15] Xian Song and Jieyan Gu, "SNHM: Connecting the Public with Its Natural History Collections," *Museum International* 65, no. 1-4 (2013): 69.

[16] "What Is GBIF?," Global Diversity Information Facility, 2018, https://www.gbif.org/what-is-gbif.

[17] H. Ariño Arturo, "Approaches to Estimating the Universe of Natural History Collections Data," *Biodiversity Informatics* 7, no. 2 (2010): 81.

[18] Vladimir Blagoderov et al., "No Specimen Left Behind: Industrial Scale Digitization of Natural History Collections," *ZooKeys* 209 (2012): 134.

[19] McLean et al.: 288.

continue to be discovered within collections. In March 2018, researchers reported that pygmy marmosets within the Brazilian Amazon are two separate species. This distinction was made using phylogenies (reconstructed evolutionary histories) and comparison of specimen pelage (fur).[20]

In addition to traditional study types, using an example university museum collection in "Natural History Collections-Based Research: Progress, Promise, and Best Practices," Bryan Mclean et al. identified four main areas of research loan purpose. These were genomics, the study of the full genetic complement of an organism; morphometrics, the study of form; stable isotope ecology; and parasites and pathogens.[21] In addition, the time depth represented in collections increases understanding of the impact that people have on our world. In collections, comparisons can be made between organisms and ecologies before global warming, ocean acidification, or other human modification of climate and those living after periods of change.[22] Paleozoologists too make use of the collections for comparisons permitting taxonomic identification of species found in paleontological and zooarchaeological contexts.[23] Identified specimens can be used to build studies that permit understanding of past responses to climate change, morphological change, assignment of status as a native or invasive species, disease histories, effects of competition, and extinction rates—all of which can be employed to build scientific models predicting future change.[24] Educators have recognized collections as sites for student-centered learning experiences and exploration of the content of current science and the

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[20] P. Boubli et al., "How Many Pygmy Marmoset (Cebuella Gray, 1870) Species Are There? A Taxonomic Re-Appraisal Based on New Molecular Evidence," *Molecular Phylogenetics and Evolution* 120 (2018): 170-182.

[21] McLean et al.: 288-291.

[22] Adrian M. Lister, "Natural History Collections as Sources of Long-Term Datasets," *Trends in Ecology and Evolution* 26, no. 4 (2011): 153-154.

[23] R. L. Lyman, "Paleozoology's Dependence on Natural History Collections," *Journal of Ethnobiology* 30, no. 1 (2010): 126-129.

[24] R. Lee Lyman, "A Warrant for Applied Palaeozoology," *Biological Reviews* 87, no. 3 (2012): 515-521.

process of constructing science.[25] Additional collection uses include toxicology, food security, and wildlife forensics.[26]

Museums may be the strongest sources of spatial and temporal data available for rare species. Conducting population viability analysis on collection data, researchers have shown that collections can be used to predict trends in declining or increasing abundance,[27] useful for conservation planning. Scientists have differentiated between seahorses by cranial morphology (form), permitting tracing of seahorses harvested for traditional medicine to their population of origin. This may aid both international law enforcement and conservation given that seahorse trade is controlled under the Convention on the International Trade in Endangered Species of Wild Fauna and Flora.[28] Natural history collections have also been built in tandem with community engagement and oral history to address social, cultural, and environmental impacts of resource management over time, as with marine conservation efforts in Fiji.[29] Finally, collections can be used to predict epidemics and health hazards. By comparing historical and current mosquito distributions, researchers in Belgium reported heightened spatial proximity between people and mosquito species known to transmit malaria, arboviruses, or *Plasmodium* species.[30]

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[25] Joseph A. Cook et al., "Natural History Collections as Emerging Resources for Innovative Education," *BioScience* 64, no. 8 (2014): 728-729.

[26] Graham H. Pyke and Paul R. Ehrlich, "Biological Collections and Ecological/Environmental Research: A Review, Some Observations and a Look to the Future," *Biological Reviews* 85, no. 2 (2010): 247; McLean et al.: 287.

[27] Olav Skarpaas and Odd E. Stabbetorp, "Population Viability Analysis with Species Occurrence Data from Museum Collections," *Conservation Biology* 25, no. 3 (2011): 578-584.

[28] Francisco Otero-Ferrer et al., "When Natural History Collections Reveal Secrets on Data Deficient Threatened Species: Atlantic Seahorses as a Case Study," *Biodiversity and Conservation* 26, no. 12 (2017): 2791-2802; A. C. J. Vincent, S. J. Foster, and H. J. Koldewey, "Conservation and Management of Seahorses and Other Syngnathidae," *Journal of fish biology* 78, no. 6 (2011): 1681-1724; Julia K. Baum and Amanda C. J. Vincent, "Magnitude and Inferred Impacts of the Seahorse Trade in Latin America," *Envir. Conserv.* 32, no. 4 (2005): 305-319.

[29] Abigail S. Golden et al., "Combining Natural History Collections with Fisher Knowledge for Community-Based Conservation in Fiji.(Research Article)," *PLoS ONE* 9, no. 5 (2014).

[30] W. F. Dekoninck et al., "Changes in Species Richness and Spatial Distribution of Mosquitoes (Diptera: Culicidae) Inferred from Museum Specimen Records and a Recent

Collections are crucial, because we simply do not know how they will matter to future researchers.[31] In "The Contribution of Small Collections to Species Distribution Modelling: A Case Study from Fuireneae (Cyperaceae)," Glon et al., showed that small collections, which may seem insignificant, hold specimens unique in time and place of origin, providing continuity of data and allowing stronger definition of species' habitats.[32] Rather than attempting to be encyclopedic, some collections, such as that of the Museum of Vertebrate Zoology of the University of California document change over time in a specific region,[33] permitting them to specialize in specimens that may not be represented in museums with broader geographic and/or taxonomic foci.

Despite their utility and additive nature, natural history collections often face uncertain futures. Pekarik describes this logic, "Long-term thinking is not in fashion. Preservation for the sake of some future, unspecified, unimagined benefit is increasingly hard to justify."[34] Between 1988 and 1996, the Natural History Museum in London lost governmental funding, needing to source a third of its budget elsewhere.[35] This tendency is not new. In the 1930s, the University of Pavia, Italy, removed a collection of roughly a half-million specimens dating as far back as the 1770s to a local castle attic, where it deteriorated.[36] As recently as March 2017, the University of Louisiana in Monroe made national headlines when the administration gave the campus

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Inventory: A Case Study from Belgium Suggests Recent Expanded Distribution of Arbovirus and Malaria Vectors," *Journal of Medical Entomology* 50, no. 2 (2013): 237-243.

31 Grant Blankenship, "Old Specimens May Hold the Key to New Discoveries," *NPR* (13 April 2018).

32 Heather E. Glon et al., "The Contribution of Small Collections to Species Distribution Modelling: A Case Study from Fuireneae (Cyperaceae)," *Ecological Informatics* 42 (2017): 67.

33 Joseph Grinnell, "The Methods and Uses of a Research Museum," *The Popular Science Monthly* 77 (1910): 164-166.

34 Andrew J. Pekarik, 369.

35 Nigel Williams, "A Plea to Protect Threatened Collections," *Science* 273, no. 5283 (1996): 1792.

36 "Secret Treasure-Troves Restored: Reflecting on the Endeavours of Scientists Past Can Provide Both Inspiration and Pleasure," *Nature* 451, no. 7178 (2008): n. pag.

natural history museum notice to find a new location for its collections or arrange to give them to another institution—with the caveat that by the end of July, if not removed, the collections would be destroyed.[37]

This study aimed to better understand collection loss in order to mitigate potentially avoidable damage to irreplaceable resources. This study addressed the following questions:

- *To what extent does skeletal element attrition occur in museum collections?*
- *Does skeletal element attrition increase in natural history museum research collections with specimen time spent in the collections?*
- *Can type of loss be determined? Examples of loss types include loss during preparation or collection, unreturned loan, theft, destructive sampling, transfer to another institution, and disposal.*
- *Are particular elements more prone to loss and/or specific types of loss?*
- *Does uncharacterized loss, that which is not associated with archival record of a loss type, show positive correlation with specimen monetary value, scientific value, or element size?*
- *What magnitude of risk exists per element and type of loss?*

By introducing this conversation in the realm of zoological collections, this study will permit collection management and preventive conservation decision-making with a basis quantitative data; explicitly connect loss and risk management; and provide a model and raise additional questions for future explorations of collection loss with particular focus on its detriment to global science. While the scope of this study is within the realm of natural history, the methods employed can be repurposed for study of a wide range of collection materials across all museum subject disciplines.

[37] Rachael Lallensack, "In Louisiana, a Threatened Natural History Collection Gets a Reprieve," *Science* (4 April 2017), http://www.sciencemag.org/news/2017/04/louisiana-threatened-natural-history-collection-gets-reprieve.

Chapter 2: Literature Review

The following literature review explored that which currently was and was not known about collection object loss within museum settings with particular emphasis on natural history collections. This review examined four bodies of literature—studies of or mentions of loss within museum collections, the process of mammalian specimen preparation, primate anatomy, and risk management.

The Remains of the Day: Loss Within Museum Collections

In a search of the literature, three broad surveys of loss within collections were found. All three focused on collection types that may be found within natural history museums, one on archaeological research collections, another on objects on exhibit, and the third on a research collection of human skeletal remains. In the archaeological example, "Archaeological Artifact Attrition: Time's Arrow and Collection Depletion," Robert R. Kautz posited that understanding collection context is comparable to the need to understand post-depositional contexts, such as taphonomy and looting processes, in interpreting archaeological materials in a museum setting. Kautz analyzed attrition during consultation on an inventory of all California Department of Parks and Recreation collections with human remains. The process involved contact with and record verification for more than one million objects with varied provenance, including museum donations and agency accessions. Kautz found that "attractiveness" of the material type for research loan had no impact on loss; that there was greater loss of prehistoric material, heavy, and/or large material, and "less desirable" materials for theft; and that loss did not appear to be linked to time since collection. Kautz concluded that the main factor at play in loss is casual determination of archaeological worth. Comparison of actual observed attrition and survey results in which museum professionals were asked to determine which object types they would discard if told to do so by management result in a strong positive correlation.[38] However, similar studies could not be located for comparison to determine if the results are indicative of only California Department of Parks and Recreation practice or if they reflect field-wide practice.

[38] Kautz, 34-38.

In the second broad survey, "Risk Assessment of Collections in Exhibitions at the Canadian Museum of Nature," Garnet Muething, Robert Waller, and Fiona Graham reported on risk assessment of 1,498 specimens on exhibit in the Victoria Memorial Museum Building of the Canadian Museum of Nature. The survey applied the Cultural Property Risk Analysis Model, in which generic agent of deterioration-based risks are assessed for applicability and rated by frequency and severity. They concluded that the greatest risks, based on collection object types, facility design, and institutional practice, were light/UV, pests, fire, physical damage from staff activity and/or maintenance, and dust and/or off gassing.[39] The Muething et al. study is not centered on specimen absence, although absence in the form of theft is among the identified generic risks. It focuses on specimen damage. It also differs in that it provides a basis for preventive care action, while Kautz does not explicitly call out priorities, instead indicating the importance of maintaining all accessioned archaeological materials for future research without selective culling. Kautz is concerned with artifact presence, and Muething et al. focus primarily on specimen condition.

In a third survey, "Pressures on Osteological Collections: The Importance of Damage Limitation," Anwen C. Caffell et al. explored element damage and loss in two collections of archaeological human remains curated and studied at the University of Bradford Department of Archaeological Sciences. This study classified 40 adult human skeletons by degree of suspected use and by archaeological site of origin. Of these skeletons, while under collection curation, 40% had lost large elements, 42% had lost hand elements, 40% had lost foot elements, and 32% had lost teeth with more heavily used remains more likely to be missing elements (94% of "heavy use" skeletons versus 77% "light use").[40] All quantified loss is correlated to degree of specimen use in physical anthropology coursework. However, the primary focus of the article is on collection damage and condition with loss only a portion of the study.

The study including zoological specimens considered objects on exhibit, rather than in storage, and focused on damage rather than total loss. The other two studies, while focused on

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[39] Garnet Muething, Robert Waller, and Fiona Graham, "Risk Assessment of Collections in Exhibitions at the Canadian Museum of Nature," *Journal of the American Institute for Conservation* 44, no. 3 (2005): 233, 235, and 238.

[40] Anwen C. Caffell et al., 191-192.

collections in storage, were not of zoological collections, and neither tied its results into existing risk management formulae, providing quantitative analysis to aid collection care decision prioritization.

Additional examples of loss can be found buried within individual research projects not intended for study of object loss. For example, in discussing archaeological artifacts and human skeletal remains planned for inclusion in dissertation research, Gretchen Dabbs writes, “The skeletal remains have always been housed at the American Museum of Natural History, and there are no records of them ever being lost. However, during the course of this project, it has become apparent that some skeletal elements have been lost or misplaced during the 60 plus years between excavation and analysis.”[41]

Comparison of database searches and accession or catalog record presence may provide an indication of the scope of loss. In 1883, Col. James Stevenson published his 1879-1880 collection of 3,905 Zuni, Hopi, Rio Grande, Apache, and Navajo objects in the second annual report of the Bureau of Ethnography. The report included United States National Museum (USNM) catalog numbers, indicating that the full collection was accessioned.[42] In “Lost in Museums: The Ethical Dimensions of Historical Practices of Anthropological Specimen Exchange," an analysis of the effects of object exchange on museum collections, Catherine A. Nichols noted that only 2,673 of these objects appeared in the National Museum of Natural History’s (the USNM) public database with the remaining objects lost either through exchange, accidental destruction, or otherwise unspecified means. Nichol’s main point in sharing this data was to exemplify how public databases, displaying results for objects physically present in the museum, can obscure our understanding of the past and breadth of materials previously

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[41] Gretchen Dabbs, "Health and Nutrition at Prehistoric Point Hope, Alaska: Application and Critique of the Western Hemisphere Health Index" (dissertation, University of Arkansas, 2009), 7.

[42] James Stevenson, “Illustrated Catalogue of the Collections Obtained from the Indians of New Mexico and Arizona in 1879," in *Second Annual Report of the Bureau of Ethnology to the Secretary of the Smithsonian Institution, 1880-81*, ed. by J. W. Powell (Washington, D. C.: Government Printing Office, 1883), 337-421; James Stevenson, “Illustrated Catalogue of the Collections Obtained from the Indians of New Mexico in 1880," in *Second Annual Report of the Bureau of Ethnology to the Secretary of the Smithsonian Institution, 1880-81*, ed. by J. W. Powell (Washington, D. C.: Government Printing Office, 1883), 435-465.

collected.[43] However, it also presents a collection in which 31% of the objects have been lost in the years since collection.

Reported thefts offered another opportunity to explore scope. A search for museums and theft turns up a broad range of news and scholarly writing on art theft. Writing for *Curator*, Anna Kisluk noted, "Art theft is epidemic—and perennial—not a sporadic event that occurs only infrequently,"[44] connected to its value as "movable property."[45] French authorities recorded 124 art thefts from French museums alone in 1976.[46] However, natural history museums appeared to be largely outside of the academic conversation, although archaeological collections, which may overlap institutionally, appeared in the scholarly record.[47]

A search for popular sources of information on natural history museum specimen theft suggested that it does occur, and can occur on a grand scale. For example, a former employee of the Australian Museum was charged with 179 counts of larceny and disposing of stolen property following five years of collection theft. While some of the stolen specimens were retrieved, 32 were disassociated from their collection data, compromising their utility in scientific study.[48] In 2011, more than 30 rhinoceros horns were stolen across Europe. Victims of theft included museums such the Ipswich Museum.[49] A Natural History Museum in Tring, Hertfordshire

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[43] Catherine A. Nichols, "Lost in Museums: The Ethical Dimensions of Historical Practices of Anthropological Specimen Exchange," *Curator: The Museum Journal* 57, no. 2 (2014): 229-230.

[44] Anna Kisluk, "Stolen Art and "Due Diligence"," *Curator: The Museum Journal* 41, no. 3 (1998): 161.

[45] Ibid.

[46] Lawrence J. Fennelly, *Museum, Archive, and Library Security* (Boston: Boston : Butterworths, 1983), 742-743.

[47] Karen D. Vitelli, "Theft from Peabody Museum," *Journal of Field Archaeology* 5, no. 4 (1978): 479.

[48] Jennifer Cooke, "Museum Thief Jailed," *The Sydney Morning Herald* (20 April 2007).

[49] Sarah Lyall, "Rhino Horns Put Europe's Museums on Thieves' Must-Visit List," *The New York Times* (26 August 2011).

responded by replacing their rhinoceros ivory with resin replicas,[50] indicating awareness within the museum community of the risk of theft.

