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Mammal collections of the Western Hemisphere: a survey and directory of collections

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As a periodic assessment of the mammal collection resource, the Systematic Collections Committee (SCC) of the American Society of Mammalogists undertakes decadal surveys of the collections held in the Western Hemisphere. The SCC surveyed 429 collections and compiled a directory of 395 active collections containing 5,275,155 catalogued specimens. Over the past decade, 43 collections have been lost or transferred and 38 new or unsurveyed collections were added. Growth in number of total specimens, expansion of genomic resource collections, and substantial gains in digitization and web accessibility were documented, as well as slight shifts in proportional representation of taxonomic groups owing to increasingly balanced geographic representation of collections relative to previous surveys. While we find the overall health of Western Hemisphere collections to be adequate in some areas, gaps in spatial and temporal coverage and clear threats to long-term growth and vitality of these resources have also been identified. Major expansion of the collective mammal collection resource along with a recommitment to appropriate levels of funding will be required to meet the challenges ahead for mammalogists and other users, and to ensure samples are broad and varied enough that unanticipated future needs can be powerfully addressed.

Aproximadamente cada 10 años, el Comité de Colecciones Sistemáticas (CCS) de la Sociedad Americana de Mastozoologia, evalúa el estado de las colecciones mastozoológicas del hemisferio occidental. En el último censo, el CCS encuestó un total de 429 colecciones y compiló un directorio de 395 colecciones activas que contenían 5,275,155 especímenes catalogados. En comparación con el censo previo, durante la última década 43 colecciones se han cerrado o han sido absorbidas, pero se agregaron al censo 38 nuevas colecciones. Se documentó un incremento en el número total de especímenes, la expansión de la disponibilidad de colecciones

de recursos genómicos, además de avances substanciales en digitalización y accesibilidad a la web. También, se detectaron cambios en las proporciones de grupos taxonómicos debido a la representación geográfica cada vez más equilibrada de las colecciones en comparación con encuestas anteriores. Si bien consideramos que las colecciones del hemisferio occidental estan en buen estado en algunas áreas, también identificamos brechas claras en la cobertura espacial y temporal, así como amenazas al crecimiento y vitalidad de estos recursos a largo plazo. Un crecimiento substancial, acompañado de compromisos de adecuado financiamiento, serán necesarios para asegurar que las colecciones incluyan muestras lo suficientemente amplias y variadas como para permitir a mastozoologos y otros científicos abordar las necesidades, muchas de ellas imprevistas, que traerá el futuro.

Key words: biodiversity, biorepository, collection management, database, genetic resources, infrastructure, museum, natural history collections, specimen, voucher

Natural history collections and collections-based science have played an essential role in many of the major revolutions in science (Funk 2018). This deep association between collections and natural sciences dates to the earliest period of collecting and classifying nature and continues to this day, as collections contribute to research across an array of critical disciplines including biodiversity studies, emerging diseases, biological invasions, environmental contaminants, and global climate change (Suarez and Tsutsui 2004). In mammalogy specifically, collections represent essential infrastructure for research, training, and education that continue to play vital roles in long-established fields (systematics, taxonomy, and natural history) while also contributing to new research areas (e.g., genomics, stable isotopes, pathogen discovery). Looking into the future, it is easy to visualize collections as a physical nexus for environmental informatics and big data synthesis (McLean et al. 2016; Funk 2018; Cook and Light in press). However, achieving this goal will depend on whether or not current collections remain adequately positioned in terms of taxonomic, temporal, and spatial coverage to address new questions in a period of unprecedented environmental change (Malaney and Cook 2018). As stewards and builders of these invaluable resources, mammalogists must critically evaluate specimen holdings, their accessibility, and the overall health of the infrastructure to direct growth and develop plans to meet future challenges. With these aims in mind, over the course of its history, the American Society of Mammalogists (ASM) has undertaken periodic evaluations of the mammal collections held in the Western Hemisphere.

History of collection surveys.—In April 1922, just 3 years after the formation of the ASM, A. Brazier Howell (1923) completed the first survey of mammal collections of North America. His stated purpose was to make known the available sources of specimens as study materials, but additionally to stimulate the "interest of the small collector, the beginner and the amateur" (Howell 1923:113–114). At that time, over one-half of the 77 reported collections were private and the total specimens reported was 410,239. Only 9 collections (2 public, 7 private) were reported from Canada and none from Mexico.

About 20 years later, the second survey, completed in 1943 (Doutt et al. 1945), reported almost 4 times the number of collections (297) and more than twice the specimen holdings (861,569) of Howell (1923). Large numbers of private collections were still reported (113) but these had dropped to 38% of the total, likely reflecting increased public interest and support for collections among North American biologists. The number of Canadian collections had grown to 23, but there were still no collections reported from Mexico.

The third survey documented collection information through 1962 (Anderson et al. 1963). Although the authors stated that the purposes for previous surveys were relevant to the 1962 survey, they also considered these periodic surveys an important practice for tracking the history of North American mammalogy at large. Their survey increased the number of collections to 307 with a total number of specimens reaching approximately 1,586,000. A declining trend in the number of personal collections (43) continued, with 53% fewer than in 1943. For the first time, 2 Latin American collections (1 in Mexico and 1 in Costa Rica) were included.

The fourth survey was completed in December of 1973, marking a 10-year interval rather than the previous 20-year survey intervals (Choate and Genoways 1975). That survey was partially funded through the National Science Foundation (NSF) and aimed to assess resources for mammalian systematics in particular. The number of collections surveyed was 388, and the total number of specimens stood at 2,542,000. Rates of collection growth increased markedly relative to previous surveys. The number of private collections (36) again declined relative to earlier surveys. The Systematic Collections Committee (SCC) was formally established by the ASM in 1972, and the committee first played a role in this 1973 survey. From that point on, the responsibility of the periodic survey of mammal collections of North America fell to members of that committee.

The fifth ASM survey of North American collections was undertaken in 1983 and published as a supplement to the *Journal of Mammalogy* (Yates et al. 1987). That survey reported 474 North American collections, with a cumulative total of 3,139,000 specimens. Notably, 33.7% of those collections were already using computers for curatorial or management functions. Yates et al. (1987) also emphasized collections infrastructure in terms of specimen care, including the number of collections reporting protection from fire, humidity, water, pests, and other environmental risks to mammal specimens. That survey also was the first to include a report of collections accredited by the ASM SCC (49) as meeting standards established for long-term maintenance of collection resources.

The sixth and most recent published survey of Western Hemisphere mammal collections (Hafner et al. 1997), included as a supplement to the *Journal of Mammalogy* and covering

collections status through 1996, expanded to survey collections throughout the Western Hemisphere and included 62 collections from Latin America and the Caribbean region and 23 from Canada. Combined with 306 collections in the United States, a total of 391 collections was included, an 18% reduction from the 474 collections reported by Yates et al. (1987). This decline was attributed, in part, to inclusion in the 1983 survey of many collections which did not respond and likely were no longer operating, thus resulting in an overestimation of active collections. Notably, private collections were essentially absent from the 1997 survey. Despite the dramatic decrease in overall number of collections, the total specimens reported for that survey increased to 4,194,305. The growing trend of computerized catalogues was evident in the 1996 survey, with one-half of the collections from Canada and the United States and 37% of Latin American collections digitized to some extent (Hafner et al. 1997).

The last survey completed by the ASM SCC was in 2007 under the direction of William Stanley and, although unpublished, was maintained as a spreadsheet available on the committee's page of the ASM website. Relative to the previous survey, collection numbers had more or less stabilized at 394 and the total number of specimens reached 4,502,000.

As the ASM approaches 100 years as a professional society, and in light of the conservation and research challenges in mammalogy worldwide, a renewed effort to describe and analyze trends in mammal specimen infrastructure and accessibility is timely. We report herein the status of systematic collections of mammals throughout the Western Hemisphere as of 2017, with special reference to temporal and geographic trends in collections growth, digitization, and global, web-based accessibility, and expansion into genetic resources for mammals. The present survey extends a tradition that dates back to the earliest years of the ASM and which, like past surveys, provides a framework for assessing the health and growth of collections resources so vital to the science of mammalogy.

Present Survey

The primary objective of this survey was to update the comprehensive directory of the collections of Recent mammals in the Western Hemisphere, but doing so also provides an opportunity to analyze collections growth, maintenance, and accessibility. We therefore not only provide an overview of how natural history collections and associated data are being maintained, but also highlight the strengths and weaknesses of current holdings along temporal, geographic, and taxonomic axes, and evaluate new avenues of growth and digitization within existing collections.

The present survey is geographically focused on the Western Hemisphere; specifically, collections from North, Central, and South America and the Caribbean region. We note that surveys encompassing collections worldwide have been undertaken (Genoways and Schlitter 1981, 1985) and that expansion of this survey to a global directory was proposed (Hafner et al. 1997). We agree that this would be important for the mammalogical community, and suggest that expanding the survey to a global scale will become more feasible as digitization of collection data grows and institutions increasingly provide viable database access via the internet. A web-based collection directory enabling collections to update their statistics and collection contact information as needed is in development. This document will be linked to the ASM SCC website and will facilitate future survey efforts as well as provide a more real-time assessment of the collection resource.

Contact list.—The unpublished 2007 survey of 398 collections served as the starting point for the current survey, but was expanded to include new collections and existing collections not previously reported. Collections were parsed to the SCC members for data collection, based primarily on regional affiliations and personal knowledge of committee members. The listed point of contact (usually a curator or collection manager) for each collection was contacted via e-mail with a request outlining the goals of the survey and requesting updated information to be deposited in a Microsoft Excel file (collections for which 2007 data were collected were sent this file for updating). Information request letters were provided in both English and Spanish as necessary. Future surveys should consider including a Portuguese version to facilitate information retrieval from Brazilian collections.

Survey metrics.—Collection contacts were asked to provide original or updated information in the following areas:

- Collection physical address
- Contact information (phone and e-mail) for curator and collection manager
- Number of catalogued mammal specimens
- Number of preserved tissues and tissue preservation type(s)
- Number of holotypes
- Geographic and taxonomic strengths
- State of digitization of specimen data and web accessibility of digitized data
- Incorporated collections
- Past ASM accreditation dates

As a supplement to questionnaire responses, which contained only coarse information on geographic and taxonomic strengths of collections, we also compiled and analyzed data from those collections with digitized and web-accessible specimen records. These data were gathered using institutional searches on GBIF and SpeciesLink (accessed March–June 2018), downloading all available records from each queried collection. Taxonomic holdings from these collections were summarized at the ordinal level, and ordinal taxonomy of specimens was updated as necessary. Geographic scope of collections was summarized at the country level, as not all digital specimen records contain geocoordinates. To provide perspective on representation of global mammal diversity contained in Western Hemisphere collections, the digital specimen records were summarized according to their country of collection. These data were then paired with information from the IUCN on species endemicity within countries (IUCN 2017; accessed at http://www.iucnredlist.org/about/summary-statistics), allowing visualization of how effectively Western Hemisphere collections have targeted mammal diversity both locally and globally.

Survey Results

Response.—Four hundred and twenty-nine collections were identified and we attempted to contact each. A large number of initial contacts were unanswered, presumably because many collection contacts had changed since the previous survey. In those cases, web searches were used to locate new contact information, and a second round of e-mail or phone queries was made. In some cases, up to 4 rounds of queries were necessary to successfully locate current contacts and obtain collection data.

Of the 429 collections we identified in our preliminary list, 395 were deemed to be active and are included in the current directory, while the remaining 34 were determined to be either defunct or incorporated into other existing collections. Of the active collections, 327 responded with updated collection and contact information while 68 did not respond. Of the nonresponders, 53 are updated with information contained in collection websites or publications, and 15 are reported based on information from previous surveys.

Collection and specimen growth.—The 395 collections of the Western Hemisphere covered in this survey currently archive a minimum of 5,275,155 catalogued specimens (Fig. 1; Table 1). The total number of active collections has remained between 390 and 395 over the past 20 years (Fig. 1). However, this perceived equilibrium actually masks an underlying state of flux, because we detected large numbers of collections as defunct or transferred, and many newly created or previously unsurveyed collections were added. Since the 2007 survey, 9 collections are missing and their dispositions unknown, 34 were fully or partially transferred to other collections, and 38 new or unsurveyed collections were added. Over the 2 decades since Hafner et al. (1997) published a list of defunct or transferred collections, 45 additional collections have closed or have been transferred (Supplementary Data SD1). A troubling statistic is that the majority of these (31) were university-based collections, indicative of a trend of decreasing institutional support for such resources within universities (Dalton 2003; Gropp 2003, 2004; Schmidly 2005). This is a significant problem for mammalogy, as fewer young mammalogists are exposed to museum specimens and their value and centrality in biological science (Cook and Light, in press). Other areas also have not been immune to contraction, as 7 federal or state agency collections were transferred or lost and private collections further declined in number since the last survey. Only a few privately held collections remain active and at least 2 prominent collections of this type (the Robert and Virginia Rausch and the E. Thomas Seton collections) were recently transferred to university-based collections. We view the incorporation of private collections into public collections as a positive trend as their accessibility and physical security are greatly increased.

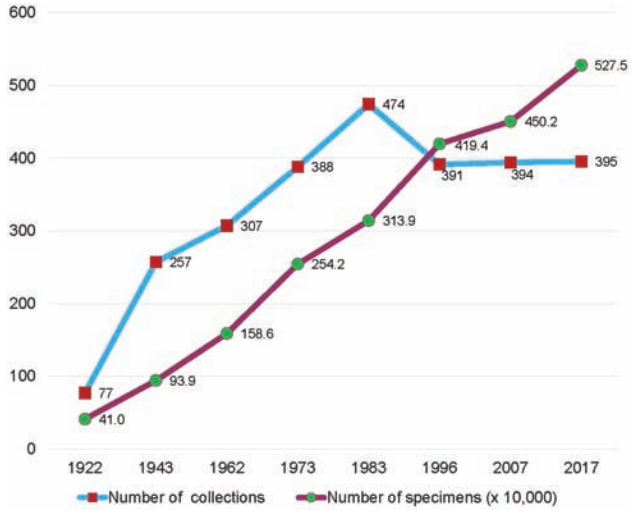

Fig. 1.—Historical trends in mammal collection growth (1922–2017). Total reported specimens from each of the previous collection surveys were taken from original publications.

More than 770,000 specimens were added to Western Hemisphere collections since the 2007 survey (77,000/year). Annual growth rates exhibited an overall downward trend over the past 50 years (90,000/year [1963–1973]; 60,000/year [1973–1983]; 56,000/year [1983–1995]; 31,000/year [1997–2007]—Choate and Genoways 1975; Hafner et al. 1997; ASM SCC 2007), a trend consistent with the findings of Malaney and Cook (2018) for the United States specifically. The higher growth rate over the most recent decade reflected in our survey includes approximately 150,000 specimens (20% of total growth) reported by 38 collections not previously surveyed, and thus does not entirely represent new material collected over the last decade. The specimen growth we recorded also was not evenly distributed across collections. About 58% of the overall growth since 2007 was in the 20 largest collections (those with > 50,000 specimens), which added 449,823 specimens (ca. 45,000/year). The remaining 337 collections accounted for 22% of the decadal growth. Therefore, growth trends across decades (Table 1) should be viewed with some caution due to variation in reporting methods, inclusion of uncatalogued specimens in some reports, and the inherent issues concerning precision of data related to surveys.

Geographic distribution of collections.—The 395 collections contained in this report are geographically distributed throughout North, Central, and South America and the Caribbean (Fig. 2). Twenty-one of 35 Western Hemisphere countries have at least 1 collection included in the survey and all 50 US states and Puerto Rico are represented (Fig. 3). Western Hemisphere countries not represented in the survey were predominantly from the Caribbean.

Approximately three-quarters of collections are located in the United States and Canada, and the remainder are in Mexico, Central, and South America and the Caribbean (Fig. 4). In the 2007 survey, 325 (82%) of the collections were located in the United States or Canada and 73 (18%) were in Latin American countries. Currently, 294 collections (75%) are in the United States or Canada and 101 (25%) in Latin American or Caribbean countries. Potential reporting differences notwithstanding, this represents an overall reduction in the number of collections in the United States and Canada and an increase in Latin America and the Caribbean. Growth in Latin American natural history

Table 1.—Holdings summary of the mammal collections of the Western Hemisphere.

Year	Number of collections surveyed	Number of specimens	Number of collections with tissues	Number of specimens with tissues	Number of holotypes
1922	77	410,000	0	0	NA
1943[a]	257	939,000	0	0	NA
1962	307	1,586,000	0	0	NA
1973	388	2,542,000[b]	0	0	5,726
1983	474	3,138,690[c]	6	21,300	6,208
1996	391	4,194,305[d]	35	473,614[e]	6,625
2007	394	4,502,294	74	426,436	6,456[f]
2017	395	5,275,155	114	767,250	6,908

[a]Previous surveys incorrectly listed 1943 values as 959,000 specimens (Yates et al. 1987) and 297 collections (Hafner et al. 1997).
[b]Includes 100,000 uncatalogued specimens and 68,000 unreported from 1963 survey.
[c]Includes 147,662 uncatalogued specimens and 154,494 unreported from 1973 survey.
[d]Includes 264,327 uncatalogued specimens.
[e]Value inflated based on some collections reporting cryovials as opposed to individuals.
[f]Value underreported due to lack of responses in unpublished 2007 survey.