Natural history museum specimen loss appeared most regularly in the academic literature within the context of rediscovery of objects within collections. Examples included 62 paleobotanical type specimens initially lost at the Academy of Natural Sciences of Philadelphia (ANSP) and Yale Peabody Museum following the death of an erstwhile ANSP employee. This employee retained part of the collection even after leaving the institution.[51] In another instance, a type specimen of banded iguana (*Brachylophus fasciatus*) was lost and then found in the Paris Natural History Museum collections with no associated data.[52] It should be noted that in these instances, the loss is of at least one entire specimen, and that those specimens are type specimens, the specimens used in describing a particular species and therefore valuable for determining if other specimens are or are not of that species.[53] Additional type rediscoveries have occurred in the Shanghai Natural History Museum and Museu Argentino de Ciências Naturales following collection moves and at the Canterbury Museum of New Zealand following data disassociation due to misnumbering.[54] These were not true losses because the specimen was

[50] News agencies, "Rhino Horn Thief Who Stole Fakes from Natural History Museum Jailed" *The Telegraph* (7 December 2013).

[51] James C. Lendemer, "Rediscovery Of 'Lost' Triassic Fossil Plant Types: Components of the Wilhelm Bock Collection in the Academy of Natural Sciences of Philadelphia and in the Yale Peabody Museum," *Proceedings of the Academy of Natural Sciences of Philadelphia* 152 (2002): 205-207.

[52] Ivan Ineich and Robert N. Fisher, "Rediscovery of the 220-Year-Old Holotype of the Banded Iguana, *Brachylophus fasciatus* (Brongniart, 1800) in the Paris Natural History Museum," *Zootaxa* 4138, no. 2 (2016): 381.

[53] Matthew Haber, "How to Misidentify a Type Specimen," *Biology & Philosophy* 27, no. 6 (2012): 768.

[54] A. Braun, C. P. Groves, and P. Grubb, "Rediscovery of the Type Specimen of *Bubalus mindorensis* Heude, 1888," *Mammalian Biology* 67, no. 4 (2002): 247; A. N. Zerbini and H. Castello, "Rediscovery of the Type Specimen of the Antarctic Minke Whale (*Balaenoptera bonaërensis*, Burmeister, 1867)," *Mammalian Biology* 68, no. 2 (2003): 120; A. B. Freeman and A. N. D. Freeman, "Rediscovery of an Original Type Specimen of *Sphenodon guntheri* Buller in the Canterbury Museum, New Zealand," *New Zealand Journal of Zoology* 22, no. 3 (1995): 357.

present but not recognized for its scientific significance as a type specimen. The disappearance and/or reappearance of non-type specimens did not figure prominently, if at all, in the literature.

Scarcity of the literature may arise from the fact that acknowledging loss entails risk. Although under long-term loan, rather than under museum title, the Chicago Museum of Science and Industry was sued after inventory of approximately 300 loaned dolls revealed that half of the dolls were not present.[55] However, acknowledging loss allows examination of the types of loss which occur, the extent of potential damage this loss may cause, and may assist collection managers in making informed decisions on the destructive tests that may be run on specimens, altering storage decisions to assist in retention of frequently lost elements, and otherwise developing best practices to address specific needs.

Creating a Specimen: From Death to Accession

A review of the literature of natural history collection over time made it apparent that analysis of a collection without understanding its time and place of origin could result in significant overestimation of skeletal element loss. Naturalists of the Western world have been collecting biological specimens for study since the 1500s, if not earlier. However, until at least the mid-1700s dialog on specimen preparation techniques remained unpublished. While natural history generated a large proportion of the communications of the eighteenth century, this communication existed on a more individual basis between interested parties.[56,] After this time, a more general, published dialog became available.[57] Within the United States, Spencer Fullerton Baird, Assistant Secretary of the Smithsonian Institution in the 19th century, increased collection and preservation technique instruction distribution through the existing circles of natural

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[55] William Mullen, "Museum Sued over Loss of Dolls: Half of Collection Allegedly Missing," *Chicago Tribune* (8 August 2004).

[56] Bettina Dietz, "Making Natural History: Doing the Enlightenment," *Central European History* 43, no. 1 (2010): 37; Robert McCracken Peck, "Preserving Nature for Study and Display," in *Stuffing Birds, Pressing Plants, Shaping Knowledge: Natural History in North America, 1739-1860*, ed. Sue Ann Prince (Philadelphia: American Philosophical Society, 2003): 11-12.

[57] Peck,12.

scientists in the country.[58] He did this through both circulars and the penning of thousands of individual letters. Baird wrote up to 3,000 letters a year with the majority concerning natural history and/or to individuals with interest in natural history. Correspondents included doctors, professors, government scientists, farmers, tradesmen, clerical workers, and manual laborers.[59]

In a circular dating to circa 1848, Baird provided preparation direction for skulls and skeletons and the skins of mammals.[60] However, it is clear that preparation of full skeletons and their subsequent storage in collections was not the norm. Writing “A Method of Cleaning Skulls and Disarticulating Skeletons” in 1914, Harvey F. Holden of the University of California Museum of Vertebrate Zoology described the lack, “Although skins of birds and mammals have been preserved by museums and private collectors for many years, the saving of complete skeletons has, to a large extent, been neglected. Anyone engaged in intensive scientific research will realize that it is almost impossible to find representative skeletons in even the larger museums, while the private collector seldom if ever saves this part of his specimens. . . ”[61] Holden believed that one of the primary reasons for the lack is the “unpleasant and laborious” nature of specimen preparation.[62] As late as 1984, specialists advocated for preservation of the skin and skeleton, rather than the skin and skull, stating that while traditional systematics (the study of categorizing organisms that informs taxonomy or the naming of those organisms) focused on the crania, a wide range of approaches to biology, including ecology, necessitated study of a greater portion of the skeletal body.[63]

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[58] Daniel Goldstein, "’Yours for Science’: The Smithsonian Institution's Correspondents and the Shape of Scientific Community in Nineteenth-Century America," *Isis* 85, no. 4 (1994): 576.

[59] Ibid., 575-576.

[60] Spencer F. Baird, "General Directions for Collecting and Preserving Objects of Natural History" (circular, c. 1848): n. pag.

[61] F. Harvey Holden, "A Method of Cleaning Skulls and Disarticulated Skeletons," *The Condor* 16, no. 5 (1914): 239.

[62] Ibid.

[63] David J. Hafner, John C. Hafner, and Mark S. Hafner, "Skin-Plus-Skeleton Preparation as the Standard Mammalian Museum: Specimen," *Curator: The Museum Journal* 27, no. 2 (1984): 142-144.

Another area in which completeness bias may appear is the means of acquisition of specimens within a collection. In "When Commerce, Science, and Leisure Collaborated: The Nineteenth-Century Global Trade Boom in Natural History Collections," Anne Coote et al. identified private collectors, other museums, exhibitions, auctions, field collections, and businesses as sources from which museums acquired their specimens. Even prior to reaching a given museum, a specimen may have made several previous transfers of ownership within this supply chain. In addition, terms such as field collector may suggest a cohesiveness of purpose or training that did not actually exist. In fact, field collectors included a wide range of people from salaried collectors to military personnel, missionaries, or representatives of indigenous populations, among others. [64] When Charles Willson Peale sent his sons to Europe in 1802 in part to acquire specimens for his museum, they wrote back, "A very good collection of Curiosities might be bought in London. . . Preserved Birds and beasts are in windows all over the Town."[65] Even Baird urged readers of his c. 1848 circular to send specimens free of charge via public wagons and vessels returning from Mexico, Texas, and the interior to public collections.[66]

Acquisition methods today are more controlled. Collections intake salvage carcasses, animals found dead and collected by trained individuals for museums, as in roadkill or birds killed by impact with windows; carcasses and animal byproducts confiscated by state and federal agencies; purposefully collected specimens from specialists in the field; animals killed by exterminators; donated deceased animals from zoos and aquaria; aquatic animals that died before or after stranding; specimens exchanged with or transferred from other institutions; occasional purchase; acquisition from private collectors; specimens collected by researchers who do not have the means or desire to provide long term preservation and care, if accompanied by appropriate legal documentation; and "permanent loan." [67]

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[64] Anne Coote et al., "When Commerce, Science, and Leisure Collaborated: The Nineteenth-Century Global Trade Boom in Natural History Collections," *Journal of Global History* 12, no. 3 (2017): 325.

[65] Rubens Peale (letter, 1802), **quoted in** Peck, 19.

[66] Baird, n. pag.

[67] Burke Museum, "Animal Specimen Prep: Learning from Visitor Reactions," Burke Museum of Natural History and Culture, 2017, http://www.burkemuseum.org/blog/animal-

Other forms of loss and damage may accompany specific provenience. For example, carcasses collected as roadkill might have been subjected to strong a crushing or glancing force, resulting in a comparatively poor condition specimen.[68] Writing "How to Use Roadkill to Study the Skeleton," Kenneth W. Gobalet of California State University observed, "Excessively damaged roadkills may be unsuitable for the exercise because the bones may not be recognizable."[69] Similarly, specimens that were collected following their deaths in the wild, such as carcasses from window strikes, roadkill, and strandings, may be subject to bone loss as indicated by scavenging studies. In "Hit and Run: Effects of Scavenging on Estimates of Roadkilled Vertebrates," Rebecca L. Antworth found that more than half of the bird and snake carcasses they placed on a Florida roadway disappeared within 36 hours.[70] Moreover, scavengers may partially disarticulate skeletons. In a forensic study of the impact of canid scavenging on human remains, "Canid Scavenging/Disarticulation Sequence of Human Remains in the Pacific Northwest," Haglund et al. found that disarticulation occurred in stages. Element loss followed a predictable pattern.[71]

Other skeletal losses are encountered in animals under human care for all or a portion of their lives. For example, veterinary intervention and treatment can result in bone loss. This can

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specimen-prep-learning-visitor-reactions; Takeshi Yamazaki, "Animal Bone Specimens Preparation Method" (Nara, Japan: Nara National Research Institute for Cultural Properties, 2010), http://www.nara.accu.or.jp/elearning/2011/animal.pdf; Joseph A. Cook and Jonathan L. Dunnum, "Division of Mammals Collection Management Procedures Manual, Museum of Southwestern Biology, University of New Mexico" (Albuquerque: University of New Mexico, 2017), https://msb.unm.edu/divisions/mammals/_pdf/procedures-manual.pdf; Biodiversity Research and Teaching Collections, "Collection of Mammals," Texas A&M University, 2018, https://brtc.tamu.edu/collections/mammals/.

[68] Yamazaki, n. pag.

[69] Kenneth W. Gobalet, "How to Use Roadkill to Study the Skeleton," *The American Biology Teacher* 65, no. 9 (2003): 650.

[70] Rebecca L. Antworth, David A. Pike, and Ernest E. Stevens, "Hit and Run: Effects of Scavenging on Estimates of Roadkilled Vertebrates," *Southeastern Naturalist* 4, no. 4 (2005): 647.

[71] W. D. Haglund, D. T. Reay, and D. R. Swindler, "Canid Scavenging/Disarticulation Sequence of Human Remains in the Pacific Northwest," *Journal of Forensic Sciences* 34, no. 3 (1989): 587.

be seen in both zoo, such as amputation of the forelimb of a white-cheeked gibbon (*Nomascus leucogenys)* at Chicago's Lincoln Park Zoo following injury,[72] and wild populations. The fact that a specimen was directly collected from the wild does not preclude the possibility of human medical interference. For example, in "Surgical Treatment of Osteoarthritis in Harbor Seals (*Phoca vitulina*)," Ana Rubio García, D. V. M., et al. described hind flipper amputation of several harbor seals prior to release into the wild from the Seal Rehabilitation and Research Centre in Pieterburen, The Netherlands.[73] In other cases, such losses may be the result of injury in life or congenital absence of particular skeletal elements.[74]

Another potential source of impact on bone presence is necropsy. By 1983 more than 12,000 individual animals had been necropsied at the San Diego Zoo and Wild Animal Park.[75] While not necessarily indicative of wider practice, as previously mentioned, museums may acquire specimens from zoos.[76] This number suggests that many animal remains that museums may acquire may have undergone necropsy. Necropsy procedure is not consistent. Dorrestein and van der Hage claim, "There are probably as many ways to dissect an animal as there are pathologists."[77] Post-mortem procedures may cause damage or loss to select skeletal elements

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[72] Emily C. Sayer, Jessica C. Whitham, and Susan W. Margulis, "Who Needs a Forelimb Anyway? Locomotor, Postural and Manipulative Behavior in a One-Armed Gibbon," *Zoo Biology* 26, no. 3 (2007): 216.

[73] Ana García et al., "Surgical Treatment of Osteoarthritis in Harbor Seals (*Phoca vitulina)," Journal of Zoo and Wildlife Medicine* 46, no. 3 (2015): 553.

[74] Andrés Barreiro et al., "Congenital Skeletal Abnormalities in a Tawny Owl Chick (*Strix aluco*)," *Avian Diseases* 47, no. 3 (2003): 774; Gerry Doyle, "Wolf Injury Prompts Changes at Zoo Exhibit: Brookfield Workers Probe Loss of Foreleg," *Chicago Tribune* (10 March 2006).

[75] M. E. Fowler, "Pathology of Zoo Animals (Book Review)," *The Journal of Zoo Animal Medicine* 14, no. 1 (1983): 42.

[76] Yamazaki, n. pag.

[77] Gerry M. Dorrestein and Marein M. van der Hage, "Post-Mortem Procedures," in *Transmissable Diseases Handbook* (European Association of Zoos and Wildlife Veterinarians, 2010), http://www.eazwv.org/page/inf_handbook.

due to actions such as opening of the cranium to remove the brain or severing of the ribs in order to expose the viscera for examination.[78]

Preparation method provides the final layer of complication to be discussed. The National Park Service identified several means of reducing a carcass to a skeletal specimen. These methods included removal of fresh or dried tissue, generally by hand, followed by soaking in water or an ammonia solution, simmering in warm water, or simmering with sodium perborate or sodium hydroxide. They also offered use of a dermestid beetle colony as an option. With this technique, the specimen needs to be skinned, the tongue and organs removed, and the specimen dried prior to placement in the beetle colony where the remainder of the flesh will be eaten. The specimen is then removed from the colony before the elements fully disarticulate, followed by freezing, heating, or introduction to an anoxic environment to kill any dermestids harbored in or on the resulting skeleton. Additional steps can then be undertaken to degrease the skeleton.[79] Allowing decomposition to occur after burial is another means of defleshing carcasses sometimes employed.[80]

As early as the mid-1800s, Baird cautioned that when left to dry, specimens may become disassociated, and the various pieces of the specimens should be marked.[81] More recently, museums have employed a range of techniques to maintain the association between elements during drying, simmering, or maceration (soaking). These include insertion of wire in the vertebral canal,[82] straining water through a fine mesh colander if prepared by maceration,[83]

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[78]M. H. Woodford, D. V. M., FRCVS, "Post-Mortem Procedures," in *Post-Mortem Procedures for Wildlife Veterinarians and Field Biologists*, ed. M. H. Woodford (Paris, France: Office International des Epizooties, 2000), 25 and 27.

[79] National Park Service, "Vertebrate Skeletons: Preparation and Storage," *Conserve O Gram* 11, no. 7 (2006): 2-5.

[80] Yamazaki, n. pag.

[81] Baird, n. pag.

[82] "Skeletons: Preparation Techniques for Display and Research Collections," 2018, Queensland Museum, http://www.qm.qld.gov.au/Find+out+about/Behind+the+Scenes/Skeletons/Preparation+techniques#.WtzANdvMx3M; Brandon Rowley, "Protocols for Cleaning and Articulating Large Mammal Skeleton," *Symposium: Student Journal of Science and Math* 2, no. 1 (2015): n. pag.

rolling the manually defleshed skeleton into a bundle tied with string to keep elements in proximity while drying,[84] placement in mesh nylon bags for maceration, and careful examination of piles of frass (dermestid excrement) for loose bones.[85] In “Evaluation of a Rapid and Efficient Method for Preparation of Skeletons of Rabbit and Goose,” M. T. Mussa et al. cautioned that maceration may cause loss of small elements,[86] while Brandon Rowley notes in “Protocols for Cleaning and Articulating Large Mammal Skeleton” that turbinates (thin bones in the nasal cavity) are highly susceptible to degradation during preparation.[87] Further care must be exercised dependent on the type of animal carcass being prepared. For example, in bats the tail vertebrae may remain attached to the skin rather than the skeleton if care is not taken during the skinning process.[88]

As with medical intervention during a creature’s lifetime, purposeful decisions made during preparation may result in apparent loss. For example, leg elements may be left attached to mammalian skins, rather than stored as a part of a skeletal specimen.[89] A figure in Gerrit S. Miller’s 1932 mammalian specimen preparation guide, published in the United States National

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[83] Yamazaki, n. pag.

[84] Cook and Dunnum, n. pag.; Hafner, Hafner, and Hafner, 142.

[85] Cook and Dunnum, n. pag.

[86] M. T. Mussa et al., "Evaluation of a Rapid and Efficient Method for Preparation of Skeletons of Rabbit and Goose," *Bangladesh Journal of Veterinary Medicine* 13, no. 2 (2016): 30.

[87] Rowley, n. pag.

[88] Nancy B. Simmons and Robert S. Voss, “Collection, Preparation, and Fixation of Bat Specimens and Tissues,” in *Ecological and Behavioral Methods for the Study of Bats*, ed. Thomas H. Kunz and Stuart Parsons (Baltimore: The John Hopkins University Press, 2009), 86.