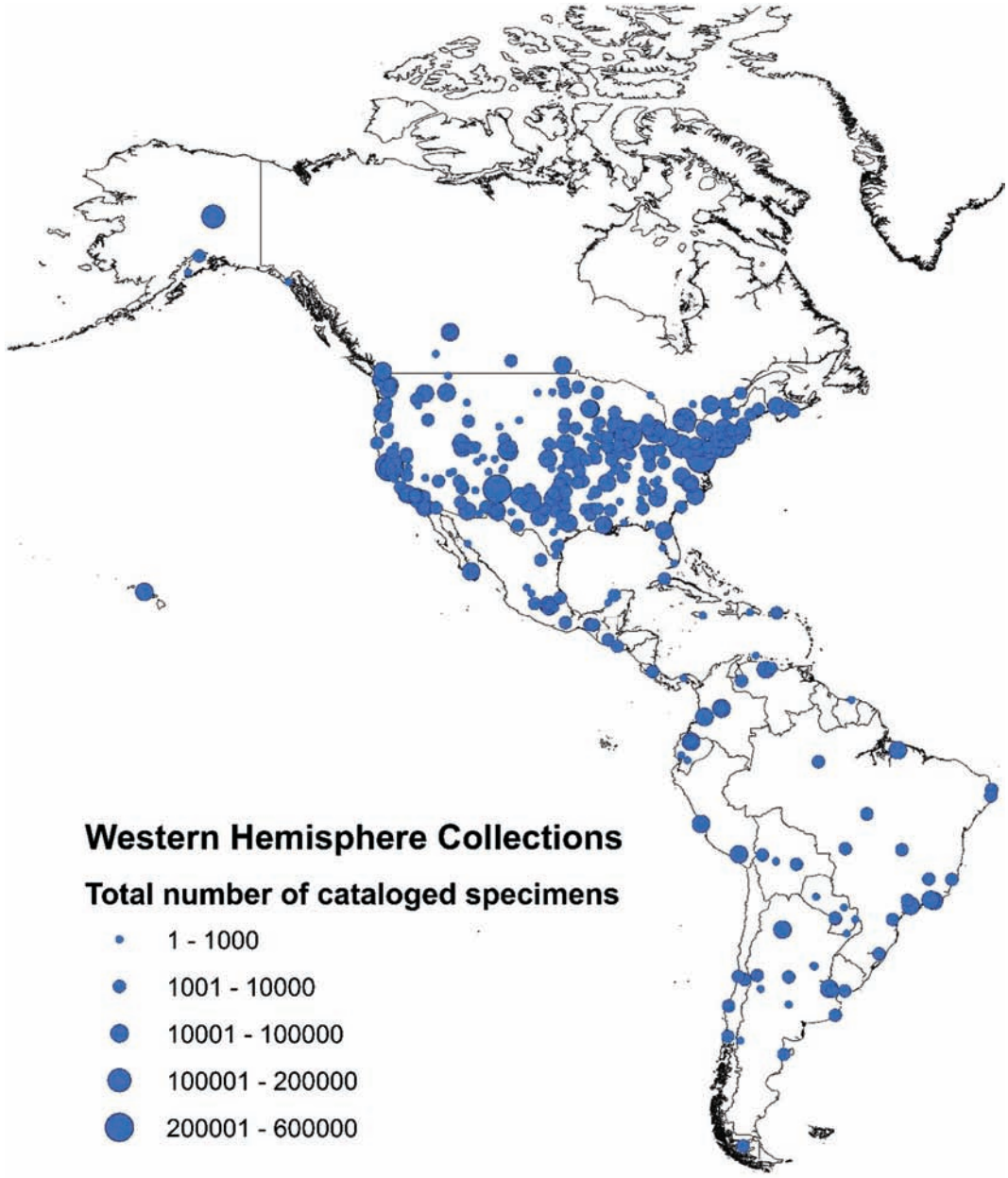

Fig. 2.—Geographic distribution of mammal collections of the Western Hemisphere.

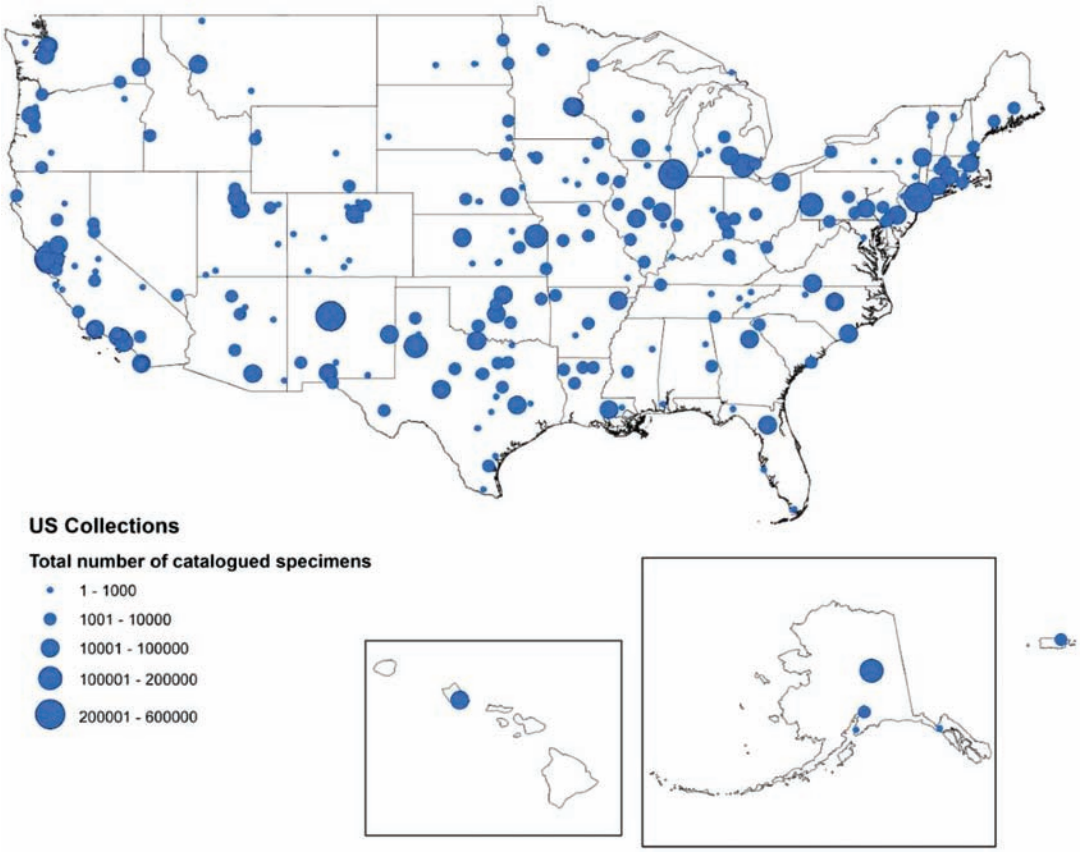

Fig. 3.—Geographic distribution of mammal collections within the United States.

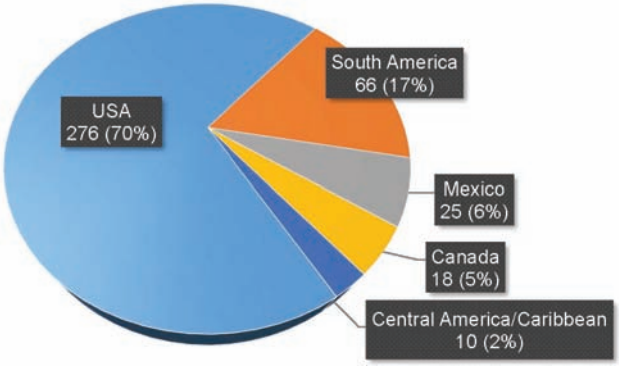

Fig. 4.—Number and percentage of collections by geographic region in 2017.

collection infrastructure is an encouraging trend as these biodiverse areas are experiencing rapid human development and conversion of mammalian habitat, leading to a critical need for fundamental discovery, documentation, and monitoring of biodiversity, and associated environmental research.

Size of existing collections.—The sizes of Western Hemisphere collections are heavily skewed toward smaller collections (Fig. 5), with 79% containing 10,000 or fewer specimens. Across surveys, there has been a steady increase in mid- to large-sized (> 10,000 specimens) collections. Eighty-four collections (21% of the total) currently have holdings exceeding 10,000 specimens, with 75 (19%) reported in 2007 by ASM SCC, 58 (15%) listed by Hafner et al. (1997), and 51 (11%) reported by Yates et al. (1987).

The 64 mid-sized collections (10,000–50,000 specimens) are about 16% of the total collections; thus, combined with the small collections, 95% of all Western Hemisphere collections are < 50,000 specimens. The other 5% of collections is composed of the 20 largest collections (Table 2), including 17 US, 2 Canadian, and 1 Brazilian collection. Those collections range in size from 56,000 to 600,000 specimens and contain 59% of all specimens in Western Hemisphere collections (Fig. 6). This percentage is slightly down from 1997, when the largest 20 collections held 61% of all specimens.

Holotypes.—There are at least 6,908 mammal holotypes held in 77 Western Hemisphere collections. This represents an increase of 283 since the 1996 total of 6,625 (Hafner et al. 1997) and can be partly attributed to the ongoing description of new mammalian species (Burgin et al. 2018) as well as inclusion of holotypes contained in previously unsurveyed collections. The 20 largest collections hold 88% (6,085) of holotypes (Table 2), down slightly from the 90% reported by Hafner et al. (1997).

Mammal collections and their archives of frozen tissues are increasingly used for screening and discovery of a diverse array of parasites and zoonotic pathogens. This has led to a large increase in deposition of type host specimens or "symbiotypes" (Frey et al. 1992) in some collections (MSB, TTU, MVZ, FMNH). We anticipate more collections will begin serving as biorepositories for pathogen research and symbiotypes will increase growth in type specimens. Mammal collections

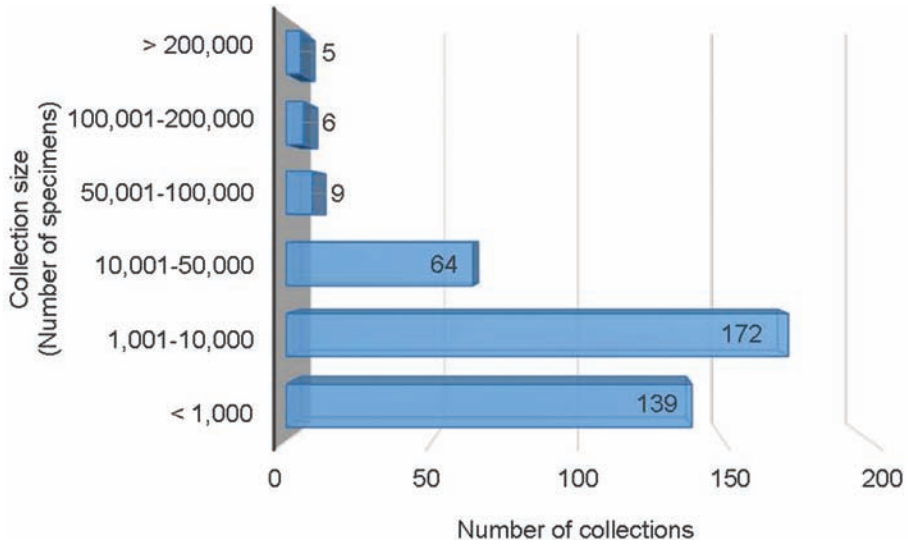

Fig. 5.—Size distribution of collections of the Western Hemisphere in 2017.

not only have the specimens and samples required for research, but also possess the rigorous archival and database standards that ensure best practices in pathogen discovery, designation and deposition of host symbiotypes, and robust linkages between host specimens, their pathogens, genetic sequences, and any other derived data (Dunnum et al. 2017).

Genomic resources.—At least 114 Western Hemisphere collections currently maintain frozen or ethanol-preserved tissue collections from over 767,000 mammal specimens (Fig. 7; Table 1). Since the development of the first tissue collections in the late 1970s and their initial inclusion in the ASM SCC surveys (Yates et al. 1987), between 30 and 40 new tissue collections have been added during each survey period (Fig. 7). The majority of tissue collections have relatively small holdings, with over 52% (60) containing < 1,000 specimens and 88% (102) containing < 10,000 specimens. Only 12 collections currently have tissue holdings in excess of 10,000 specimens (Table 3), and most of these larger tissue collections are in US institutions, although 2 are Latin American and 1 is a Canadian collection. Overall collection size does not strongly correlate with tissue collection size; only 8 of the top 20 collections are also represented in the largest tissue collections (Table 3). While 18 of the 20 largest mammal collections now have associated tissue collections, many only recently began to develop this resource and have minimal tissue holdings (Table 2).

Growth of tissue collections specifically in terms of numbers of catalogued individuals has proven more difficult to track because of variation in reporting methods. Some collections have reported number of individuals with tissues, others have reported gross numbers of cryovials containing tissues, and others may have simply reported estimates due to storage in freezers and insufficient object tracking software for tissue collections. Due to these issues, the apparent drop in number of tissue specimens for 2007 (Fig. 7) is likely not the result of a loss of specimens but overreporting in Hafner et al. (1997). We recommend that both metrics (number of catalogued individuals represented, total estimated number of cryovials) be collected in future surveys.

Genetic resources have become a fundamental and central element of natural history collections that have expanded the value and usefulness of traditional scientific specimens to include genetic analyses (Zimkus and Ford 2014). Collection of tissue should now be standard operating procedures for all mammal collections. Resources and physical infrastructure vary greatly among institutions across the Western Hemisphere and this has played a large role in determining the types of tissue collections an institution possesses. Current collections range from ethanol-preserved samples at ambient temperatures, to those frozen in various systems and temperatures (−20°C deep freezer, −80°C ultracold freezer, −196°C vapor-phase N_2).

For many collections, tissue loans now represent the majority of outgoing loans (McLean et al. 2016) and many requests are now from research areas not previously served. As new questions and technologies arise, the limiting resource often will be availability of quality samples with associated temporal and spatial data. An encouraging development is the enhanced DNA extraction and high-throughput next generation sequencing techniques that are now allowing successful utilization of a variety of historic dry and fixed specimens for genome level molecular research (e.g., Rowe et al. 2011; Burrell et al. 2015; Hykin et al. 2015; McDonough et al. 2018). This extremely positive advance points to the increasing value of museum specimens through time, and will certainly increase use of specimens in the future. However, high-quality tissue, when available, remains the gold standard for many current research areas (e.g., transcriptomics, pathogen discovery). Natural history collections are already leaders in traditional specimen and data archiving infrastructure. In the future, curators and collection managers need to enhance our capabilities as major tissue biorepositories capable of not only addressing traditional questions but also imminent issues concerning emerging zoonotic diseases, human health, and environmental change (Dunnum et al. 2017). Because collections provide the physical infrastructure, knowledgeable personnel, and protocols necessary to carefully curate specimen vouchers and their associated molecular vouchers (e.g., DNA,

Table 2.—Specimen holdings of the 20 largest mammal collections in the Western Hemisphere. All the top 20 collections are electronically databased in some format, most are available via web-accessible data portals (e.g., VertNet, GBIF, SpeciesLink).

Collection		Specimens				Annual growth[a]	Specimens with tissue	Holotypes	Accredited
		2017	2007	1995	1975				
1.	United States National Museum of Natural History (USNM)	600,000	590,000	585,000	475,000	1,000/year	20,000	3198	1975, 1977, 1979
2.	University of New Mexico, Museum of Southwestern Biology (MSB)	302,000	146,000	116,000	35,000	15,600/year	173,000	21[b]	1975, 1987, 2008
3.	American Museum of Natural History (AMNH)	290,333	277,480	277,480	240,000	1,285/year	2,864	1107	1975, 1978
4.	University of California, Berkeley, Museum of Vertebrate Zoology (MVZ)	235,301	215,540	187,500	144,000	1,976/year	36,000	364	1975
5.	The Field Museum of Natural History (FMNH)	226,074	192,101	156,400	110,000	3,397/year	72,111	520	1975, 1983
6.	University of Kansas, Natural History Museum and Biodiversity Research Center (KU)	171,626	162,000	156,000	132,000	963/year	6,900	140	1975, 1987
7.	Collection of Recent Mammals, Museum of Texas Tech University (TTU)	138,689	100,592	70,000	23,000	3,809/year	100,000	23	1975, 1983, 2017
8.	University of Alaska Museum (UAM)	133,657	96,000	38,000	13,000	3,766/year	73,497	1	1975, 1983, 2009
7.	University of Michigan Museum of Zoology (UMMZ)	128,075	126,440	138,517[c]	111,800	164/year	7,289	127	1975, 1987
10.	Royal Ontario Museum (ROM)	125,000	110,000	100,000	68,360	1,500/year	23,000	27	1975, 1995
11.	Carnegie Museum of Natural History (CM)	120,361	118,500	113,994/	55,000	1,861/year	14,000	45	1975, 1984
12.	Universidade Federal do Rio de Janeiro, Museu Nacional (MN)	100,000	90,000	90,000		1,000/year	0	72	
13.	Natural History Museum of Los Angeles County (LACM)	98,800	98,000	97,000	43,000	80/year	4,000	22	1978
14.	Harvard University, Museum of Comparative Zoology (MCZ)	89,000	85,917	72,000	69,000	308/year	3,500	327	1975
15.	University of Oklahoma, Sam Noble Oklahoma Museum of Natural History (SNOMNH)	67,000	40,000	32,000	11,000	2,700/year	7,500	1	1975, 1982, 2009
16.	Washington State University, Charles R. Conner Museum (CRCM)	65,000	39,000	32,500	3,781	2,600/year	600	0	1977
17.	Biodiversity Research and Teaching Collection (formerly Texas Cooperative Wildlife Collection; TCWC)	64,500	59,000	56,500	27,000	550/year	6,554	30	1975, 1984
18.	Georgia Museum of Natural History (GMNH)	60,000	27,100	18,083	3,002	3,290/year	500	0	1985
19.	University of Washington, Thomas Burke Memorial Washington State Museum (UWBM)	57,000	52,000	40,000	7,400	500/year	9,000	2	1975
20.	Canadian Museum of Nature (formerly National Museum of Natural Sciences; CMN)	56,077	53,000	53,000	42,500	308/year	0	58	1975, 1987