[89] D. W. Nagorsen and R. L. Peterson, *Mammal Collector's Manual: A Guide for Collecting, Documenting, and Preparing Mammal Specimens for Scientific Research* (Toronto: Royal Ontario Museum, 1980), 38.

Museum Bulletin, depicts a mouse study skin of which the left paws clearly still contain their skeletal structure.[90]

Still other aspects of preparation may cause unexpected loss years after accession. Two scientists on Louisiana State University's avian collections discussion forum discussed the detrimental effect of enzyme cleaning: Research scientist Sergei V. Drovetski of the Research Centre in Biodiversity and Genetic Resources, noted that enzyme-cleaned quail bones had a tendency to crumble. Similarly, Thomas E. Labedz, Collections Manager of zoology and botany at the University of Nebraska State Museum, observed, "Some of the enzyme prepared mammal skeletons in our collections from the early 1970s are little piles of dust with some teeth mixed in."[91]

As stated by American cultural and environmental historian Amy Kohout in "More Than Birds: Loss and Reconnection at the National Museum of Natural History," "When we layer historical context underneath individual specimens, we see both their scientific value and the complex, often non-scientific circumstances and relationships that led them to their particular places inside the museum."[92]

Understanding the Whole Picture: Primate Anatomy

The formal study of non-human primate anatomy conducted as more than a proxy for human anatomy began at least as early as the 17th century. The majority of the resulting publications focused on the anatomy of one species or specimen rather than on generalized primate anatomy.[93] However, order Primates is diverse in form, ranging in weight from 5 grams

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90 Gerrit S. Miller, *Directions for Preparing Specimens of Mammals* (Washington, D. C.: Government Pringting Office, 1932), 9.

91 "Skeleton Preparation Techniques," Museum of Natural Science, Louisiana State University, 2018, http://www.museum.lsu.edu/~Remsen/AVECOL-SkeletonPrep.htm.

92 Amy Kohout, "More Than Birds: Loss and Reconnection at the National Museum of Natural History," *Museum History Journal* 10, no. 1 (2017): 92.

93 Bernard Wood, "Primate Anatomy: An Introduction," *Journal of Human Evolution* 39, no. 4 (2000): 451.

to more than 200,000 grams,[94] and including the prosimians such as lemurs, lorises, and tarsiers; monkeys; apes; and humankind. Significant variation exists in the postcranial skeleton of members of the same species.[95] While certain elements typically appear in the same number across individuals or species, other element counts, such as that of vertebrae, may vary in life.[96]

It is crucial to understand to the greatest degree possible what elements are expected to be present in a given specimen of a given species. The primate skull is homologous to that of other mammals. The bones which form the region of the nose and upper jaw include two premaxillae and two maxillae, which contain the upper teeth; two nasals; the ethmoid, turbinates, and the vomer within the nasal cavity; two palatines, which form the roof of the mouth; and two zygomatics, which form part of the orbit around the eye.[97] The meeting point of the maxilla and zygomatic can be felt in the apples of the cheeks on humans. The orbits are also formed in part by the two lacrimals, near the tear duct of each eye, the sphenoid through which the optic nerve runs, and two frontals, which can be felt in people at the forehead and brow.[98] In some primates the frontals may be fused and appear as one bone, rather than two discernible, symmetrical bones.[99] Similar fusions may be seen in other bones of the face, such as in the nasal bones of *Papio* species and *Macaca mulatta*.[100]

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[94] Daniel Lee Gebo, *Primate Comparative Anatomy*, ed. Mat Severson (Baltimore: Johns Hopkins University Press, 2014): 5.

[95] Friederun Ankel-Simons, *Primate Anatomy: An Introduction* (Boston: Elsevier Academic Press, 2007): 283.

[96] A. H. Schultz and W. L. Straus, Jr, "The Numbers of Vertebrae in Primates," *Proceedings of the American Philosophical Society* 89 (1945): 609-611.

[97] Gebo, *Primate Comparative Anatomy*, 63.

[98] Ibid., 65-67.

[99] Alfred L. Rosenberger and Anthony S. Pagano, "Frontal Fusion: Collapse of Another Anthropoid Synapomorphy," *Anatomical Record: Advances in Integrative Anatomy and Evolutionary Biology* 291, no. 3 (2008): 308-309.

[100] Daris Ray Swindler and Charles D. Wood, *An Atlas of Primate Gross Anatomy: Baboon, Chimpanzee, and Man* (Seattle: University of Washington Press, 1973), 2; W. E. Sullivan, "Skeleton and Joints," in *The Anatomy of The Rhesus Monkey (*Macaca mulatta*)*, ed.

Dorsal to the facial region, the skull continues backward in a series of large bones. These consist of the two parietals, forming the sides of the cranium; the occipital and basioccipital forming the back of the skull and permitting the spinal cord access to the brain through the foramen magnum; and the two temporals, which include the sites with which the lower jaw articulates. The basiocciput or basioccipital is that portion of the occiput that sits across the foramen magnum (large hole for the spinal cord) from the main portion of the occipital. The mandible (lower jaw) may be fused or found as a left and right piece (dentaries) dependent on taxa. [101] Additional bones of the skull include the ear ossicles and hyoid,[102] which may remain cartilaginous rather than fully ossifying.[103]

The primate axial skeleton consists of the vertebral column, ribs, and sternum.[104] Inter- and intra- specific variation are particularly apparent in this portion of the skeleton. The sternum, for example, fuses in the apes (Hominoidea), but remains unfused in lemurs, tarsiers, lorises, bushbabies, and monkeys.[105] The vertebrae, which make up the spine, are the most complicated elements in terms of quantification. The vertebrae consist of five types: the cervical, thoracic, lumbar, sacral, and caudal. However, as primate anatomist A. H. Schultz and W. L. Straus, Jr. noted in “The Numbers of Vertebrae in Primates,” “[T]here still exists no universal agreement regarding the precise definition of the different types of vertebrae.”[106] In reviewing the existing literature on vertebral quantities, Schultz’s calculations appeared in many publications.[107]

Carl G. Hartman, William L. Straus, Jr., and Theodore H. Bast (Baltimore: Williams & Wilkins, 1933): 47.

[101] Gebo, *Primate Comparative Anatomy*, 65-67 and 80.

[102] Ankel-Simons, *Primate Anatomy*, 164.

[103] Swindler and Wood, 10.

[104] Gebo, *Primate Comparative Anatomy*, 284.

[105] Ankel-Simons, *A Survey of Living Primates*, 166-167.

[106] Schultz and Straus, 601.

[107] Swindler and Wood, 12; Liza Shapiro, "Functional Morphology of the Vertebral Column in Primates," in *Postcranial Adaptation in Nonhuman Primates*, ed. Daniel L. Gebo (DeKalb, IL: Northern Illinois University Press, 1993): 126.

According to Schultz, cervical vertebrae are those between the skull and thorax, the thoracic vertebrae are set apart by their attachment to ribs, the lumbar vertebrae lie between the thorax and the sacrum and do not form part of the sacral foramina (channels for nerves to pass through the sacrum), the sacral vertebrae or sacrum contains the aforementioned foramina, and the caudal or coccygeal vertebrae are the remaining vertebrae.[108] Using his definitions of vertebral categories, Schultz provided calculations of the average number of each vertebra type in 41 genera of primates.

Limitations of application of this data are three fold. First, the sample size by genera varies between one and 318 specimens used to determine vertebral averages. As a result, the accuracy of his data is likely variable. Second, application of the data to current primate taxa is imprecise. Some of the genera that Schultz described, such as *Hapale*, are not currently recognized. Because Schultz did not share the species that make up each genera sample size, it is unclear how best to assign specimens of more newly recognized genera to his data categories for comparison. Finally, Schultz's numbers were based on study of primate skeletons in 19 museum collections rather than imaging techniques or dissection. Regardless, Schultz calculates averages of 11.8 to 16.1 thoracic vertebrae, 3.6 to 9.3 lumbar vertebrae, and 2.4 to 33 caudal vertebrae for the various primate genera.[109] Cervical vertebrae total seven in nearly all extant mammals, including all primates.[110]

A singular study of primate rib numbers across a wide range of species was located during research. This study contains taxonomically uneven groupings with no indication of which species were utilized to derive the numbers. For example, the "Macaci" were separated from the "Cercopitheci" (so-called Old World monkeys), when macaques are among the Old World monkeys. Moreover, the Cercopitheci data was based on only six specimens for what is a diverse taxonomic grouping. The apes, in contrast, were grouped by common names and each

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[108] Schultz and Straus, 602-603.

[109] Ibid., 609-611.

[110] Lionel Hautier et al., "Skeletal Development in Sloths and the Evolution of Mammalian Vertebral Patterning," *Proceedings of the National Academy of Sciences of the United States of America* 107, no. 44 (2010), 18903.

name may account for one or more species. Finally, the study having been published in 1897, it was concerned with equating biological observations to “rise in the animal scale”[111] and separates study of “dark” and “light” man.[112] Ultimately, it is not a useful source of quantitative data for comparison to current taxonomic groupings.

In a small number of cases, specific rib and vertebrae number counts are available for genera or species. For example, the literature indicates that there are 24 ribs in *Papio* (baboons); 26 in *Pan* (chimpanzees and bonobos);[113] and, in *Macaca mulatta* (rhesus macaques), usually 24 ribs, seven cervical, 12 thoracic, 7 lumbar, and about 20 caudal vertebrae.[114] Regardless, the most comprehensive numbers known to be quantified using a consistent classification method remain Schultz’s quantification of vertebra. No particularly reliable rib number surveys exist, and counts are only available in a limited number of studies of particular taxa.

The appendicular skeleton consists of the shoulder, pelvic, and limb bones.[115] Each hind limb consists of one each of the long bones known as the femur, tibia, and fibula, as well as a patella (kneecap), seven tarsals (ankle elements), five metatarsals (foot elements), and 14 phalanges—three elements each in all but one digit, which contains two elements.[116] The pelvis consists of three fused elements—the ilia, ischia and pubis—per side of the body.[117] The shoulder area consists of two clavicles and two scapula; and each arm contains one each of the

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[111] A. F. Tredgold, "Variations of Ribs in the Primates, with Especial Reference to the Number of Sternal Ribs in Man," *Journal of Anatomy and Physiology* 31, no. 2 (1897): 289.

[112] Ibid., 289-290 and 294.

[113] Swindler and Wood, 24.

[114] Sullivan, 57 and 62.

[115] Gebo, *Primate Comparative Anatomy*, 284.

[116] Ankel-Simons, *Primate Anatomy*, 185 and 329; Gebo, *Primate Comparative Anatomy*, 151-152; Daniel L. Gebo, "Functional Morphology of the Foot," in *Postcranial Adaptation in Nonhuman Primates*, ed. Daniel L. Gebo (DeKalb, IL: Northern Illinois University Press, 1993): 178.

[117] Gebo, *Primate Comparative Anatomy*, 142.

long bones known as the humerus, ulna, and radius, [118] as well as eight or nine carpals (wrist elements), five metacarpals (hand elements), and 14 phalanges—arrayed like those of the feet.[119] The known exceptions to the norm in hand element count are the olive colobus (*Procolobus verus*) and spider monkeys (*Ateles*), which possess 13 phalanges, having only one in the thumb.[120] Another known exception exists in the wrist. The central and navicular (carpals or wrist elements) fuse or one reabsorbs, resulting in a reduction from nine to eight carpals in the genera *Indri*, *Lepilemur*, *Avahi*, *Pan*, *Gorilla*, and *Homo*.[121] *Papio* and the Old World monkeys have nine carpals.[122]

Moving Forward: Risk Management

The American Association of Museums (AAM) identifies five core documents essential to museum function. These include a disaster and preparedness and emergency response plan and a collection management policy. These documents both contain elements that assist in loss prevention—preparation for recovery from disaster and loan, documentation, inventory, collection care, access, and responsibility assignment policies.[123]

In March 2004, the AAM and AWP Research in Herndon, Virginia, conducted a survey of 6,879 museums—both AAM member museums and non-member museums. They received 1,210 responses. Of the responding institutions, only 65.8% of institutions possessed an emergency and/or disaster plan. Of the 46 respondents categorized as natural history or

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[118] Ankel-Simons, *Primate Anatomy*, 313-314 and 317-318.

[119] Paul F. Whitehead, "Aspects of the Anthropoid Wrist and Hand," in *Postcranial Adaptation in Nonhuman Primates*, ed. Daniel L. Gebo (DeKalb, IL: Northern Illinois University Press, 1993): 103-104.

[120] Michael Schultz, "The Forelimb of the Colobinae," in *Systematics, Evolution, and Anatomy*, ed. Daris R. Swindler and J. Erwin (New York: Alan R. Liss, Inc., 1986): 575; Whitehead, 104.

[121] Ankel-Simons, *A Survey of Living Primates*, 185.

[122] Swindler, 36.

[123] "Core Documents," American Alliance of Museums, 2018, https://www.aam-us.org/programs/ethics-standards-and-professional-practices/core-documents/.

anthropology museums, 76% had such a plan.[124] Natural history museums may be more likely to possess this core document than other museum types, but nearly a quarter of responding natural history and archaeology museums still had no such document. Moreover, while 94% of institutions could identify a staff member responsible for risk management, it was not written into the job description of the person with chief responsibility in 57.4% of institutions. Job performance often being rated in direct comparison to the official job description, responsibility for risk management may be viewed as expendable or of lesser importance in an individual's career than those actions for which he or she is directly evaluated.[125]

Actions taken to avoid or lessen future damages or losses of collection objects through change of the object's environment rather than alteration of the object itself fit within the purview of preventive preservation or preventive conservation.[126] Examples of actions that may be undertaken in preventive conservation practice include "monitoring, recording, and controlling environmental agents; inspecting and recording the condition of objects; establishing an integrated pest management program; practicing proper handling, storage, exhibit, housekeeping and packing and shipping techniques; and incorporating needed information and procedures about objects in emergency operation plans."[127] In the first decade of the 2000s, the UNESCO Chair for Preventive Conservation, Maintenance and Monitoring of Monuments and Sites adopted a model of preventive conservation analogous to cyclical processes in preventive medicine. The cycle consists of data acquisition (analysis), determination of causation of damage (diagnosis), choice of action to be taken (therapy), and intervention (control). This model makes explicit that preventive conservation is not passive. It is an ongoing process requiring data

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[124] Elizabeth E. Merritt and American Association of Museums, *Covering Your Assets: Facilities and Risk Management in Museums* (Washington, DC: American Association of Museums, 2005), 7-8, 48, and 116.

[125] Ibid., 42-43.

[126] Salvador Muñoz Viñas, *Contemporary Theory of Conservation* (Burlington, MA: Butterworth-Heinemann, 2005), 21-22.

[127] National Park Service. *The Museum Handbook* (Washington, D.C.: Government Printing Office, 2007), 3.20.

capture and analysis, followed by application of that analysis to prioritization and implementation of mitigation activities.[128]

One tool for prioritization in use within museums today is risk management. Risk management first entered the academic literature in 1963, focusing on insurance and business enterprise, with engineers developing technological risk management concurrently.[129,] In current corporate spheres, risk management empowers companies to use event frequency and severity of consequence to determine priorities for strategic preparation and risk response, essentially ranking need to respond to and prepare for uncertainty by probability and degree of potential damage.[130]

Applied to the museum, in *Risk Assessment for Object Conservation* conservator Jonathan Ashley-Smith clarifies that risk management follows risk assessment wherein a quantitative measure of risk from a given exposure is assigned to a group of objects. Risk management, in contrast to assessment, is the decision-making mechanism whereby evaluation of mitigation options is undertaken.[131] This definition is not universal within the museum field. The AAM defines risk management as "an institution-wide activity encompassing functions as diverse as building and site security, visitor services, integrated pest management, storage and use of hazardous materials, and insurance."[132] This definition fails to provide explicit direction on how to proceed with risk-related problem-solving instead focusing broadly on the goals of ensuring museums "the safety of their staff, visitors and neighbors, maintain[ence of] their

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[128] K. Van Balen, "Preventive Conservation in the International Context of the PRECOM[3] OS Network" (presentation, International Conference on Preventive Conservation of Architectural Heritage, Nanjing, China, 29-30 October, 2011).

[129] Robert Irwin Mehr and Bob A. Hedges, *Risk Management in the Business Enterprise* (Homewood, IL: R.D. Irwin, 1963), *vii*; Georges Dionne, "Risk Management: History, Definition, and Critique," *Risk Management and Insurance Review* 16, no. 2 (2013): 147.

[130] Ibid., 154.

[131] Jonathan Ashley-Smith, *Risk Assessment for Object Conservation* (Boston: Butterworth-Heinemann, 1999), 20-21.