[a]Growth is average annual increase over the past decade (2007–2017).
[b]Includes 179 parasite symbiotypes and 35 viral symbiotypes.
[c]Total included approximately 15,000 uncatalogued specimens.

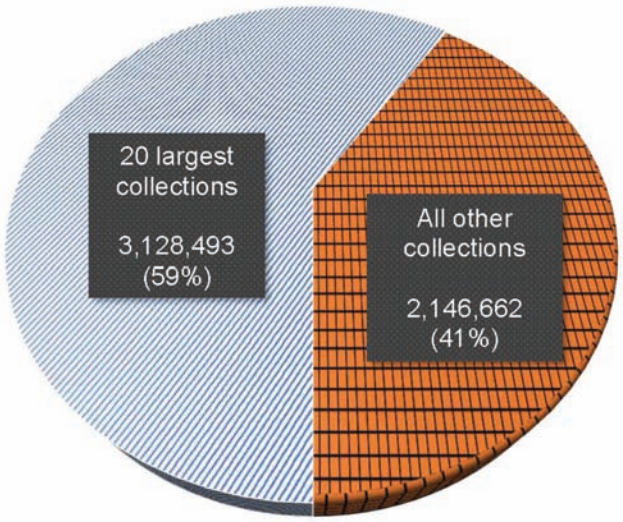

Fig. 6.—Percentage of specimens contained in the 20 largest collections in the Western Hemisphere.

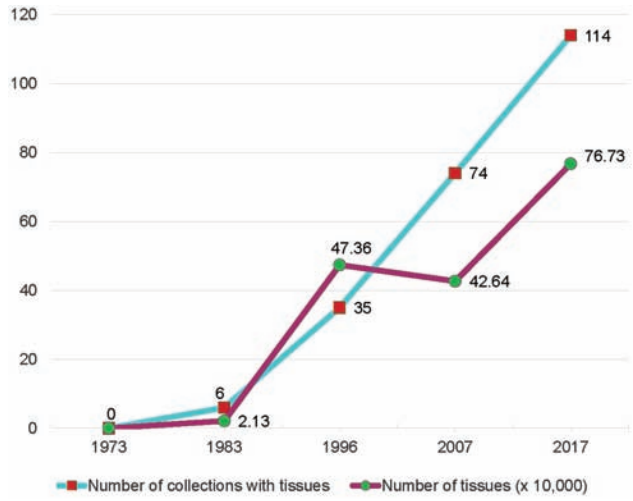

Fig. 7.—Historical trends in genomic resource collection growth (1975–2017).

tissue), they are ideal places to establish and build large-scale biorepositories (Astrin et al. 2013).

In light of the recent expansion of genomic resource collections, the ASM SCC has developed a set of standards and best practices for mammalian genomic resources collections and instituted a separate accreditation program for these types of collections (Phillips et al. in press). Collections archiving tissues should meet best practices and maintain cryopreservation at the coldest temperature possible, as that is the most effective method for the long-term stabilization of genetic samples (Zimkus and Ford 2014). Because molecular-based research and especially that requiring high-grade tissue (e.g., transcriptomes, RNA viruses) increases, storage at −190°C in vapor-phase nitrogen is the gold standard (Phillips et al. in press).

Digitization.—Over the past 2 decades, digitization of collections has been a major initiative within the natural history collection community, with NSF-funded programs in particular (e.g., MaNIS, VertNet, iDigBio) facilitating many digitization projects. In 2007, approximately 36% of collections and 77% of specimens were digitized in at least some form (Fig. 8). Since that survey, an additional 100 collections have been digitized, resulting in 62% of collections and 94% of specimens being digitized in some format. While a substantial number of collections remain undigitized, these are predominantly smaller collections, and only account for 6% of all specimens (Fig. 8). However, these smaller collections typically document regional and local faunas that may not be represented in larger, digitized collections. Thus, despite their relatively low numbers of specimens, these collections could add great value to the overall resource if digitized and made available to the global research community. Digitization would also allow the status of smaller collections to be monitored more efficiently (e.g., in SCC surveys). Indeed, accurate data on smaller collections will be critical given that these comprise the majority of Western Hemisphere collections and in view of existing data deficiencies and rates of collection transfers that we observed for these types of collections.

Currently, about 73% of digitized specimen data is accessible via an online aggregator (Fig. 9). Thus, of the total digitized data (94%; Fig. 8), approximately 21% would simply need standardization and formatting and could likely be uploaded to an aggregator with minimal effort. This simple step would greatly enhance those collections' impact and contribution to the overall specimen resource.

Although initial digitization is a critical first step in enhancing access to, and redundancy of, collection data, the most significant gains in accessibility and research usage come through data standardization (e.g., with use of Darwin Core terms), precise georeferencing of localities, and especially web accessibility of the data through searchable, relational databases (e.g., Arctos.db, specifysoftware.org). Distribution of these databases to larger data aggregators (e.g., VertNet, GBIF, SpeciesLink) is also key, and should be accompanied by direct links to specimen records and the various data already derived from them (e.g., GenBank, Isobank, Morphobank). Once standardized and accessible, researchers, students, educators, and the general public alike can easily investigate mammalian biology and biogeography through a host of applications and web-based tools (e.g., Google Earth, BerkeleyMapper, Map of Life, Tree of Life, Encyclopedia of Life). Many new initiatives are integrating digitized museum data and specimen-based research directly into education (Cook et al. 2014, 2016c; Lacey et al. 2017). These new uses of collections and associated data can be instrumental in training the next generation of specimen-based mammalogists as well as engaging teachers, students, and the public to help address scientific questions and societal issues such as climate change, biodiversity loss, and emerging pathogens (Cook et al. 2016c). Additionally, digitization allows a collection to provide efficient and accurate documentation of use and research impact to administrators or funding agencies. An effective mechanism for tracking research impact is the creation of a Google Scholar profile for studies involving use of a collection's specimens (Winker and Withrow 2013; Cook and Light, in press).

Taxonomic and geographic holdings.—Seventy-nine mammal collections (20% of all collections) reporting 3,691,406 specimen records (70% of all estimated specimens) were located in GBIF and SpeciesLink searches. That figure is comparable to, but slightly lower than, the number of specimen records reported to be web-accessible in our survey results (i.e., 73%). To use aggregated data as a broad proxy for the taxonomic and geographic scope of specimens contained in Western Hemisphere collections (i.e., in this and future surveys), it is necessary to ensure that major sampling biases do not exist. Because our analysis is limited to the level of mammalian orders, as well as to broad geographic regions above the level of individual countries, we believe taxonomic and geographic biases should be limited. It is more difficult to determine the taxonomic and geographic distribution of the 30% of specimens not available via GBIF and SpeciesLink. Based on physical locations of the unavailable collections, about one-third are from collections in Latin America and the Caribbean and two-thirds from US and Canadian collections. Under the assumption that specimen localities are, for the most part, from

Table 3.—Western Hemisphere mammal collections containing tissue holdings of over 10,000 specimens.