[132] "Facilities and Risk Management Standards," American Alliance of Museums, 2018, https://www.aam-us.org/programs/ethics-standards-and-professional-practices/facilities-and-risk-management-standards/.

buildings and grounds, and minimiz[ation of] risk to the collections that they preserve for future generations."[133]

The primary voices in museum risk management quantification are Robert Waller and Stefan Michalski.[134] Writing in "Conservation Risk Assessment: A Strategy for Managing Resources for Preventive Conservation," Robert Waller introduced his methods for estimating risks in order to plan more effectively for preventive conservation in museum environments. In doing so, he defined types of risk by category and severity. Categories align with Michalski's nine agents of deterioration, alongside one new category–custodial neglect, which includes loss, lack of legal title, and data disassociation. Magnitude of risk is then calculated as probability or extent of agent occurrence (P or E) multiplied by the fraction of the collection susceptible (FS) multiplied again by loss in value (LV), defined as utility for natural science collections (Magnitude of Risk = P or E x FS x LV). Within this model, specimen value determination is subjective.[135]

Fleshed out in "The ABC Method: A Risk Management Approach to the Preservation of Material Culture," Stefan Michalski and José Luiz Pedersoli, Jr.'s ABC Method is similar to Waller's approach at face value. In this instance, magnitude of risk (MR) is equal to the frequency or rate of damage (A) added to the loss of value to each object caused by damage (B) and to the percentage of the asset affected (C) (Magnitude of Risk = A + B + C). A, B, and C are all values from one to five which have specific coded meanings, such that for example an A of three suggests 100 years would likely elapse before recurrence of a similar damage event. Magnitude of risk is calculated at both a high and low end value to reflect uncertainty in the actual value, instead suggesting a range.[136] Perhaps the key difference between Waller and

[133] Ibid., n. pag.

[134] Agnes W. Brokerhof and Anna E. Bülow, "The QuiskScan —a Quick Risk Scan to Identify Value and Hazards in a Collection," *Journal of the Institute of Conservation* 39, no. 1 (2016): 18.

[135] Robert Waller, "Conservation Risk Assessment: A Strategy for Managing Resources for Preventive Conservation," *Studies in Conservation* 39, no. 12 (1994): 12-14.

[136] Stefan Michalski and José Luiz Pedersoli, Jr., "The ABC Method: A Risk Management Approach to the Preservation of Material Culture," (Ottawa: Canadian Conservation Institute, 2016): 87-90.

Michalski's methods is that Waller's method (CPRAM) permits addition of calculated magnitudes of risk to express additive risk from several scenarios without recalculation.[137]

The British Columbia Museums Association presents a simplified version of risk management. They propose creating a grid system in which museum professionals identify a risk type and assign that risk to a level of probability and a level of impact severity. In this method, the highest risk would be to frequent "major" and "significant" impact risks and "common," "major" risks. The issue here is that there is no standard definition for major, significant, frequent, or common. All are subjective categories, and based on perceived risk rather than accumulated data and therefore both susceptible to individual biases and not comparable among institutions—or potentially even among departments in a single institution or individuals within a department.[138] An additional model, *QuiskScan* [sic], generates comparative levels of risk from percentages of a collection represented by a particular type of object, its vulnerabilities to agents of deterioration, and its value. This model relies on existing understanding and may measure perceived risk since no probability or frequency measure is included to base the resultant predictions on quantified observation.[139]

In "Proposal for a New Environmental Risk Assessment Methodology in Cultural Heritage Protection," Massimo Andretta et al. have introduced yet another model in the past year. This model, the New rIsk assessment methodology for Cultural HEritage protection [sic] (NICHE), estimates risk as a probability matrix of adverse effect and magnitude of effect. Magnitude is measured by finding the difference between monitored data and published thresholds.[140] While this method quantifies risk from actual rather than projected or imagined states, it is optimized for microclimate effect on works of art. It is not able to incorporate total

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[137] Brokerhof and Bülow, 19.

[138] David Hall and Rick Duckles, "Best Practices Module: Risk Management," (Victoria, British Columbia: British Columbia Museums Association, 2005), 4, http://museumsassn.bc.ca/wp-content/uploads/2013/07/BP-7-Risk-Management.pdf.

[139] Brokerhof and Bülow, 22-25.

[140] Massimo Andretta et al., "Proposal for a New Environmental Risk Assessment Methodology in Cultural Heritage Protection," *Journal of Cultural Heritage* 23 (2017): 22-23.

physical loss of an object or to predict total loss, instead predicting impact of microclimate states and variables such as relative humidity and illuminance on individual target objects.[141]

Other models are employed within museum walls. However, not all have been applied with an emphasis on collections. For example, the SOBANE strategy (screening, observation, analysis, expertise) has been applied to analyze the compatibility of preventive conservation, human comfort, and energy efficiency within museum environments.[142] Similarly, risk mapping has been used to generate risk "hot zones" within a collection space by considering both light levels throughout a collection space and the perceived value of all collection objects distributed within that space.[143]

In Synthesis

The body of academic literature and documents examined above directly pertinent to loss within museum collections is low in quantity, widely spread among subject area publications, and inconsistent in scope. Of the sources on museum object loss cited in this literature review, only Kautz; Kisluk; Nichols; and Muething, Waller, and Graham published in museum field journals. While Kisluk's discussion of art theft and Nichols' examination of the differences between physical and databased collections were published in a museum field journal, *Curator*, the other two articles were published in sub-specialty professional association journals for natural history collections and conservation. The remainder were published in anthropological journals or texts,[144] news outlets,[145] and biological journals.[146] Treatment of museum object loss

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[141] Ibid., 22.

[142] Elena Lucchi, "Multidisciplinary Risk-Based Analysis for Supporting the Decision Making Process on Conservation, Energy Efficiency, and Human Comfort in Museum Buildings," *Journal of Cultural Heritage* 22 (2016): 1081 and 1087.

[143] A. W. Brokerhof, "Exhibiting with Minimal Light Risks" (presentation at The Future's Bright: Managing Colour Change in Light Sensitive Collections, Stockholm, Sweden, 15 November 2012).

[144] Caffell et al.; Dabbs; Vitelli.

[145] Cooke; Lyall; Mullen.

was found as often in popular communications and subject area literature as in museum literature.

The majority of studies in which collection object loss was found tended to obliquely reference loss, either as an explanation for lack of analytical material,[147] as rediscovery of type specimens,[148] or in assessment of other museum functions such as databasing.[149] Only two studies specifically examining extent and cause of museum object loss were located, those by Kautz and Caffell et al.[150] While Muething, Waller, and Graham include loss in their risk management study of collections on exhibit, the study focus is on damage rather than loss. Of the two surveys of loss, neither Kautz nor Caffell et al. assessed zoological research collections, instead focusing on archaeological collections consisting of or including human remains. Neither of these surveys examined extent or cause of loss of non-type specimens, non-human skeletal remains, or non-archaeological collections. Finally, neither Kautz nor Caffell et al. explicitly linked their findings to collection management action prioritization through use of risk management formulae.

Chapter 3: Methodology

The purpose of this study was to characterize element loss within natural history collections. Specifically, this study addressed if loss occurs, to what extent it occurs, and what means of loss occur. In order to investigate these questions, an instrumental case study was undertaken. In the context of this study, loss within the study collection will not characterize loss within all collections worldwide or even statewide, but it will permit creation of more focused questions for future iterations of examination into loss.

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[146] Ineich and Fisher; Haber; Braun, Grovers, and Grubb; Zerbini and Castello; Freeman and Freeman.

[147] Dabbs .

[148] Ineich and Fisher; Haber; Braun, Grovers, and Grubb; Zerbini and Castello; Freeman and Freeman.

[149] Nichols.

[150] Katuz, Caffell.

Site selection for this study ultimately centered on convenience and access. At the time of study, the nearest natural history museum, the Burke Museum of Natural History and Culture (Burke Museum), was in the process of transferring collections to a new museum building. As a result, the Burke Museums collections were inaccessible for research. Instead, the non-human primate collections of the University of Washington Department of Anthropology's physical anthropology collection were selected for study.

This collection proved advantageous in numerous ways. The Department of Anthropology offered all hours access as needed for completion of the study. By confining this study to one case, sampling bias could be avoided through study of the full collection. This provided a larger number of skeletons, sample size (n=202), than that studied in previous quantifications of loss with 40 archaeological human skeletons. [151] One hundred sixty-two of the 202 specimens are non-human primates with descriptions of completeness believed to have been created at the time of cataloging. Collection card catalog entries contain age, sex, taxonomic, and completeness data. Completeness descriptions list bones known to be missing at the time of cataloging, providing baseline completeness data.[152]

The apparent weakness of the collection selected is that it is not housed within a museum, but within a university research collection. The International Council of Museums maintains a definition of "museum," last updated in August 2007. It reads, "A museum is a non-profit, permanent institution in the service of society and its development, open to the public, which acquires, conserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for the purposes of education, study and enjoyment."[153] The University of Washington is a public university that defines itself as a community with the conviction "that together we can create a world of good."[154] The physical anthropology collection, curated by the Department of Anthropology, is used for coursework and graduate

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[151] Caffell et al., 190.

[152] Patricia Kramer, discussion with author, 11 January 2018.

[153] "Museum Definition," International Council of Museums, 2007, http://icom.museum/the-vision/museum-definition/.

[154] "Discover the University of Washington," University of Washington, 2018, http://www.washington.edu/about/.

student research.[155] While the collection does not fit the definition of "museum proper" which requires exhibition for direct benefit of the public, it does perform the same function as those specimens which are not regularly exhibited, which may indirectly benefit the public through research and application to conservation, law enforcement, public health, and more. The collection essentially represents the thousands of specimens not on exhibit within a natural history museum, and can stand in for study of all forms of loss that occur off the exhibit floor.

The physical anthropology collection was formed by primatologist Daris Swindler during his years teaching at the University of Washington, where he served as a Professor of Anthropology and Adjunct Curator of Primate Anatomy at the Burke Museum between the years of 1968 and 1991.[156] Active collection ended with his retirement, making the resultant collection the efforts of a single individual, rather than an aggregate of the individual peculiarities of generations of curators. Thus, a level of consistency of practice is likely within the collection that may not be in collections accrued over longer time periods. Many of the primates represented in the collections were acquired from the Washington National Primate Research Center (WaNPRC), a medical research facility at the University of Washington, following euthanasia. Swindler taught a cadaver-based primate anatomy course, and many of the specimens in the collections were dissected in the course and skeletonized for accession into the collection. Student hires, known in the department as "monkey boilers," would prepare the skeleton by heating in fluid until the soft tissue was removed from the bone.[157] Other specimens, immediately following necropsy at the WaNPRC, were sent to the Burke Museum for skeletonization at Swindler's request prior to accession. All of the WaNPRC animals were part of the center's Tissue Donation Program (TDP). Under this program, tissues may be sold to researchers following animal death. The WaNPRC is not aware of any requests made for skeletal materials under the TDP.[158] The WaNPRC specimens do not make up the entirety of the

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[155] Kramer.

[156] Joseph R. Siebert and Robert L. Anemone, "Obituary: Daris R. Swindler (1925–2007)," *American Journal of Physical Anthropology* 137 (2008): 2.

[157] Kramer.

[158] Charlotte Hotchkiss, emails to author, 16 and 18 January 2018.

collection—for example, *Galago* species were acquired from several sources for a student dissertation.[159]

Since Swindler's retirement, the collection has been under the curation of two other individuals, Gerald Eck and Patricia Kramer of the University of Washington. The specimens have always been stored in a controlled environment, graduate students have always had access to the collection but the use has been minimal, and the entirety of the collection has physically moved locations twice.[160] Collection movement, variables related to personnel with curatorial responsibility for the collection, and source-based differences are likely at a relative minimum when compared to centuries-old natural history collections.

Two methods were used to gather the raw data for this study, occurring simultaneously. The first was a quantitative survey of the entirety of the collection, essentially inventory. Collection contents were recorded specimen-by-specimen, bone-by-bone on a custom data record sheet. This sheet listed every element type to be counted, and was completed with the number of that element present for each specimen. Full inventory was conducted to remove selection bias, allow for discovery of uncataloged specimens or elements, and as a courtesy to the Department of Anthropology in gratitude for the permission to use the collection for this study. The process required identification of all elements present by sight and touch. Cervical vertebrae were identified by the unique form of the atlas and axis and the presence of transverse foramina and/or complex transverse processes lacking a tubercular facet (articulation site for the ribs). Thoracic vertebrae were identified by the presence of tubercular facets and/or costal facets or costal demi-facets, all articulation points for ribs.

That end of the rib that articulates with the vertebral column was selected for counting. This may underestimate the number of ribs present as it is possible that, in some cases, ventral (closer to the sternum than backbone) portions of ribs may be present without an accompanying head or tubercle end. If only the ventral portion of a rib was present, with this counting method, that rib would not be included in the count.

When elements were fractured or partial, they were counted as present. The completeness of the bone was not taken into account, and "present" bones may be more absent than present if a

[159] Nancy Cordell, "Craniofacial Anatomy and Dietary Specialization in the Galagidae" (dissertation, University of Washington, 1991), 115-117.

[160] Kramer.

portion remained. This was done to maintain the study focus on element loss rather than element damage. When multiple partial vertebrae or long bones were present, attempts were made to determine if they originated from the same element. If they did, they were counted as one. If it was unclear, they were counted as the minimum number of elements possibly represented. This may slightly inflate estimates of loss. When identification could not be made confidently, the elements were excluded from study.

Only five cervical vertebrae and five tarsals were expected per specimen, because the atlas and axis in the neck and the talus and calcaneus in the ankle and heel are distinct in form and were counted separately than the remainder of the cervical vertebrae and tarsals.

Dentition was not included in this study. Observed apparent absence of dentition in specimens could be classified as lost in life with bone remodeling, lost either after death or near death with obvious alveoli (the holes in which the teeth sit), possible human intervention in the form of canine removal during life, and erupting dentition during growth from fetus to adult. Thus, tooth loss shortly before death or after death has a similar appearance. Other than the dentition, ethmoids, turbinates, and sesamoids were not inventoried. Altogether, 30,303 skeletal elements, excluding teeth, which accounted for an additional approximately 4,000 identifications, were recorded as present and identified to element within the collection over the course of the study.

In addition to the element inventory, this study employed document analysis. The documents identified and analyzed were chosen to align with the research questions proposed. The text of specimen tags; labels and notes spatially associated with specimens; a digital catalog; and the physical card catalog were recorded in order to assess specimen completeness, data disassociation, and unreturned loans. Preserved specimen records in GBIF; anthropology dissertations from the University of Washington and publications by Daris Swindler, Gerald Eck, and Patricia Kramer were analyzed for use, scientific value, of the collection; and auction records and ongoing skeletal element sales were analyzed to glean insights into monetary value. WaNPRC records were requested to gather euthanasia dates as a proxy for amount of time in collections. Unfortunately, formal records of loan and dates of accession do not exist, so data proxies and presence of notes tucked in with specimens were essential to estimate collection variables. The initial intention was to code listed descriptors of loss, and request another individual to similarly code the text for inter-rater reliability. However, only three instances where loss was described were encountered, and the text left little room for multiple interpretations.

For those specimens with a catalog record of skeletal completeness, two quantitative datasets were developed—the actual inventory and the expected inventory. This was done on a specimen-by-specimen basis, since the expected numbers could vary with, for example, the number of vertebrae expected for the particular species or with catalog data indicating that the hyoid, clavicles, or other elements were never present in the collection. Specimens or parts of specimens described in the catalog as "partial" were not included, because this does not indicate which particular elements were absent at time of accession into the collection. The expected number of vertebrae utilized is the genera average developed by Schultz and discussed in the literature review.

Of the primate rib quantities found in the literature, the number of ribs was consistently nearly double Schultz's thoracic vertebra number (*Pan*: 26:13.2, *Papio*: 24:12.5).[161] For this study, it is assumed that primates possess two ribs per thoracic vertebrae, so the expected rib quantity used is two times Shultz's thoracic vertebra average. This is the most consistent estimation method currently plausible using data from existing literature. Finally, the sternum is classified as present even if only one component, or sternebra, is present. *Galago* and *Otolemur* are conflated under *Galago*, as the collection lists the genera interchangeably. The expected element number per specimen based on the card catalog was determined subtractively from the expected number per genus. For example, if a specimen was listed as missing a hand, five metacarpals and 14 phalanges were subtracted from the expected total for that genus in order to find the expected elements present for that particular specimen.

[161] Schultz and Straus, 609; Swindler and Wood, 24.