Collection		Tissue specimens	Accredited
1.	University of New Mexico, Museum of Southwestern Biology (MSB)	173,000	1975, 1987, 2008
2.	Collection of Recent Mammals, Museum of Texas Tech University (TTU)	100,000	1975, 1983, 2017
3.	University of Alaska Museum (UAM)	73,497	1975, 1983, 2010
4.	The Field Museum of Natural History (FMNH)	72,111	1975, 1983
5.	University of California, Berkeley, Museum of Vertebrate Zoology (MVZ)	36,000	1975
6.	Centro de Investigaciones Biológicas del Noroeste (CIB)	24,000	1999
7.	Royal Ontario Museum (ROM)	23,000	1975, 1995
8.	United States National Museum of Natural History (USNM)	20,000	1975, 1977, 1979
9.	Angelo State Natural History Collection (ASNHC)	14,000	1992
10.	Carnegie Museum of Natural History (CM)	14,000	1975, 1984
11.	Pontificia Universidad Católica del Ecuador, Museo de Zoología-División Mamíferos (QZAC)	12,800	2011
12.	University of Vermont, Zadock Thompson Natural History Collections (ZTNH)	12,000	NA

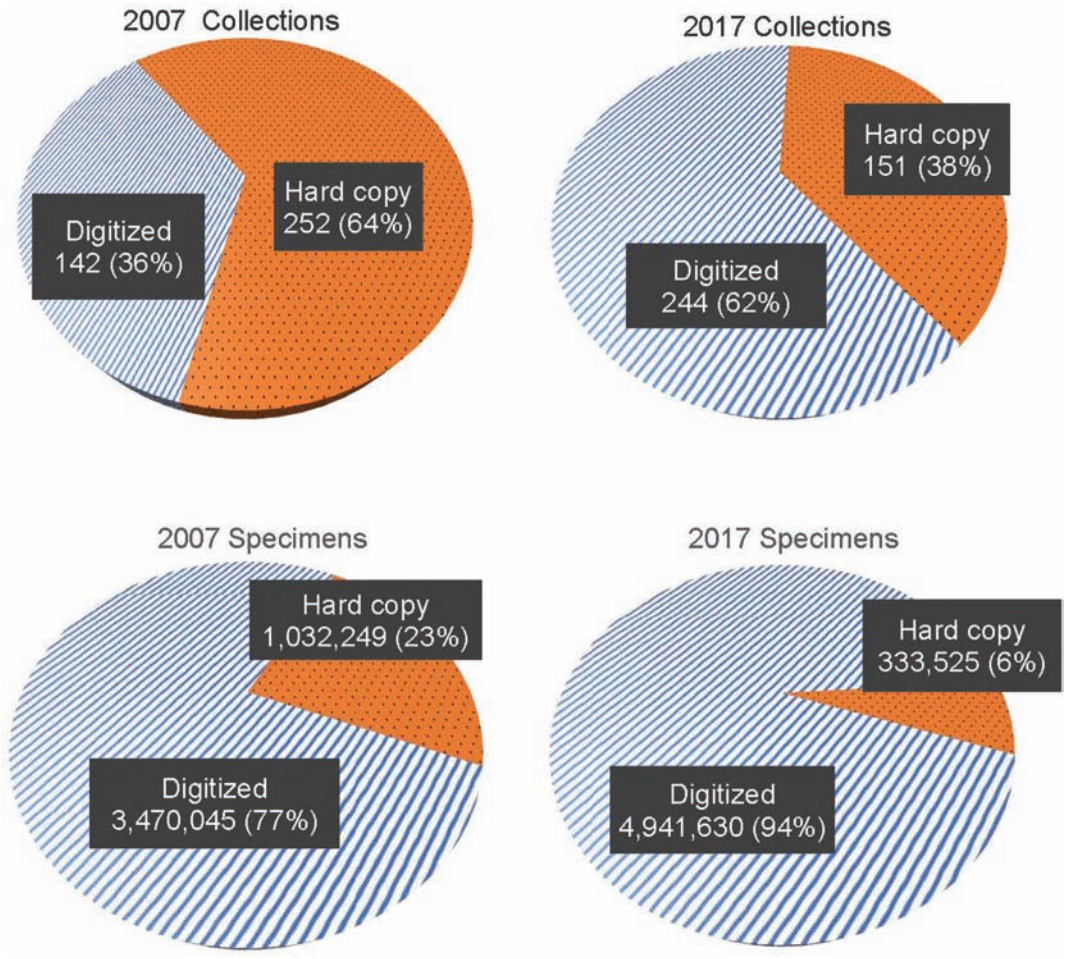

Fig. 8.—Growth of digitized collections and specimen data in collections of the Western Hemisphere (2007–2017).

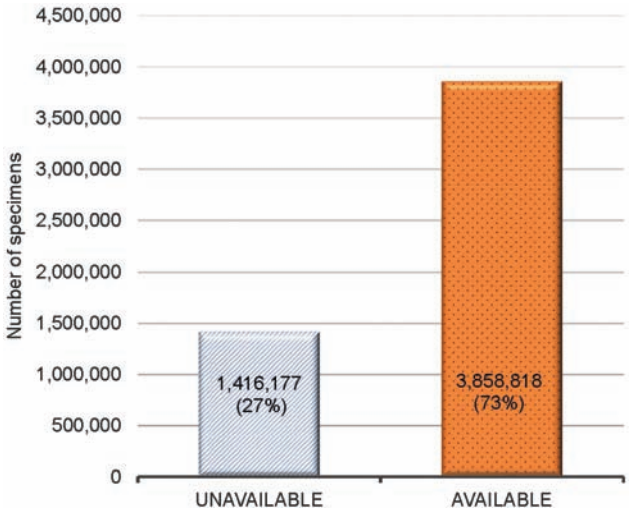

Fig. 9.—Percentage of specimen records digitized and available through online data aggregators (e.g., VertNet, GBIF, SpeciesLink).

the country in which the collection is based, approximately 531,000 specimens held in Latin American and Caribbean collections and 911,000 in Canadian and US collections are missing from our analyses. Because these percentages are not drastically different than total collection representation, we do not think our analyses based on available data should be heavily biased.

Taxonomic summary.—Taxonomic representation of the digitized specimen data roughly reflects the species diversity of mammalian orders in the Western Hemisphere at large. Rodentia is by far the most highly represented order (60% of all specimens), followed by Chiroptera, Carnivora, and Eulipotyphla. The orders Artiodactyla and Lagomorpha make up an additional 5% of specimens, while the remainder of mammalian orders comprise 3% of the total (Fig. 10). However, some smaller-bodied taxa (rodents, shrews, bats) are likely overrepresented in collections relative to their actual species diversity due to an easier ability to collect multiple specimens per species. For example, when compared to their proportion of extant mammalian species diversity (~40%—Burgin et al. 2018), rodents are significantly overrepresented (60%) and most other orders are underrepresented, a pattern seen specifically in US specimens as well (Malaney and Cook 2018).

The identities of the 6 most common mammalian orders are similar between the present survey and the last published survey (Hafner et al. 1997), notwithstanding recent taxonomic rearrangements that include abandonment of Insectivora and inclusion of cetaceans within Artiodactyla. Even when considering the potential for sampling biases in our data, important differences in relative representation of the various taxa exist between surveys; there is a substantial increase in the percentage of rodents and bats, and a corresponding decrease in carnivorans, artiodactyls, and lagomorphs. Chiropterans have replaced carnivorans in our survey as the second-most abundant group in collections. These changes in taxonomic proportions likely reflect the addition of regional Neotropical collections that tend to contain proportionally larger numbers of bat and rodent species (and potentially numbers of specimens as well).

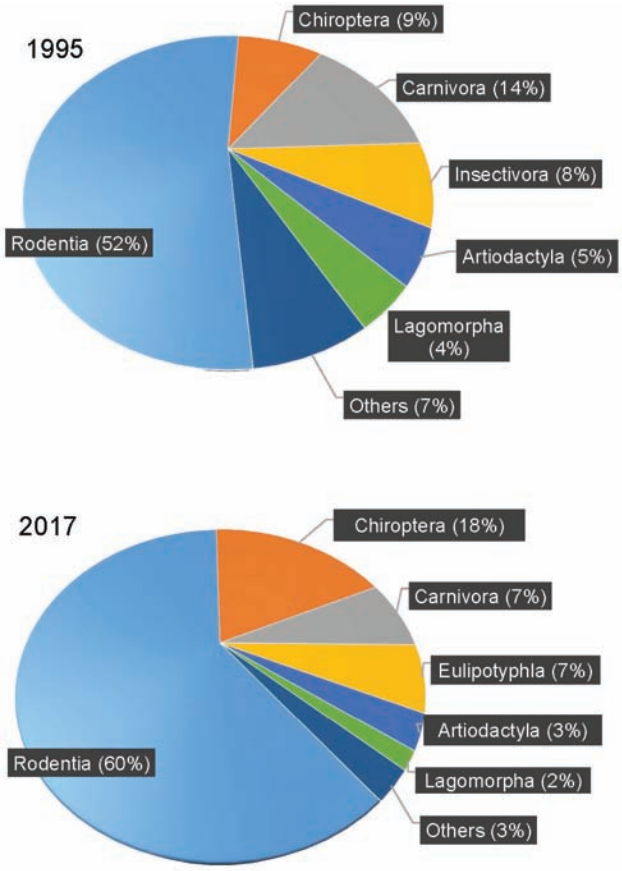

Fig. 10.—Taxonomic breakdown of specimens held in mammal collections of the Western Hemisphere in 1995 (Hafner et al. 1997) and 2017 (this study).