Table 3.1 Expected Element Counts in a Fully Complete Specimen

	Expected Element Count by Genus														
Element	Maca -ca	Pa- pio	Lago- thrix	Colo- bus	Le- mur	Pan	Pres- bytis	Gala- go	Cercop- thecus	Hylobates	Nyctice- bus	Ate- les	Microce- bus	Erythroce -bus	Sai- miri
Frontal	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Palatine	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Vomer	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Premaxilla	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Dentary	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Nasal	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Maxilla	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Zygomatic	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Occipital	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Parietal	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Temporal	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Alisphenoid	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Basisphenoid	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Orbitospheno id	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Presphenoid	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Pterygoid	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Basiocciput	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Lacrimal	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Femur	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Fibula	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Tibia	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Patella	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Humerus	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Radius	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2

	Maca-ca	Pa-pio	Lago-thrix	Colo-bus	Le-mur	Pan	Pres-bytis	Gala-go	Cercop-thecus	Hylobates	Nyctice-bus	Ate-les	Microce-bus	Erythroce-bus	Sai-miri
Clavicle	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Scapula	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ilium	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ischium	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Pubis	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
1st Phalanx	20	20	20	20	20	20	20	20	20	20	20	16	16	16	16
2nd Phalanx	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16
3rd Phalanx	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Talus	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Calcaneus	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Carpal	18	18	18	18	18	16	18	18	18	18	18	18	18	18	18
Metacarpal	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Tarsal	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Metatarsal	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Atlas	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Axis	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Hyoid	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Cervical Vertebrae	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Thoracic Vertebrae	12.2	12.5	13.8	12	12.1	13.2	0	13.2	12.2	13.1	16.1	14.1	13	12	13.3
Lumbar Vertebrae	6.9	6.5	4.3	6.8	6.7	3.6	0	6	6.9	5.1	7.1	4.1	7	7	6.7
Sacrum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Caudal Vertebrae	19.1	19.7	24	26	27	3.2	0	25.7	26.4	2.7	7	31	0	0	26.7
Ribs	24.2	25	27.6	24	24.2	26.4	0	26.4	24.4	26.2	32.2	28.2	26	24	26.6
Sternum	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

*Zeros represent lack of data from Schultz. Schultz collapses all Galaginadae under *Galago*, thus the lack of expected values for *Otolemur*.

Statistical analyses were run within SPSS or Excel. Percentages and standard deviations were calculated within Excel with all other statistical analyses conducted in SPSS. The remainder of the methodology section will address the methods employed for analysis of different types of loss.

General Description of Loss

To what extent does skeletal element attrition occur in museum collections? Are particular elements more prone to loss and/or specific types of loss?

The first analyses conducted described the state of the collection, rather than examining potential loss types. The specimens with known completeness (n = 162) were compared to the expected element inventory for that specimen in order to determine the percent of the specimens that were 100% complete with completeness defined as possessing all of the elements possessed at the time of cataloging. This determined the percentage of specimens affected by loss without discerning magnitude of element loss. The percentage of these 162 specimens found to be absent in totality was also calculated.

Next, the number observed and number expected of each element of the specimens with known completeness were used to calculate the percent of expected occurrences of each element actually observed during inventory. The same test was run for the number observed and number expected of total elements per genus of specimens with known completeness. These tests indicate if there is greater proportional loss among particular genera or of particular elements.

Data Disassociation

Are particular elements more prone to loss and/or specific types of loss?

The next test characterized data disassociation, in which specimens are separated from their descriptive data, such as species identification, age, or source. For this test, the observed number of each element not associated with a catalogued specimen was summed. Each element sum was then divided by the number of elements expected within an anatomically complete specimen. For example, if 435 metacarpals were observed that did not belong to one of the catalogued specimens, 435 would be divided by the number expected in any one individual, 20. This would suggest that at least 22 individuals, the Minimum Number of Individuals (MNI), are represented in the unnumbered metacarpals. After MNI was calculated for each element, the highest numerical result indicated the lowest number of possible specimens that are not cataloged. For vertebrae and ribs, the expected value was the highest Schultz average of a genus represented in the collection, 16.1 thoracic vertebrae, 7.1 lumbar vertebrae, 26.7 caudal vertebrae, and 13.2 ribs. MNI was chosen over the Number of Identified Specimens (NISP), because each disassociated element cannot represent a separate individual since articulated limbs were located in the collection. The result was used to determine the minimum percentage of the collection that was not cataloged, and, therefore, lacks corresponding, accessible data.

Loan

Are particular elements more prone to loss and/or specific types of loss?

Instances where a loan slip or note indicating loan was tucked in with the specimen were counted. Dates of loan initiation were unavailable, and there was no recorded, intended loan end date. The percentage of cataloged specimens with an unresolved loan was calculated. Percentages of the elements lost to unresolved loan were also calculated.

Time in Collections

Does skeletal element attrition increase in natural history museum research collections with time spent in the collections?

First, specimen number was used to provide the rank order of specimen entry into the collections. While multiple specimens were cataloged in a given year, given the lack of accession and catalog year data available, specimen number provided a means of identifying the relative “oldness” and “newness” of specimen addition to the collection. Specimens with lower specimen numbers have presumably been in the collection a longer period of time than those with higher specimen numbers. The specimen number was plotted against the percent of expected elements observed per specimen to determine if older specimens display reduced completeness relative to newer specimens, indicative of loss over time (n=162).

A second test was run with actual year data. The necropsy year of the specimens from the WaNPRC that could be matched to a collection specimen was subtracted from the current year, 2018, in order to calculate the number of years each specimen had been in the collection. It is possible that specimens were held in a freezer for some period of time between necropsy and entry to the collection. Years since necropsy were plotted against the percent of expected elements observed per specimen to determine if older specimens displayed reduced completeness relative to newer specimens, indicative of loss over time (n=47). This indicated if a correlation existed between loss and time in collection for the specimens as a whole. The idea behind this test was the assumption described and tested in Kautz's study of archaeological collection attrition, "the simple likelihood that more time provides more opportunity for loss."[162]

Size

Does uncharacterized loss, that which is not associated with archival record of a loss type, show positive correlation with specimen monetary value, scientific value, or element size?

Correlation between loss and size is complicated by the fact that natural history collections represent a range of individual specimens at different points in their lifespan, of different biological sexes, and often of a range of taxonomic categories. A number of tests were run to seek correlations between size and loss and to test the assumption that smaller elements are more prone to loss than larger elements.

First, the percent of elements expected actually observed was plotted against the average genus weight in grams, as compiled by John G. Fleagle in *Primate Adaptation and Evolution*, [163]

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[162] Kautz, 35.

[163] John G. Fleagle, *Primate Adaptation and Evolution* (San Diego: Academic Press, 1988) **table values in** Michael D. Rose, "Functional Anatomy of the Elbow and Forearm in Primates," in *Postcranial Adaptation in Nonhuman Primates*, ed. Daniel L. Gebo (DeKalb, IL: Northern Illinois University Press, 1993), 85.

to determine if smaller genera were more prone to element loss than larger genera (n=38). For example, one might imagine it would easier to misplace a pygmy marmoset element than a gorilla element. Fleagle's values average male and female weights. The number of specimens used in this test was limited to genera with data available from Fleagle, known adult status, and recorded completeness data. This test uses genus body weight as a proxy for relative element size. Specimens not found during inventory were included in this test at zero percent completeness. Genera, from least to greatest average weight, included in this test were *Microcebus*, *Galago*, *Nycticebus*, *Lemur*, *Cercopithecus*, *Presbytis*, *Ateles* and *Colubus*, and *Pan*.

Next, percentages of expected completeness observed in total and for each element were compared between male and female specimens of sexually dimorphic species. Because not all primates are sexually dimorphic, species were selected for this test using T. H. Clutton-Brock, H. Harvey Paul, and B. Rudder's primate sexual dimorphism chart, published in "Sexual Dimorphism, Socioeconomic Sex Ratio and Body Weight in Primates."[164] Species selected had to both be represented in the collection and the male had to weigh, on average, at least 1.25 times that of the female. As a result, the subsample for this test consisted of n=15 females and n=11 males, identified in the catalogs as adult, and either *Macaca nemestrina*, *Macaca fascicularis*, or *Cercopithecus neglectus*, species for which the male is 1.25 to 1.75 times the weight of the female on average. Fully absent specimens were not included. A t-test was performed to determine if differences between the two population means were statistically significant.

Additional tests were run to compare losses of individual elements according to their relative sizes. First, percentages of expected elements present were compared across the collection for the metacarpals and metatarsals, first, second, and third phalanges (hand and foot elements). While the relative lengths of the elements in primate hands and feet vary by species, longer phalanges relative to metatarsals occurs within the prosimians, [165] of which this collection

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[164] T. H. Clutton-Brock, H. Harvey Paul, and B. Rudder, "Sexual Dimorphism, Socioeconomic Sex Ratio and Body Weight in Primates," *Nature* 269, no. 5631 (1977): 798.

[165] Gebo, "Functional Morphology of the Foot," 178.

contains relatively few. A similar test was run comparing thoracic to lumbar vertebrae, as Hill describes lumbar vertebrae as the most robust primate vertebral category.[166]

Finally, elements were categorized by general size to determine if the largest and smallest elements of the body showed different tendencies for degree of loss. Complex elements such as the skull and pelvis, which consist of multiple smaller elements were excluded, since inventory did not differentiate between disarticulated and articulated elements. The category of largest elements included the femur, fibula, tibia, humerus, radius, and ulna. Mid-sized elements were defined as the clavicle, scapula, sacrum, the ribs, and all vertebrae excluding the caudal vertebrae. Small-sized elements were defined as the patellae, all bones of the hand and foot, hyoid, caudal vertebrae, and the sternum since the primate sternum is not fused in the vast majority of specimen genera represented. Percentages of expected elements observed were compared across the three size categories. These three tests used all specimens of known completeness value not fully absent (n=143). A one-way ANOVA test was used to compare the means of the percentages of expected elements observed across the three element size categories.

Value

Does uncharacterized loss, that which is not associated with archival record of a loss type, show positive correlation with specimen monetary value, scientific value, or element size?

In "Natural History Conservation and the Concept of Value," Catharine Hawks and Rebecca Kaczkowski, natural history conservators, note, "In the sub-specialty of natural science conservation, the primary focus is maintaining the scientific utility of specimens, often even when the specimens are historically or aesthetically important as well. For example, no one is likely to question the historical importance of the Lewis and Clark herbarium, but this collection is still sampled destructively for research purposes."[167]

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[166] W. C. Osman Hill, *Primates: Comparative Anatomy and Taxonomy: A Monograph, Volume 7* (Edinburgh: University Press, 1953), 34.

[167] Catharine Hawks and Rebecca Kaczkowski, "Natural History Conservation and the Concept Of 'Value,'" *AIC News* 40, no. 2 (2015): 8.

Auction records were sought to quantify monetary value and the number of publications utilizing the collection to quantify scientific value. However, auction records proved rare and difficult to compare. Similarly, no publications were found that used the physical specimens after their entrance to the collection. Dental publications were not reviewed, and were not within the scope of this study.

Specimen rarity was used as an index of value. For the purpose of this study, the value of any given specimen was defined against the number of specimens of the same species in GBIF and in the University of Washington physical anthropology collection, providing a numerical suggestion of the comparative ease or difficulty of finding a similar specimen in collections worldwide or locally. Plotting percent expected completeness observed against species rarity within GBIF and the collection itself displayed the relationship among rarity, commonality, and loss at global and local levels. For both of these tests, the sample included all specimens with recorded completeness data with a species-level identification (n=109).

Post-Mortem Treatment

Does uncharacterized loss, that which is not associated with archival record of a loss type, show positive correlation with specimen monetary value, scientific value, or element size?

Seventy-eight of the specimens with a record of completeness showed signs of necropsy, most apparent in removal of the calvaria (skull cap) with a saw. The removal of the skullcap permitted specimens to be divided into a necropsied (n=78) and an un-necropsied (n=38) group. The remainder lacked a cranium. The percentage of expected elements observed was compared by element and in total between these two groups. A t-test was performed to determine if differences between the two populations are statistically significant.

Risk Management

What magnitude of risk exists per element and type of loss?

Magnitude of risk was calculated with the data findings to provide unbiased assessment of risk and to prioritize preventive care actions. Robert Waller's CPRAM method was utilized, because it was the singular method of those identified in the literature review to be originally applied within a natural history museum.

Chapter 4: Findings and Analysis

Analysis of tray labels and the physical card catalog showed that of the 202 cataloged specimens, 162 non-human primate specimens had a listed description of completeness. Nineteen of those 162 specimens were not found during inventory, suggesting total specimen losses from the catalogued collection with listed completeness represent 11.73% of specimens (Table 4.1 and 4.2). Of the 143 remaining specimens, all of the elements believed to be present from the description in the card catalog were observed in only 31 specimens or 21.53%. Thus, 78.47% of the present specimens of listed completeness appear to have suffered loss of at least one skeletal element since time of cataloging.

Table 4.1: Taxonomy of Specimens with Available Completeness Data, but Absent from the Collection in Totality (n=19)

Genus	Specimens	Species	Specimens	Common Name
Ateles	1	Unidentified	1	Spider monkey
Colobus	1	Unidentified	1	Black-and-white colobus
Erythrocebus	1	*patas*	1	Patas monkey
Hylobates	1	Unidentified	1	Gibbon
Lemur	1	*catta*	1	Ring-tailed lemur
		fascicularis	2	Crab-eating macaque
		fuscata	1	Japanese macaque
		mulatta	3	Rhesus macaque
Macaca	7	*nemestrina*	1	Southern pig-tailed macaque
Microcebus	1	*murinus*	1	Gray mouse lemur
Pan	1	*troglodytes*	1	Common chimpanzee
		cynocephalis	1	Yellow baboon
Papio	2	Unidentified	1	Baboon
Presbytis	1	Unidentified	1	Surili
Saimiri	2	*sciureus*	2	Common squirrel monkey

Table 4.2: Taxonomy of Specimens with Available Completeness Data in the Collection, Including Fully Absent Specimens (n=162)

Genus	Specimens	Species	Specimens	Common Name
Ateles	1	unidentified	1	Spider monkey
		aethiops	1	Grivet
		neglectus	1	De Brazza's monkey
Cercopithecus	6	unidentified	4	Guenon
Colobus	2	unidentified	2	Black-and-white colubus
Erythrocebus	1	*patas*	1	Patas monkey
Galago	2	*moholi*	1	Mohol bushbaby
Galago or Otolemur	2	unidentified	2	
Hylobates	2	unidentified	2	Gibbon
		catta	1	Ring-tailed lemur
		fulvus	1	Common brown lemur
Lemur	3	unidentified	1	Lemur
		lagotricha	1	Brown woolly monkey
Lagothrix	2	unidentified	1	Woolly monkey
		arctoides	1	Stump-tailed macaque
		fascicularis	12	Crab-eating macaque
		fuscata	2	Japanese macaque
		mulatta	17	Rhesus macaque
		nemestrina	36	Southern pig-tailed macaque
Macaca	83	unidentified	15	Macaque
Macaca or Papio	1	unidentified	1	
Microcebus	1	*murinus*	1	Gray mouse lemur
Nycticebus	1	*coucang*	1	Sunda slow loris
		crassicaudatus	2	Brown greater galago
Otolemur	4	*garnettii*	2	Northern greater galago
Pan	4	*troglodytes*	4	Common chimpanzee
		cynocephalis	36	Yellow baboon
Papio	43	unidentified	7	Baboon
Presbytis	2	unidentified	2	Surili
Saimiri	2	*sciureus*	2	Common squirrel monkey

Either loss is prevalent among the collection or record keeping at time of cataloging did not fully capture the elements absent from each individual specimen at the time of entry to the collection.

Note that partial loss is distributed among specimen genera with *Pan* and *Nycticebus* showing loss outside of the one standard deviation (Table 4.3). Only *Nycticebus* falls outside of the range of two standard deviations. *Nycticebus* is an outlier, as one numbered femur of the single *Nycticebus* specimen was located in a box of seemingly unrelated elements.

Table 4.3: Percent of Expected Elements Observed by Genus (n=142): Mean Percent Expected Observed of 78.66% with One Standard Deviation of 31.78%

Genus	Number of Specimens	Elements Present	Elements Expected	Percent of Expected Observed
Nycticebus	1	1	235.4	0.42%
Pan	4	84	256.4	32.76%
Lemur	2	248	400.2	61.97%
Macaca	75	10869	12020.5	90.42%
Papio	41	7628	8342.2	91.44%
Galago/Otolemur	8	522	556.6	93.78%
Colubus	1	36	38	94.74%
Cercopitehcus	6	363	368.9	98.40%
Hylobates	1	31	31	100.00%
Presbytis	1	31	31	100.00%
Lagothrix	2	256	252.7	101.31%
Total	142	20069	22532.9	89.07%

The percent of expected elements observed during inventory also varied greatly across elements (Table 4.4). The term “expected” is used to indicate the baseline number of elements derived from the card catalog. The hyoid was observed in only 45.36% of specimens expected, whereas the tibia and fibula were observed slightly over 100% of the times expected. The tibia and fibula instances suggest either that absences were not always correctly described on the catalog cards or that additional tibiae and fibulae were incorrectly associated with specimens. As large leg bones, it is highly improbable that the specimens possessed extra of these particular elements in life. No elements were found to have a 1:1 observed to expected ratio, with the mean element presence 89.38% of that recorded in the card catalog. Of the six highest percentages, five are the long bones or major elements of the leg and arm. However, the humerus, the final major limb element is among the three lowest percentages at 67.89% of expected occurrences observed. This suggests that the long bones are rarely lost and/or their absence is most frequently noted, although the absence of the humerus is curious and potentially a result of collection usage or study. Only the percentages of expected occurrences observed of the hyoid, sternum, and humerus fall outside of two standard deviations.

Table 4.4 Percent of Expected Elements Observed in All Non-Human Primate Specimens of Known Completeness, Excluding Total Absences (n=143): Mean Percent Expected Observed of 89.38% with One Standard Deviation of 9.71%

Element	No. Observed	No. Expected	Percent of Expected Observed
Hyoid	44	97	45.36%
Sternum	54	94	57.45%
Humerus	129	190	67.89%
Caudal Vertebra	1297	1765	73.48%
Orbitosphenoid	197	254	77.56%
Rib	1211	1437.6	84.24%
Patella	168	195	86.15%
3rd Phalanx	1658	1914	86.62%
Thoracic Vertebra	1016	1141.6	89.00%
Presphenoid	114	127	89.76%
Nasal	229	254	90.16%
Vomer	115	127	90.55%
Occipital	115	127	90.55%
Parietal	230	254	90.55%
Basisphenoid	115	127	90.55%
Basiocciput	115	127	90.55%
2nd Phalanx	1389	1532	90.67%
Axis	90	99	90.91%
Alisphenoid	231	254	90.94%
Lacrimal	231	254	90.94%
Pterygoid	232	254	91.34%
Palatine	233	254	91.73%
Zygomatic	233	254	91.73%
1st Phalanx	1757	1915	91.75%
Sacrum	89	97	91.75%
Metacarpals	886	965	91.81%
Dentary	236	257	91.83%
Atlas	92	100	92.00%
Cervical Vertebra	431	468	92.09%
Temporal	234	254	92.13%
Ischium	180	195	92.31%
Pubis	180	195	92.31%

Element	No. Observed	No. Expected	Percent of Expected Observed
Talus	180	195	92.31%
Clavicle	172	186	92.47%
Premaxilla	235	254	92.52%
Maxilla	235	254	92.52%
Carpal	1600	1726	92.70%
Tarsal	908	975	93.13%
Frontal	237	254	93.31%
Ilium	182	195	93.33%
Calcaneus	182	195	93.33%
Lumbar Vertebra	576	612.7	94.01%
Metatarsal	914	970	94.23%
Ulna	185	194	95.36%
Scapula	188	197	95.43%
Radius	186	194	95.88%
Femur	191	194	98.45%
Tibia	198	195	101.54%
Fibula	200	195	102.56%
Total Elements	20100	22563.9	89.08%

Data disassociation is extremely common within the collection. Numerous boxes and trays contain mixed elements of unnumbered specimens and/or specimens numbered with numbers that do not align with the collection catalog numbering system. These disassociated elements represent at least 60 individual specimens based on the presence of 60 occipital bones, the highest Minimum Number of Individuals indicated by an element type. Recall that the fully catalogued collection consists of 202 specimens. At least 262 individual specimens are represented within the full collection, meaning that at least 22.90% of the specimens present are not cataloged. In some cases, data does accompany these specimens. However, that data is located with the specimen itself rather than in an easily accessible data source. As a result, one must know the collection to know these 60 or more specimens exist, reducing research accessibility.

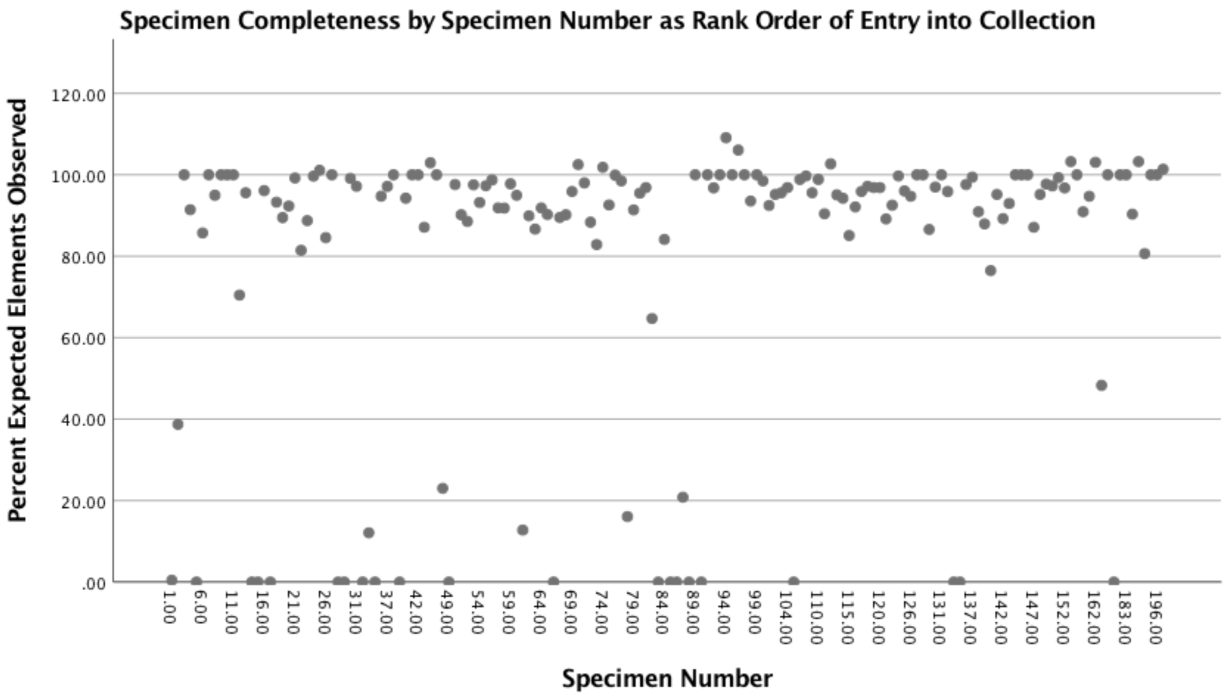
Document analysis of the specimen labels, tags, and notes found with the specimen; card catalog; and digital catalog describe only three events clearly causing absence. All three instances describe loans of elements to individuals or museums. No loan end date is indicated. In all cases, the elements represented approximately 1% of the expected total number of that element type (for example the ulna) and 0.02% of all expected elements (Table 4.5). Thus, permanent loans do account for a small amount of collection loss.

Table 4.5 Percent of Elements on Undefined Length Loan in All Non-Human Primate Specimens of Listed Completeness, Excluding Total Specimen Absences (n=143)

Element	No. on Loan	No. Expected	Percent of Expected Observed
Lumbar Vertebra	6.9	612.7	1.13%
Caudal Vertebra	19.1	1765	1.08%
Cervical Vertebra	5	468	1.07%
Thoracic Vertebra	12.2	1141.6	1.07%
Ulna	1	194	1.06%
Atlas	1	99	1.01%
Axis	1	100	1.00%
Total	46.2	22563.9	0.02%

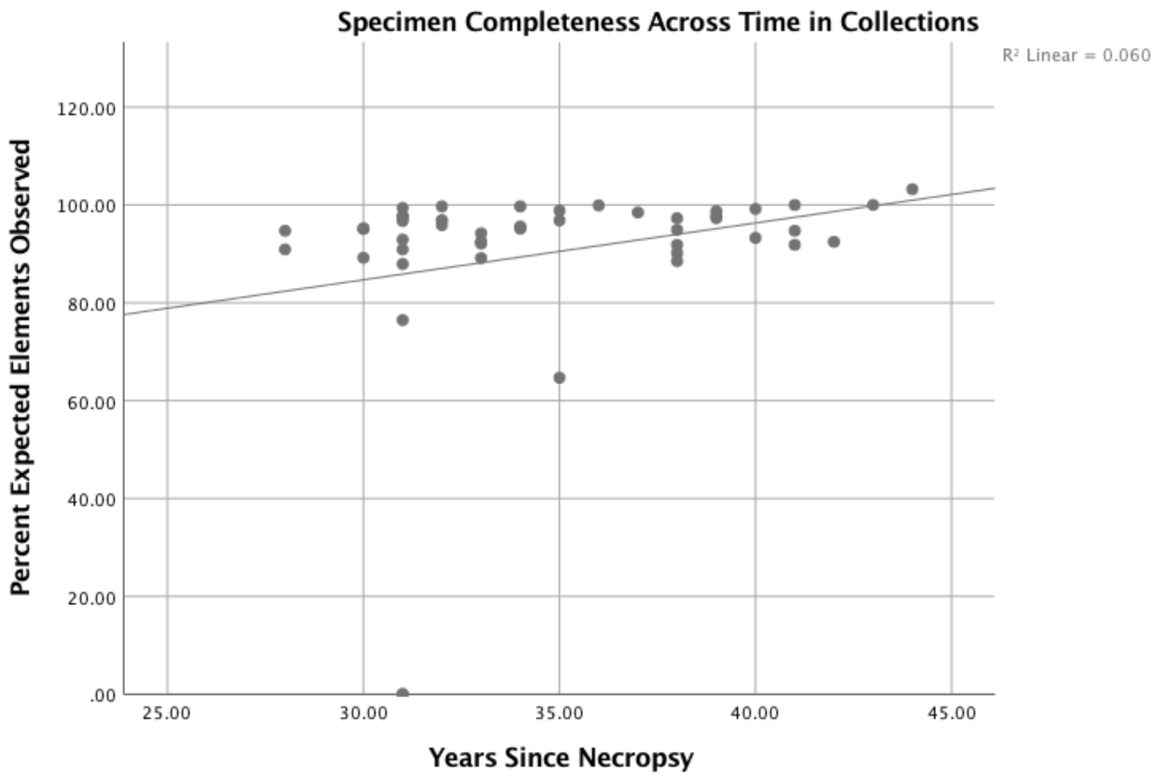
Use of specimen number to examine percent expected completeness observed by order of entry into the collection showed that completeness typically hovers between 80 and 100% for all specimens with a mean of 79.78% (Figure 4.1). Specimens with lower collection numbers showed no greater loss than specimens with higher numbers. Instead, total and partial losses appear sporadically along the timeline, suggesting that loss did not occur gradually at a relatively constant rate across time, but instead occurred occasionally as a result of intermittent events. Only those specimens missing in full fall outside of two standard deviations.

Figure 4.1 Scatter Plot Depicting the Percent of Expected Elements Observed in a Given Specimen by Specimen Number (n=162), Mean Percent Expected Observed of 79.78% with One Standard Deviation of 34.55%



When considering only those specimens with known years of necropsy, no correlation was found between time in collections and percent of the expected completeness of a specimen observed (Figure 4.2).

Figure 4.2 Scatter Plot with Line of Best Fit Depicting the Percent of Expected Elements Observed in a Given Specimen in Relationship to the Years Since Necropsy (n=47), Mean Percent Expected Observed of 90.27% with One Standard Deviation of 20.02%



Tests for correlation between expected completeness observed and various measures of size suggest that neither overall body size of the specimen nor comparable element size predicts loss to a statistically significant extent. A scatterplot summarizes the relationship between percent expected elements observed per specimen and the average weight of that specimen's genus (Figure 4.3). There was no clear relationship between the variables. There was also no clear difference in the percent of expected elements present between the males and females of species known to be sexually dimorphic, wherein the male weighs at least 1.25 as much as the female on average. Percent comparisons (Table 4.6) show that some expected elements are more likely to be absent amongst the male sample (n=11) and some amongst the female sample (n = 15). Only the hyoid, humerus, and sternum fall outside of two standard deviations, and of these three elements, only the sternum falls outside of two standard deviations for one sex (male) and not the other (female). This study found that there was no statistically significant difference in percentage of expected occurrences observed between elements of female specimens (87.97% ± 15.59%) compared to elements of male specimens (92.67% ± 14.36%), t(96) = -1.552, p = 0.124.

Figure 4.3 Scatter Plot with Line of Best Fit Depicting the Percent of Expected Elements Observed in a Given Specimen in Relationship to the Average Weight of its Genus (n=38), Mean Percent Expected Observed of 68.18% with One Standard Deviation of 41.26%

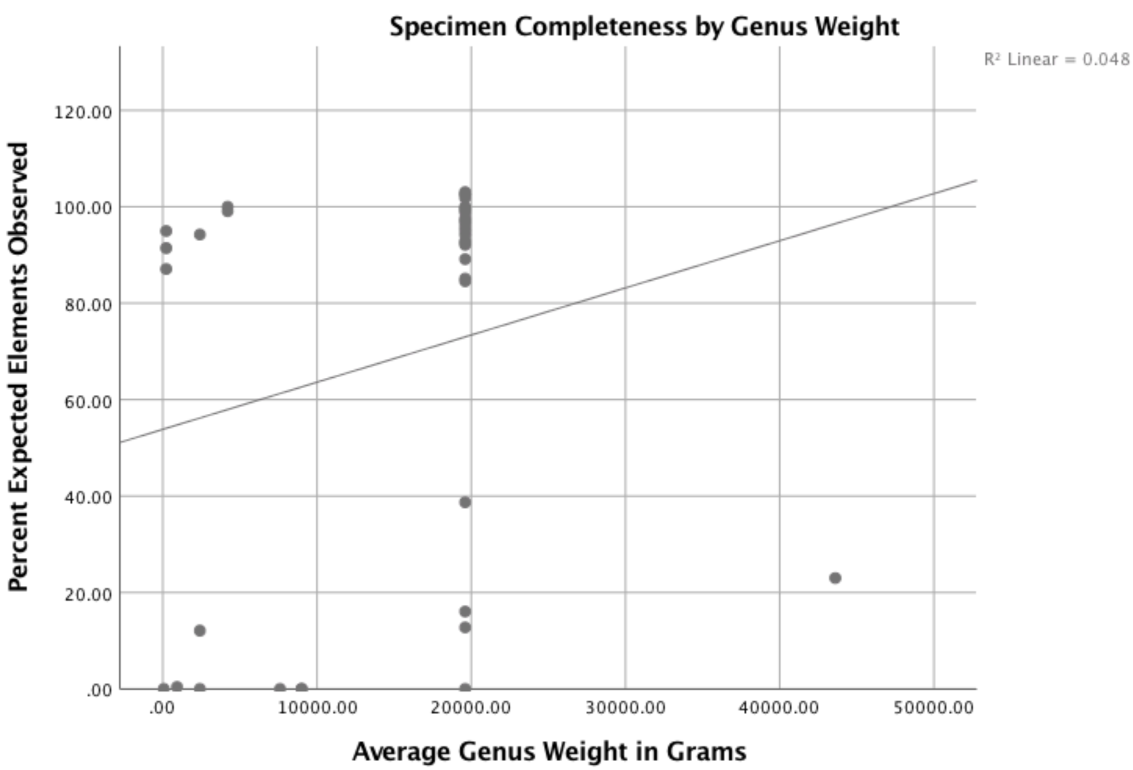


Table 4.6 Comparison of Percent Expected Elements Observed in Females (n=15) and Males (n=11) of Sexually Dimorphic Species

	Female, No. of Elements			Male, No. of Elements		
Element	**Observed**	**Expected**	**% Expected Observed**	**Observed**	**Expected**	**% Expected Observed**
Humerus	5	29	17.24%	10	22	45.45%
Rib	116	145.2	79.89%	118	121	97.52%
Patella	22	30	73.33%	20	22	90.91%
Sternum	8	13	61.54%	5	11	45.45%
Scapula	26	30	86.67%	22	22	100%
Talus	26	30	86.67%	22	22	100%
Metatarsal	139	150	92.67%	110	105	104.76%

Orbitosphenoid	23	30	76.67%	13	20	65%
Clavicle	25	28	89.29%	22	22	100%
Femur	27	30	90%	21	21	100%
Fibula	27	30	90%	22	22	100%
Tibia	27	30	90%	22	22	100%
Radius	27	30	90%	22	22	100%
Ulna	27	30	90%	22	22	100%
Ilium	27	30	90%	22	22	100%
Calcaneus	27	30	90%	22	22	100%
Vomer	15	15	100%	9	10	90%
1st Phalanx	250	280	89.29%	213	215	99.07%
Carpal	240	270	88.89%	186	189	98.41%
3rd Phalanx	231	280	82.5%	197	215	91.63%
Lumbar Vertebra	87	103.5	84.06%	70	75.9	92.23%
2nd Phalanx	198	224	88.39%	165	172	95.93%
Thoracic Vertebra	144	183	78.69%	114	134.2	84.95%
Caudal Vertebra	174	274.7	63.34%	146	210.1	69.49%
Metacarpal	134	150	89.33%	105	110	95.45%
Hyoid	6	15	40%	5	11	45.45%
Atlas	13	15	86.67%	9	11	81.82%
Cervical Vertebra	62	75	82.67%	48	55	87.27%
Axis	13	15	86.67%	10	11	90.91%
Sacrum	13	15	86.67%	10	11	90.91%
Tarsal	139	150	92.67%	106	110	96.36%
Dentary	29	30	96.67%	19	19	100%
Ischium	27	30	90%	20	22	90.91%
Pubis	27	30	90%	20	22	90.91%
Frontal	30	30	100%	20	20	100%
Palatine	30	30	100%	20	20	100%
Premaxilla	30	30	100%	20	20	100%
Nasal	30	30	100%	20	20	100%
Maxilla	30	30	100%	20	20	100%
Zygomatic	30	30	100%	20	20	100%
Occipital	15	15	100%	10	10	100%
Parietal	30	30	100%	20	20	100%
Temporal	30	30	100%	20	20	100%
Alisphenoid	30	30	100%	20	20	100%
Basisphenoid	15	15	100%	10	10	100%
Presphenoid	15	15	100%	10	10	100%
Pterygoid	30	30	100%	20	20	100%
Basiocciput	15	15	100%	10	10	100%

Lacrimal	30	30	100%	20	20	100%
Total	2771	3240.4	85.51%	2207	2383.2	92.61%

Comparisons of the percent of expected elements observed of relative sizes within the body suggested that smaller element types might have been slightly more prone to loss, but that the range of percent of elements expected falls within two standard variations for all elements tested. For example, the third phalanx (final element of the finger and toe) was present when expected less than second phalanx (the middle element), and the pattern continued into the metacarpals and metatarsals (bones of the hands and feet) (Table 4.7). Similarly, lumbar vertebrae were more likely to be observed when expected than the less robust thoracic vertebrae (Table 4.8). However, these categories of elements showed a relatively small gradation of size. As a result, elements were divided into size categories of large, mid-size, or small as described in the methodology section (Table 4.9). Results showed less than 1% difference in loss between the mid-sized and small element categories. The long bones were at approximately 5% greater expected completeness than the mid-size and small elements, and this is with the inclusion of the humerus, one of the three most frequently absent elements. If the humerus is excluded the remaining long bones are observed 98% of the times expected. Thus, element size might have had a small impact on loss in this collection. The similarity of the mid-size and small categories suggested that both categories fit under a similar threshold for loss. Alternatively, perhaps the "charismatic" long bones were the most likely to be observed absent at time of intake into the collection.