Geographic summary.—Mammal collections of the Western Hemisphere currently contain specimens from at least 238 countries, country subdivisions, or territories distributed across the globe. In the 1997 survey, 83% of specimens were from localities within the United States, 8% from Canada, 3% from Central and South America combined, 2% from Mexico, and the remaining 5% from all other countries (Hafner et al. 1997; Fig. 11). Material from the United States now accounts for just over one-half of the total, with a quarter now from Latin American countries, and over 16% from non-Western Hemisphere countries or territories (Fig. 11). Even taking into consideration the larger number of undigitized North American than Latin American specimens, there is a clear movement toward a more even geographic distribution of specimens. This is likely a result of many more Latin American collections being included in the current survey, as well as a decrease in collecting within the United States (Malaney and Cook 2018).

ASM accreditation.—A set of basic curatorial standards (Supplementary Data SD2) was established by the ASM SCC to provide minimum standards for the archiving, curation, and scientific accessibility of mammal collections and associated data. The accreditation process was developed to assist institutions with meeting these standards and to facilitate improvements and institutional support for their collections. Designation as an ASM accredited collection signifies adherence to curatorial

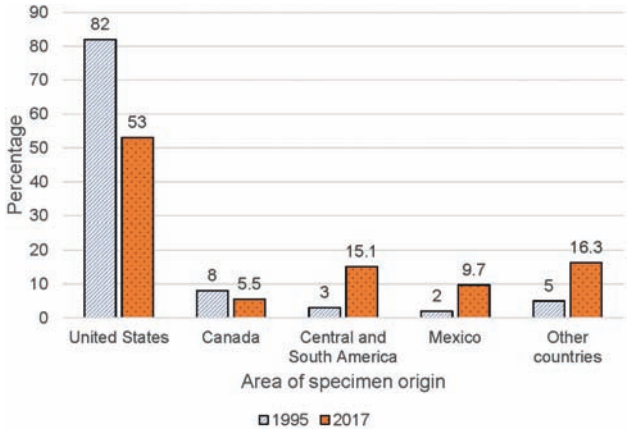

Fig. 11.—Geographic distribution of specimens held in mammal collections of the Western Hemisphere. Bars represent percentages of total specimens from each geographic region as of 1995 (Hafner et al. 1997; diagonal lined) and in the present survey (dotted).

best practices and a commitment to the long-term stewardship and accessibility of deposited specimens and data.

Eighty collections (69 from within the United States and 11 located in other countries) are currently ASM accredited (Supplementary Data SD3). The specimens held in these collections represent about 77% (4,051,735) of all specimens held in the Western Hemisphere. Although it is encouraging that this majority resides in accredited collections, a million additional specimens are held in over 300 unaccredited institutions, highlighting a critical need to engage small-to-medium-sized collections in accreditation discussions. Hafner et al. (1997) listed 65 accredited collections, and only 14 new collections have been accredited in the intervening 2 decades (in addition to 8 re-accreditations). Furthermore, substantial contraction has occurred over this period and 6 previously accredited collections (NMMNH, SUVM, TNHC, VPIMM, UIMNH, and UM) have been partially or fully transferred to other institutions (Supplementary Data SD1).

Given these trends, a concerted effort by the SCC and the ASM is warranted to increase the number of accredited collections. Hafner et al. (1997) discussed a new accreditation procedure, "Initial Accreditation," designed to accelerate the pace at which Latin American collections could receive accreditation. This was to be accomplished through preliminary accreditation without requiring a site visit by an ASM SCC member. This endeavor has clearly fallen short of its goals because, despite the large increase in Latin American collections in our survey, only 5 have been accredited to date. To achieve highest standards in deposition and maintenance of specimens, we must work to increase the number of accredited collections both nationally and internationally. Renewed efforts by the ASM and SCC to accredit such collections will also play an important role in future survey efforts. Finally, engaging Latin American mammal societies and collections in the ASM accreditation process is a critical first step, but it may also be practical going forward to provide support for the establishment of their own accreditation processes.

Health of the resource.—Systematic collections of mammals in the Western Hemisphere remain an exceptional resource for research on the ecology, evolution, and conservation of mammalian biodiversity. McLean et al. (2016) found that almost 25% of articles published in the *Journal of Mammalogy* from 2005 to 2015 used these collections in some way. As traditional specimen types are augmented with new materials (e.g., genomic resources, associated parasites, microbiomes), our concept of voucher specimens evolves (Kageyama et al. 2007), and as all of these materials are increasingly digitized and discoverable to the broader research community, their potential to contribute to biodiversity science and important societal questions related to our changing planet and human health increase significantly (Cook and Light, in press). Several caveats related to methodologies and available sampling notwithstanding, the present survey documents growth in the number of specimens, large increases in genomic resource collections and digitization and web accessibility, slight shifts in proportional representation of taxonomic groups, and increasing geographic balance relative to previous surveys.

Negative trends seen in previous surveys are also detected here, including a continued decline in rate of growth of the number of collections over the past 2 decades (Fig. 1) as a result of both a slowdown in origination of new collections and consolidation of existing collections. Although consolidation of collections is an attractive option for under-supported collections, the current climate of poor funding and waning institutional support also endangers valuable regional collections. This is a trend that is not likely to change, and thus the ASM as a whole and SCC specifically, must continue to monitor the community and help to identify threatened collections as well as the ability of larger collections to continue consolidating such collections.

Compounding the problem are issues related to maintaining the institutional relevance of mammal collections, such as increased difficulty in obtaining scientific collecting permits, IACUC constraints in training undergraduates in field collecting techniques, and a trend in hiring mammalogists to curate existing collections whose research programs are not explicitly specimen-based. To mitigate this chronic threat, curators and collection managers (with support from ASM) should be proactively educating university administrators about the long-term financial investments made in building and maintaining these resources (Bradley et al. 2012, 2014; Baker et al. 2014), as well as the potential of these research collections to help meet institutional scientific, educational, and outreach mandates (Cook and Light, in press).

When assessing how effectively Western Hemisphere collections have targeted global mammal diversity, we found that current holdings are lacking. We binned countries based on their numbers of endemic mammal species and found countries of highest mammalian endemicity were the least-well sampled in Western Hemisphere collections (Fig. 12). Total numbers of specimens were not only extremely low but the majority of specimens were also from very early expeditions, with very few specimens having been collected over the past 40 years. Thus, we lack both spatial and temporal coverage in these biologically rich and heavily impacted areas. These findings, coupled with the reality that in many of these countries the natural history collections are among the most challenged globally (Astrin and Schubert 2017), leave a large gap in our ability to address