A One-Way ANOVA test was run on the percent of expected element occurrences observed per element within the large, mid, and small-sized element groups. The mean percent expected element occurrences observed was not statistically significant among the groups ($F_{2, 29} = 1.666$, $p < 0.209$). There was no indication that element sizes result in statistically significant differences in loss, despite the observed pattern of absence.

Table 4.7 Comparison of Percent of Expected Hand and Foot Elements Observed (n=143): Mean Percent Expected Observed of 90.44% with One Standard Deviation of 2.32%

Element	No. Observed	No. Expected	Percent of Expected Observed
3rd Phalanx	1658	1914	86.62%
2nd Phalanx	1389	1532	90.67%
1st Phalanx	1757	1915	91.75%
Metatarsal or Metacarpal	1794	1935	92.71%

Table 4.8 Comparison of Percent of Expected Thoracic and Lumbar Vertebrae Observed (n=143): Mean Percent Expected Observed of 91.51% with One Standard Deviation of 2.51%

Element	No. Observed	No. Expected	Percent of Expected Observed
Thoracic Vertebra	1016	1141.6	89%
Lumbar Vertebra	576	612.5	94.01%

Table 4.9 Comparison of Percent Expected Observed by Element Size (n=143)

Element	No. Observed	No. Expected	Percent of Expected Observed
Femur	191	194	98.45%
Fibula	200	195	102.56%
Tibia	198	195	101.54%
Humerus	129	190	67.89%
Radius	186	194	95.88%
Ulna	185	194	95.36%
Large Total	1089	1162	93.72%
Clavicle	172	186	92.47%
Scapula	188	197	95.43%
Atlas	92	100	92.00%
Axis	90	99	90.91%
Cervical Vertebra	427	468	91.24%
Thoracic Vertebra	1016	1141.6	89.00%
Lumbar Vertebra	576	612.7	94.01%
Sacrum	89	97	91.75%
Rib	1211	1437.6	84.24%
Mid-Size Total	3861	4338.9	88.99%
Patella	168	195	86.15%
1st Phalanx	1757	1915	91.75%
2nd Phalanx	1389	1532	90.67%
3rd Phalanx	1658	1914	86.62%
Talus	180	195	92.31%
Calcaneus	182	195	93.33%

Carpal	1600	1726	92.70%
Metacarpal	886	965	91.81%
Tarsal	908	975	93.13%
Metatarsal	914	970	94.23%
Hyoid	48	97	49.48%
Caudal Vertebra	1297	1765	73.48%
Sternum	54	94	57.45%
Small Total	11041	12538	88.06%

The percent of expected elements present per specimen showed no correlation to the number of preserved specimens of that species known to be available worldwide through a search on GBIF. The results are summarized in a scatter plot (Figure 4.4). Similarly, there was also no linear correlation with local rarity, defined as the number of specimens of that species with known skeletal completeness within the collection. Results are also summarized in a scatter plot (Figure 4.5). Note that the R^2 values of both plots are extremely small, indicating that the percent of expected elements observed is very unlikely to be explained by a linear model. It is interesting, yet inconclusive, that the greatest percentages of apparent loss occur in the species that are most rare and most common within the collection, suggesting that there may in fact be differential specimen treatment of specimens with known local scarcity or abundance.

Figure 4.4 Scatter Plot with Line of Best Fit Depicting the Percent of Expected Elements Observed in a Given Specimen in Relationship to the Number of Specimens of That Species Listed in GBIF (n=109), Mean Percent Expected Observed of 90.13% with One Standard Deviation of 19.23%

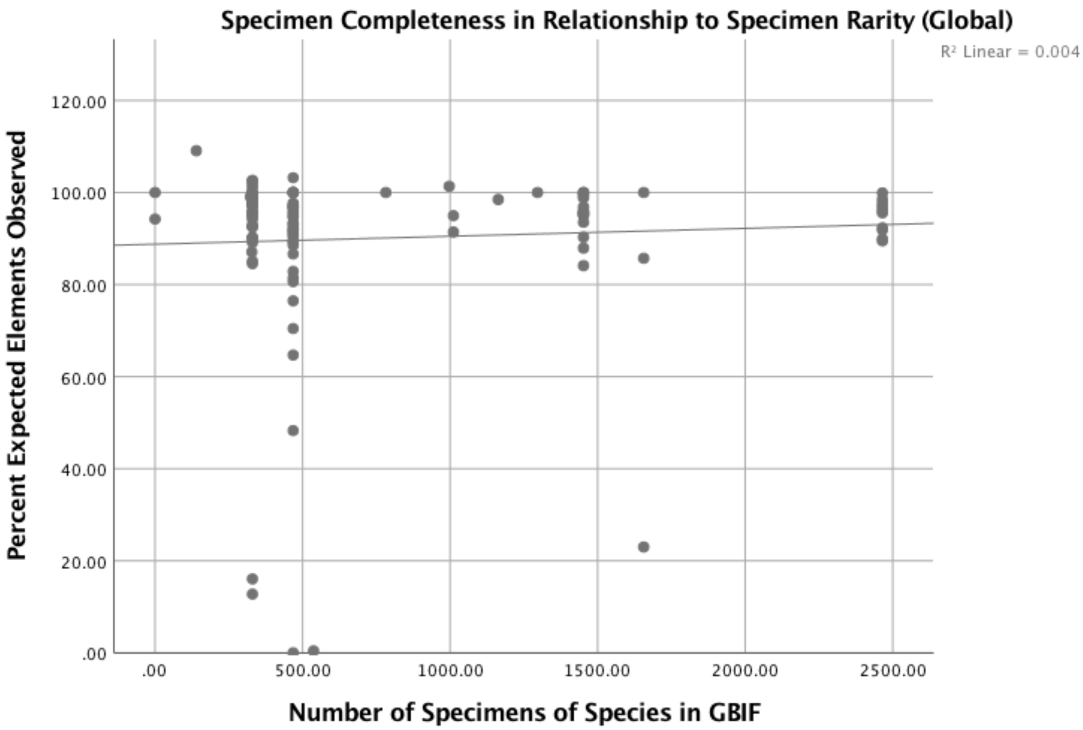
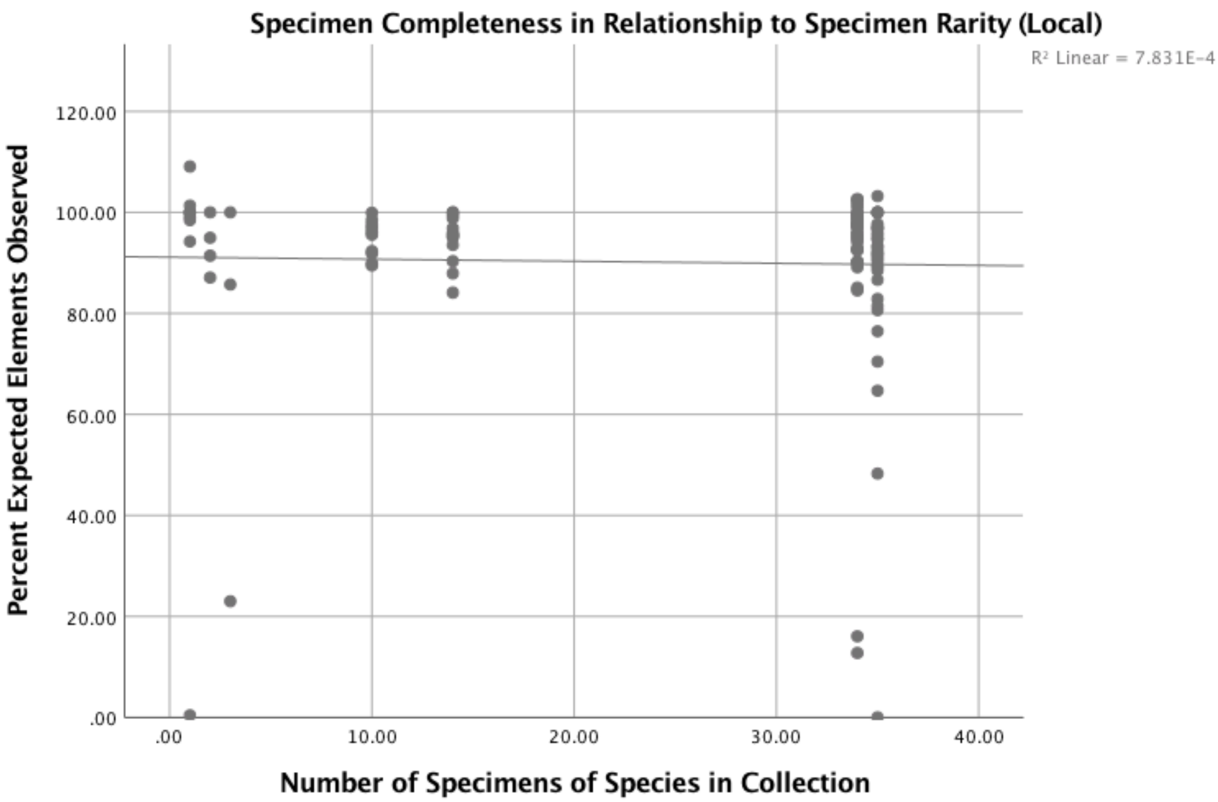


Figure 4.5 Scatter Plot with Line of Best Fit Depicting the Percent of Expected Elements Observed in a Given Specimen in Relationship to the Number of Specimens of That Species in The Collection (n=109): Mean Percent Expected Observed of 90.13% with One Standard Deviation of 19.23%



A search for articles authored by or dissertations advised by one of the three professors associated with care of the collection over the past 50 years showed no clear relationship between topic and incompleteness values. Study topics found include limb length, hind limb anatomy, spinal arthritis and lordosis, forelimb anatomy of extinct primate genera, and dentition in *Theropithecu*s, hominids, prosimians, Galagidae, and *Macaca mulatta* and *nemestrina*. There is no obvious relationship between the topics studied and more frequently absent elements. It would be tempting to assign the loss of humeri to the forelimb study, but the focus was on extinct genus, *Theropithecus*.

Finally, to test whether recordkeeping might have been the cause of losses actually occurring prior to entry into the collection, a comparison was conducted between specimens that were treated differently after death and prior to cataloging (Table 4.10). This study found that elements of specimens that have not been necropsied have statistically significantly higher percentages of expected occurrences observed (97.03% ± 7.17%) compared to elements of necropsied specimens (92.20% ± 11.69%), $t(96) = -2.468$, $p = 0.015$. When the differences between the percentages expected elements observed were compared, only the sternum, caudal vertebrae, and humerus were outside of two standard deviations (mean = 7.07%, one standard deviation of 7.94%).

Table 4.10 Comparison of Percent Expected Observed by Necropsied (n=78) or Not Necropsied (n=38) Status

	Necropsied			**Not Necropsied**		
Element	Observed	Expected	% Expected Observed	Observed	Expected	% Expected Observed
Sternum	37	71	52.11%	8	9	88.89%
Caudal Vertebra	915	1316.2	69.52%	181	185.8	97.42%
Humerus	93	139	66.91%	15	16	93.75%
Lumbar Vertebra	422	464.5	90.85%	64	57	112.28%
Atlas	62	72	86.11%	15	14	107.14%
Orbitosphenoid	119	156	76.28%	72	76	94.74%
Hyoid	32	73	43.84%	6	10	60.00%
Axis	118	144	81.94%	17	18	94.44%
Patella	63	72	87.50%	13	13	100.00%
Cervical Vertebra	311	346	89.88%	53	52	101.92%
Thoracic Vertebra	740	850.5	87.01%	109	113.6	95.95%
Carpal	1234	1269	97.24%	160	153	104.58%
Radius	139	141	98.58%	18	17	105.88%
Ulna	139	141	98.58%	18	17	105.88%
Nasal	152	156	97.44%	69	76	90.79%
Presphenoid	77	78	98.72%	35	38	92.11%
1st Phalanx	1354	1405	96.37%	180	175	102.86%
Metatarsal	719	715	100.56%	85	90	94.44%
3rd Phalanx	1290	1404	91.88%	171	175	97.71%
Occiptal	76	78	97.44%	35	38	92.11%
Basisphenoid	76	78	97.44%	35	38	92.11%
Basiocciput	76	78	97.44%	35	38	92.11%
2nd Phalanx	1077	1124	95.82%	141	140	100.71%
Femur	137	143	95.80%	18	18	100.00%
Ischium	138	144	95.83%	18	18	100.00%
Pubis	138	144	95.83%	18	18	100.00%
Lacrimal	152	156	97.44%	71	76	93.42%
Alisphenoid	152	156	97.44%	71	76	93.42%

Rib	807	882.2	91.48%	192	201.6	95.24%
Clavicle	131	136	96.32%	18	18	100.00%
Parietal	151	156	96.79%	71	76	93.42%
Sacrum	140	144	97.22%	18	18	100.00%
Ilium	140	144	97.22%	18	18	100.00%
Talus	66	72	91.67%	8	9	88.89%
Scapula	141	144	97.92%	18	18	100.00%
Tarsal	713	720	99.03%	91	90	101.11%
Vomer	75	78	96.15%	36	38	94.74%
Fibula	141	143	98.60%	18	18	100.00%
Tibia	142	144	98.61%	18	18	100.00%
Calcaneus	142	144	98.61%	18	18	100.00%
Palatine	152	156	97.44%	73	76	96.05%
Maxilla	152	156	97.44%	75	76	98.68%
Premaxilla	152	156	97.44%	75	76	98.68%
Metacarpal	687	710	96.76%	83	85	97.65%
Dentary	150	155	96.77%	71	74	95.95%
Pterygoid	151	156	96.79%	73	76	96.05%
Frontal	155	156	99.36%	75	76	98.68%
Zygomatic	151	156	96.79%	74	76	97.37%
Temporal	152	156	97.44%	74	76	97.37%
Total	14692	15907.4	92.36%	2920	2988	97.72%

The intent of this study was to characterize loss within a zoological osteology collection in order to inform collection management decisions through applied risk management. However, losses within only three of the 162 specimens that were either missing in total or in part could be assigned to a definitive loss type—loan of undefined length. Thus, the results do not allow for application of risk management formulae, which require probability of loss type. The exception is for lost loan, where, within this particular collection probability of occurrence to a given element over 50 years is 0.02%. In theory, all of the collection elements were susceptible, and loss of value was 100%, since, for a scientist wishing to study that element, if offsite, the loss would have been total. Thus, the only calculation for risk management plausible with the study data, if using Waller's method, was Magnitude of Risk = Probability x Fraction Susceptible X Loss of Value or MR = 0.0002 x 1 x 1 or 0.0002. Unfortunately, calculations such as this are meaningless without comparison to multiple magnitudes of risk from which the quantification would permit prioritization of actions and resources such as adoption of loan paperwork, acquisition of new storage cabinets, or other such collection care decisions.

Chapter 5: Discussion and Results

This study provides an indication that collections are not pristine and do undergo loss. The magnitude of that loss was unclear, since loss could not be strongly correlated to any of the tested variables except for differences in necropsy status. It was possible that recordkeeping at time of cataloging might have been inconsistent, ignoring smaller elements such as sternebrae or the hyoid, or that loss might actually have occurred during preparation. This interpretation was bolstered both by specimens appearing roughly 89% as complete as expected across all years of collection growth and necropsied specimens showing statistically significant difference in percentages of expected element occurrences observed than non-necropsied specimens. The processes a specimen undergoes prior to entrance to the collection may be where loss is most likely to occur, as this was the only statistically significant loss predictor found.