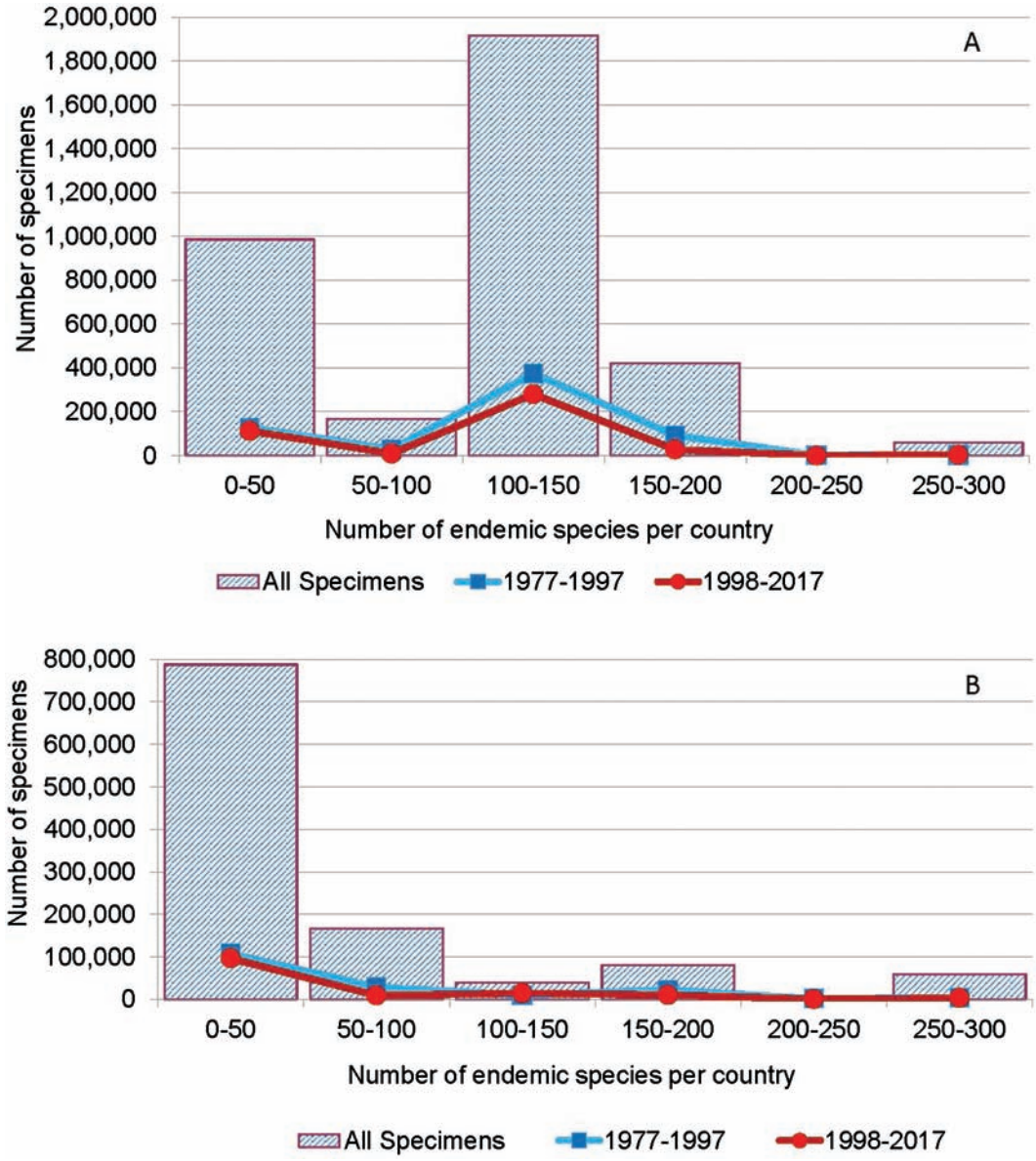

Fig. 12.—A) Numbers of specimens in Western Hemisphere mammal collections from countries of varying levels of mammalian species endemicity. Countries are binned by their numbers of endemic mammalian species as summarized by the International Union for Conservation of Nature (IUCN 2017). Hatched bars represent total numbers of specimens in collections available from each endemicity bin. Lines represent numbers of specimens collected specifically from 1977 to 1997 (squares) and from 1998 to 2017 (circles; i.e., since the last published survey of the ASM Committee on Systematic Collections—Hafner et al. 1997), and B) same data with the 3 most-represented countries removed (United States, Mexico, Canada).

questions in countries that contain the majority of our planet's biological diversity.

One of the greatest threats to the vitality of the collections resource is the decrease in specimen-collecting efforts overall (McLean et al. 2016; Hope et al. 2018), and within the United States specifically (Malaney and Cook 2018). The coarse and time-averaged metrics of collections growth used in our survey therefore belie a more precipitous decrease in specimen acquisition for some taxa and geographic areas. The masking of this trend can be partially attributed to inclusion of previously unreported collections to the survey and perhaps a shift to collecting in non-US locales as opposed to monitoring of biodiversity within the United States. We see a pattern of relatively low specimen growth across the larger and historically active collections (Table 2) and note issues with decreased funding that not only impede growth, but threaten the sustainability of even our most prominent of collections, the Biological Survey Unit at the United States National Museum of Natural History (Sikes et al. 2018).

Despite these troubling trends, some clear opportunities for reversing the decline in US sampling exist, but these require, in part, engagement of nontraditional entities by museum professionals. State game and fish departments and federal agencies (e.g., USFWS, USDA) process, and subsequently dispose of,

tens of thousands of carnivorans and ungulates each year from hunting and control activities. Over half of the US state wildlife agencies do not require deposition of collected wildlife specimens in museum collections (McLean et al. 2016). Likewise, state public health departments and the Centers for Disease Control and Prevention collect many thousands of small mammals during routine monitoring or disease investigations both nationally and worldwide. These represent opportunities for adding already collected specimens and typically just require contact and partnership with these agencies.

A second critical component lies with federally funded long-term ecological monitoring programs (e.g., LTER sites [https://lternet.edu/], National Park Service surveys) that emphasize noninvasive sampling or mark-release work as opposed to specimen collection. An example is the recently initiated National Ecological Observatory Network (NEON; http://www.neonscience.org/). This network was established to create a nationwide (continental United States, Alaska, Hawaii, and Puerto Rico) web of environmental monitoring sites (Kao et al. 2012) to be sampled over the ensuing 30 years. This presented a unique opportunity to build high-quality collections of holistic mammal specimens (e.g., full vouchers, tissues, and associated parasites and pathogens—Cook et al. 2016a) from across the United States, spanning this critical period of environmental change. The collections community was involved in early discussions on the objectives and desired products of this project, but upon implementation, environmental monitoring trumped building robust specimen-based infrastructure. Mammal collecting is part of the NEON sampling protocol; however, current methods (primarily mark-recapture with minimal sampling of hair, blood, and DNA) result in either volumes that are too small for multiple uses or sample types that are inadequate to address the majority of specimen-based research questions. Protocols stressing a more rigorous, voucher-based sampling regime of the small mammal communities, and thus their associated parasite and pathogen communities, have been proposed and endorsed by mammalogists and parasitologists (Cook et al. 2016b). The mammal research community must continue to encourage funding agencies to require that sampling be conducted in a manner that ensures usefulness of specimens for a breadth of research questions (e.g., Suarez and Tsutsui 2004).

To conclude, while we find the overall health of Western Hemisphere collections to be adequate in some areas, such as large increases in mammalian tissue collections and significant gains in digitization and accessibility, threats to long-term growth and vitality of these resources also have been clearly identified and are likely to worsen before they improve. Significant expansion of the resource along with appropriate levels of funding will be required to meet the challenges ahead for mammalogists and other users (e.g., Morrison et al. 2017), and to ensure samples are broad and varied enough that unanticipated needs in the future can be addressed (Dunnum and Cook 2012; Schindel and Cook 2018). It is incumbent upon the entire community of mammalogists to think critically and creatively about the role collections will play in the future, and to work together to develop a vision for "Next Generation Collections" (Schindel and Cook 2018) that are capable of advancing mammalogy and serving as a nexus for global environmental research and informatics.

Index and directory of the mammal collections of the Western Hemisphere.—As a supplement to this survey, we provide the updated index and directory of collections containing 395 accounts (Supplementary Data SD4) representing the most current information available when the collection provided its data. The SCC survey was initiated in 2014 and continued with additions through March 2018; thus, data for accounts range from 6 months to 4 years old at the time of this publication. For collections that did not respond to information requests, their data were updated when possible through website information or literature (Bezerra 2012; Lorenzo et al. 2012). When no updated information could be located, data from the most recent survey responded to were retained and the source noted in the "Survey data" section (e.g., Hafner et al. 1997; Yates et al. 1987). An alphabetical list of acronyms for the collections is included at the beginning of the directory. Accounts are arranged alphabetically by country, state or province, then collection name. Each account is comprised of the following data fields:

Collection Title (Collection Acronym)
Institution, address, City, State, zip code, Country
Contact: Name (e-mail address), phone
Additional contacts: Name (e-mail address), phone
Website*: website url;* ***Data availability:*** *type of collection data catalog; data aggregator;* ***Holdings:*** *number of specimens; number of holotypes;* ***Tissues:*** *number of tissues and preservation type;* ***Taxonomic emphasis:*** *main focus or strength of holdings;* ***Geographic emphasis:*** *main geographic focus or strength;* ***Other incorporated collections:*** *names of other collections held;* ***Former acronyms:*** *previous acronyms used.*
Survey data: *source of survey data*
ASM accreditation: *date accredited by ASM*

Acknowledgments

We are grateful to the many curators, collection managers, students, and other points of contact at the collections included in this survey for providing updated information, but more importantly for their efforts in building, maintaining, and facilitating access to this vital scientific infrastructure. S. Liphardt created the collection location maps and J. Salazar-Bravo provided the Spanish translation of the abstract. Thanks to J. Cook for valuable insight and comments on this manuscript and an unyielding advocacy for collections. We thank M. Hafner and J. Light for thoughtful and thorough reviews that improved the manuscript. Funds allocated by ASM Board for publication.

Supplementary Data

Supplementary data are available at *Journal of Mammalogy* online.
Supplementary Data SD1.—Mammal collections closed or incorporated into other collections between 1997 and 2017.

Supplementary Data SD2.—Basic curatorial standards for systematic collections of mammals.

Supplementary Data SD3.—Mammal collections accredited by the American Society of Mammalogists.

Supplementary Data SD4.—Index and directory of the mammal collections of the Western Hemisphere.

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