The collection card catalog lists elements known not to be present at time of cataloging, but it does not individually list all present. Thus, element presence and absence could both be overlooked during the process of cataloging. In further support of this interpretation, it was interesting to note that some of the elements with the lowest percent of expected occurrences observed included the hyoid and patellae. E. Raymond Hall of the Museum of Natural History, University of Kansas cautions in his 1962 vertebrate preparation guide, *Collecting and Preparing Study Specimens of Vertebrae*, that these elements can be easily overlooked during skeletonization.[168] The fact that only 31 of 142 specimens were observed to have all elements expected suggested that loss did occur for most specimens at some point post-mortem. However, it remains unclear if these losses occurred before or after entry to the collection.

Those losses that could be categorized as a loss type known with certainty to have occurred during time in the collection consisted of only three instances of loan of undefined duration. Total specimen absences may also be indicative of unrecorded loan.

This study also suggests that many predictors for loss within the collection are unfounded. No correlation with loss was found for either global or local specimen rarity. However, more occurrences of loss in the most rare and most common specimens within the

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[168] E. Raymond Hall, *Collecting and Preparing Study Specimens of Vertebrates* (Lawrence: University of Kansas, 1962), 25.

collection suggest that further exploration is merited to determine if rarity impacts extent of element loss.

Animal body size amongst different genera of primates was also found to have no correlation to loss, the relationship between loss and male and female body size within sexually dimorphic species was not statistically significant, and when loss was compared among overall element size classes, no statistically significant difference in loss could be found.

Heavy unexpected absence of one long bone, the humerus, suggests that loss is not random, and it seems unlikely that such a large element would be lost during the preparation process. The humeri may have been heavily studied or studied once and never returned to the collection. Unfortunately, no way of testing element or specimen use level seems plausible within the collection beyond the publication proxy described in the findings. Following completion of this study, Dr. Patricia Kramer confirmed that many humeri had been removed for an ongoing study. This information was not shared with the researcher, in part, to test if this study was able to describe their absence,[169] providing independent confirmation of the study methodology's ability to identify loss.

Of the implications of the data presented, perhaps the most surprising is that loss does not simply *preven*t future research, but may also *impact the findings* of future research within collections. Schultz's vertebral counts, if accrued from museum specimens that had already suffered undocumented loss of vertebral elements, allow for misinterpretation of the degree of loss in any collection compared to those values. Ecologist D. Pauly introduced shifting baseline syndrome in "Anecdotes and the Shifting Baseline Syndrome of Fisheries," wherein the human lifespan becomes the unit of time against which most people measure change. The assumption is that the state at which an individual became familiar with, for example, a fishery is the historical state of that fishery when it in fact could have been in decline or increase for several human lifespans prior. Pauly described the concept within fisheries: "[…E]ach generation of fisheries scientists accepts as a baseline the stock size and species composition that occurred at the beginning of their careers, and uses this to evaluate changes."[170] Schultz's primate vertebrae

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[169] Kramer, email to author, 15 May 2018.

[170] D. Pauly, "Anecdotes and the Shifting Baseline Syndrome of Fisheries," *Trends in Ecology & Evolution* 10, no. 10 (1995): 430.

counts, used for this study and widely cited, are based on counts taken in museum collections during Schultz's lifespan. They are widely cited not as the average number of vertebrae in primate museum specimens, but as the number of vertebrae in primates. If collection loss is an actuality during time in collection then one might expect a repeat of Schultz's study to find primates have fewer vertebrae than they did when Shultz conducted his study. This thesis introduces the idea of incorrect anatomical inference based on collection loss as the "shifting backbone syndrome."

As caretakers of collections for the use and education of the public, whether a collection is a zoological research collection or not, museum professionals are in a position to influence the state of knowledge in the greater world. Since museum professionals simply cannot know every way that a collection will be used, today or in the future, the state of objects in collections may have surprising implications if they are mistakenly assumed to be total and pristine. Thus, loss prevention is a crucial aspect of preventing misinformation or misinterpretation of collection objects. When known losses occur, they should be carefully documented to prevent future misinterpretation.

Another implication of this study is the suggestion that element presence percentages allow for strategic decision making within the studied collection. For example, complex objects like a primate cranium may only be labeled once when they are, in fact, a series of fused elements. Statistics from this study suggest that within the study collection, the frontal is the skull bone with the highest percentage of expected occurrences observed. If it is possible to discretely label the frontal, perhaps on the upper interior of the orbit, this may prove to be the most choice label site to ascertain that specimen data remains associated with crania in the collection. Similarly, it may be advisable to number low percentage elements if it is not already written into collection procedure to label all elements.

As a case study, the data from this study cannot be assumed to be true of other collections. However, in tandem with the limited literature on museum collection loss, this study can be evaluated in context to seek commonalities and differences among the case studies conducted to date.

Kautz leads his case study of collection attrition in archaeological collections with a quote from R. C. Sonderman's "Primal Fear: Deaccessioning Collections" claiming that archaeological objects are "not viewed as individual objects, not as tables or chairs might be, but rather, each flake or sherd is seen as part of the context from which it is recovered. It is not the individual object but the entire assemblage that is used to interpret the past."[171] When viewed as a set of constituent parts, the same is true of any museum object, be that the seat of a chair or the kneecap of macaque. If viewed as a source of data, the more of that object's context that is present—the chair or the macaque, the better the object can be interpreted. Therefore, the need for the fullest reasonable contextual knowledge is equally applicable outside of archaeology, and the motivations behind maintenance of archaeological and other research collections may be considered analogous, if not identical.

In many respects, Kautz's findings aligned with those within this study. Kautz tested a number of hypotheses regarding loss within California Department of Parks and Recreation collections. Kautz showed that the seeming attractiveness for research of an object did not predict loss; percentages were used to show that larger/heavier objects were more prone to loss than lighter/smaller objects; and "showy" objects, presumably targets of theft, were less likely to be missing than "less desirable" objects. Similarly, in this thesis, numerical rarity, with the assumption that either globally rare or well-represented species may be more desirable for study and/or theft, showed no clear correlation to the percent of expected elements observed.[172] Unlike Kautz's findings, larger or heavier specimens and elements were not prone to greater loss than smaller. The collections that Kautz evaluated were moved several times, and contained large, stone objects over 170 pounds in weight. Thus, heavier items may have been left behind during moves.[173] Individual skeletons, in contrast, do not approach the weight of the objects that Kautz encountered. The correlations or lack thereof with loss seen in individual collections is not expected to be consistent across all collections. However, it is promising to see that those tests meant to associate with the possibility of theft do not appear to correlate with loss in either study, suggesting that the impact of theft on collections may be low.

Perhaps the most surprising aspect of Kautz's study in light of the current study is the percentage overall loss. Kautz found 11.5% of catalog entries missing from each decade of

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171 R. C. Sonderman, "Primal Fear: Deaccessioning Collections," *Common Ground* 1, no. 2 (1996), n. pag.

172 Kautz, 35-36.

173 Ibid., 37.

collection.[174] It is curiously similar to both the percentage of element loss seen within those specimens of described completeness levels in the University of Washington Department of Anthropology physical anthropology collection, 10.92%, and the percent of specimens of a described completeness fully absent from the collection, 11.73%. It is plausible that this is entirely coincidental or that there is a level below which, within collections with many objects or objects with many components, loss does not appear to be occurring. Many collections may operate at a lower level, 10% or so, loss without anyone aware of the fact, particularly in collections such as skeletal collections or archaeological collections that may include a large quantity of objects with a similar appearance.

Many difficulties faced by Caffell et al. were encountered in this study as well. They claimed that, "It was originally assumed that element loss would be relatively easy to assess. However, due to the inadequate nature of the original documentation, in some cases even assessing loss proved difficult."[175] They assumed that increases in human biological collection materials are, in fact, a result of incomplete initial records.[176] While not explicitly treated in this study, a number of the completeness percentages of individual non-human primate specimens encountered in the University of Washington physical anthropology exceed 100%. These gains in element number must be either inclusion of disassociated elements of other specimens or a result of inaccurate completeness description at the time of cataloging. Another tendency observed in the collection was for a few caudal vertebrae to be stored with phalanges and vice versa, indicating that some degree of lack of anatomical knowledge was at play, whether as a result of years of student use or at the time of cataloging.

Caffell et al. attributed loss primarily to degree of collection use and the relative size of the element. No statistically significant degree of loss could be quantified in the University of Washington physical anthropology collections in relationship to relative element size. When considered purely as percentages there is a slight indication that the largest elements, the long bones of the limbs, are more likely to be observed when expected than any of the smaller bones. When subjected to comparison through a one-way ANOVA test or consideration of standard

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[174] Ibid.

[175] Caffell et al., 195.

[176] Ibid.

deviation, there is no indication that the percentage differences observed are statistically significant. Degree of use appears to have an impact in the University of Washington collection as displayed by the surprisingly low number of humeri present, a sizeable bone unlikely to be misplaced, but this assumption could not be tested. Conversation with the curator later confirmed that these elements had been removed for study.

Finally, it should be noted that the "visual fatigue" hypothesis cannot be tested in Caffell et al.'s data as presented. Their study does not present either percent of absent specimens or of absent elements from across the full collection or study sample. However, they did find that 72.5% of their study sample had lost elements, while the case study at the University of Washington found that 78.47% of specimens had lost elements. Between Kautz and Caffell's numbers, this suggests a surprising degree of similarity of loss extent across multiple study sites, although a uniform study methodology employed across multiple sites in a single study would be best equipped to determine if there is, in fact, an universal degree of collection loss or record-to-presence disparity.

Finally, it should be remembered that given that the entirety of the University of Washington physical anthropology collection was sampled, statistical significance is not meaningful. The percentage comparisons are the collection reality. However, if the collection is viewed as a subset of the zoological research collections of the world, then measures of statistical significance may provide insight into which areas of future research are most pertinent. It should be reiterated that using statistical significance in this way may only suggest future research, not be used to extrapolate the composition of other collections, as there is no proof that collections to be analyzed in the future will share similar acquisition and preparation histories, histories of use, or other peculiarities resulting in collection object retention or loss.

Chapter 6: Conclusion

The purpose of this study was to characterize the degree to which element loss has occurred in natural history museum skeletal collections, which elements were lost, and what types of loss occurred.

This study provides the first assessment of loss within a zoological collection, as well as the first attempt, if largely unsuccessful, to use loss findings to prioritize collection management decision-making through applied risk management. It also provides insight into the ways in which museum collection losses may impact future knowledge through studies conducted on collection objects assumed to be complete when they may in reality be partial; and provides a quantitative basis for label location selection on complex collection objects.

Collection "loss" may be less a function of true loss during time in collection, and more a function of the thoroughness of recordkeeping at the time of cataloging with loss occurring prior to entry to the collection. Where incompleteness beyond approximately 80% of the expected elements present was observed, it was observed sporadically, and may be indicative of loss due to use. Specimens of particularly uncommon and particularly common species within a collection may suffer greater percentages of element loss.

This case study sought to answer the following questions within the context of one collection:

To what extent does skeletal element attrition occur in museum collections?

10.93% of all expected elements in specimens present within the collection and 11.73% of all specimens with records of completeness appear to be missing from the collection. This value is similar to Kautz's quantification of loss in archaeological collections, 11.5%,[177] as is the percentage of specimens present displaying one or more lost elements, 78.47%, to that calculated by Caffell et al., 72.5%.[178]

Does skeletal element attrition increase in natural history museum research collections with specimen time spent in the collections?

[177] Kautz, 35-36.

[178] Caffell et al., 191.

There is no indication that loss correlates with time in collections. When all specimens are examined in rank order of entry to the collection most specimens appear to be 80 to 100% complete in comparison to the catalog record. While some specimens display greater percentages of loss or are totally absent from collection storage, these appear as sporadic events along the collection timeline, and are not more common among the specimens that have been in the collections longer.

Can type of loss be determined? Examples of loss types include loss during preparation or collection, unreturned loan, theft, destructive sampling, transfer to another institution, and disposal.

Definitive determination of loss type proved elusive. In three cases, loss could be ascribed with certainty to loans of undefined duration. All other types of loss could only be suggested through attempts to correlate degree of loss to collection variables. All definitive instances of loss type were a result of document analysis—in this case, notes physically left with the specimen.

Are particular elements more prone to loss and/or specific types of loss?

The percent of expected element occurrences observed varied by element. Certain elements were distinctly less likely to be present when expected, namely the hyoid, sternum, and humerus. All of the other long bones of the limbs were most likely to be present when expected. Most elements were present for approximately 90% of the occurrences expected. Specific loss types could not be definitively determined in most cases. However, it seems probable that small elements such as the hyoid and sternebrae may be overlooked in preparation and initial data entry at cataloging, while those most easily recognizable may be present the greatest percent of the times expected in the collection. The lack of the humeri was a result of collection use, but this was determined through conversation with the curator rather than correlation.

Does uncharacterized loss, that which is not associated with archival record of a loss type, show positive correlation with specimen monetary value, scientific value, or element size?

No statistically significant correlation was found between loss and relative element size, overall specimen size, species rarity within collections globally, species rarity within the collection, or scientific publication. Actual percentage values suggest that there may be slightly greater propensity of loss of the smaller elements of the skeletal system, but that this degree of loss is consistent among all bones that are not the long bones of the limbs. There may also be a greater tendency toward loss of elements of specimens which are either particularly rare or particularly common within the collection, suggesting the complexity of assignment of value and differential care of specimens perceived to be of heightened or minimal value, although this is not definitive. Monetary value proved too difficult to quantify across time and specimen completeness in auction and sale records.

What magnitude of risk exists per element and type of loss?

Magnitude of risk could only be calculated within this collection for loss to undefined duration loan. The magnitude of risk to an element in a 50-year period within this collection is 0.0002. Of those elements impacted within the case study collection, lumbar vertebrae are at the greatest magnitude of risk and the axis at least magnitude of risk. While data from this collection unfortunately did not support extensive comparison of magnitudes of risk, it is apparent that quantitative data may help make and support collection management decisions. For example, although risk is low throughout the collection for loss due to undefined duration loans, a collection manager may prefer to loan those elements with a magnitude of risk of 0 based on past loss events.

Future researchers are encouraged to explore collection loss further, building upon the methodology used in this study. It should be cautioned that the individuals best suited to conducting the study should have both strong knowledge of the object type and its component identification under study, as well as experiential knowledge within museum collection management. If possible, a study team of anatomical or subject area experts, statisticians, and collection care experts could be employed to best effect. Averaging of multiple inventory counts following identification by multiple individuals is also recommended, since identification fatigue can set in while working through large quantities of similar objects.

Further experimentation is merited. Suggested areas for exploration include the impact of preparation, storage housing, collection use, and differential interaction with specimens according to their perceived value. Baseline studies are recommended on a selection of the most recently prepared specimens in natural history collections. Optimally these studies will occur across multiple institutions and compare different methods of preparation, such as the results of simmering, maceration, enzyme cleaning, and dermestid beetle colonies. This would provide an understanding of the degree of total element loss and loss of particular elements occurring during collection and preparation, and should avoid inclusion of specimens that have been salvaged as they may have suffered element loss prior to preparation. These studies may also explore the degree to which the anatomical knowledge of the preparator may impact the completeness of the specimen in collections. This area of research should receive priority to avoid future assumption of loss in storage as it may instead occur at an earlier stage, as well as to assist in parsing which losses are more likely to be attributable to time in collections.

Storage housing was not studied in this collection. However, multi-site studies could study the impact of storage in trays, on open shelving, in boxes, within cabinets, or where particular elements are stored in separate smaller storage units, such as glass vials for phalanges, particularly where storage methods have not changed greatly in the institution over time.

The low occurrence of expected humeri, particularly given that all other long bones had the highest occurrence percentages, suggests that use is a factor in loss. No other variable, be that size, time in collections, or post-mortem and pre-collection treatment seems to adequately explain this loss. After the study, it was revealed that these elements had been removed for study with no record left in the collection of their removal. Studies of collections with strong records of specimen use in publication and/or coursework records should be pursued.

While Caffell et al. addressed skeletal loss in university collections used in coursework and research, no known study discusses the impact of scholarly research on collection loss. This should not be seen as caution against use, since without access a collection is meaningless. However, if usage corresponds heavily with loss, then a variety of mitigation measures may be undertaken.

Another area for exploration is that of collection "object fatigue." Is there a point at which the discrepancy between recorded completeness and object presence becomes noticeable without inventory? If so, are many collections operating at an unknown, "baseline" level of loss, occurring during preparation and/or time in the collection?

Finally, the complexity of specimen value should be addressed. How do collection managers, researchers, curators, registrars, students, and museum guests perceive specimen value? Is value associated more strongly with rarity, commonality, perceived monetary value, aesthetics, or other factors? How do the various museum user groups vary in this regard? How does perceived value alter the way an object is used, handled, researched, stored, secured, loaned, and exhibited?

Natural history collections provide the means to ask questions about our world that could never have been asked at the time the collections began to coalesce. This remains the unique position of natural history museums—keepers of the biological past for the benefit of human inquiry in the future. Collection loss, although potentially small, represents loss in potential. Every element that is lost signifies between one and thousands of questions that can no longer be answered about the past. As collections face financial pressures, remaining specimens grow in importance. Understanding and characterizing loss, its extent and means, is a crucial part of rational, informed risk management application. Through risk management, museum professionals have the opportunity to optimize long term care of irreplaceable collection objects, be they zoological or otherwise.

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